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COMPARISONS OF RATCHETTING ANALYSIS METHODS USING RCC-M, RCC-MR AND ASME CODES

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ABSTRACT

The present paper compares the simplified ratcheting analysis methods used in RCC-M, RCC-MR and ASME with some examples. Firstly, comparisons of the methods in RCC-M and efficiency diagram in RCC-MR are investigated. A special method is used to describe these two methods with curves in one coordinate, and the different conservation is demonstrated. RCC-M method is also be interpreted by SR (second ratio) and v (efficiency index) which is used in RCC-MR. Hence, we can easily compare the previous two methods by defining SR as abscissa and v as ordinate and plotting two curves of them. Secondly, comparisons of the efficiency curve in RCC-MR and methods in ASME-NH APPENDIX T are investigated, with significant creep. At last, two practical evaluations are performed to show the comparisons of aforementioned methods.

Keywords: Ratcheting, Thermal, Stress, Creep.

1. INTRODUCTION

The purpose of this paper is, with some examples, to compare the simplified ratcheting analysis methods used in RCC-M [1], RCC-MR [2] and ASME [3]. It includes two parts as follows:

-- Comparisons of RCC-M and RCC-MR, with negligible creep.
-- Comparisons of RCC-MR and ASME, with significant creep.

2. COMPARISONS OF RCC-M AND RCC-MR, WITH NEGLIGIBLE CREEP

In this part, comparisons of the methods in RCC-M B3234.8 (edition 2000) and efficiency curve in RCC-MR RB3261.113 (edition 2002) are investigated. And we note that, the methods in RCC-M and those in ASME are identical, with negligible creep.

In RCC-M B3234, the thermal ratcheting method is:

Definitions: $y'=Q/S_y$, and $x=P_m/S_y$
-- Q = maximal allowable value of the range of thermal stress
-- P_m = maximal general primary membrane stress due to pressure
-- S_y = yield stress

a) If temperature in linear variation along the wall, the relation is:
$y'=1/x$ while $0<x\leq 0.5$
$y'=4(1-x)$ while $0.5<x<1$

b) If temperature in parabolic variation along the wall, the relation is:

$y'=5.2(1-x)$ while $0.615\le x<1$

While $x<0.615$:

x=	0.3	0.4	0.5
y'=	4.65	3.55	2.7

In RCC-MR RB3261.113, the thermal ratcheting method, i.e. "efficiency diagram"，is:

Before obtaining the effective primary stress intensity (P1), it is necessary to calculate the relative variation in secondary stress in relation to the primary stress considered. This introduces the notion of secondary ratio in relation to the primary membrane stress and in relation to the sum of primary stresses.

These secondary ratios are evaluated in the following way:

a) Secondary ratio in relation to the primary membrane stress

The secondary ratio SR_1 in relation to the primary membrane stress is determined for the period concerned by means of the thermal stress range Q and maximal primary membrane stress Pm by the following equation:

$$SR_1=Q/P_m$$

b) Secondary ratio in relation to the sum of primary stress

The secondary ratio SR_2 in relation to the primary stress is determined for the period concerned by means of the thermal stress range Q and the maximal sum of primary stress (P_L+P_b) by the following equation:

$$SR_2=Q/(P_L+P_b)$$

In this paper, since the sum of primary stress is not considered in RCC-M B3234.8, SR_2 will not be discussed later, only SR_1 will be discussed. Moreover, to simplify it, SR_1 will be replaced with SR in the following text.

Once the secondary ratio SR is known in relation to the primary membrane stress, an efficiency index is obtained using an efficiency diagram as given in figure RCC-MR RB3261.113a.

The efficiency diagram for progressive deformation gives the relationship between the secondary ratio SR and the efficiency index v. It is defined by:

$SR \le 0.46$ $\qquad v = 1$

$0.46 < SR < 4$ $\qquad v = 1.093-0.926SR^2/(1+SR)^2$

$SR \ge 4$ $\qquad v = 1/\sqrt{SR}$

Once the efficiency index is known, the efficiency primary membrane stress intensity is obtained in the following way:

$$P = P_m/v$$

In order to compare the two methods described in previous paragraphs, refer to a special method [4], we suppose:

$v = x$, and $SR=y'/x$,

a) Considering the first relation (linear) of RCC-M, We have:

-- If $y'\ge 2$ and $0<x\le 0.5$, i.e. $(y'/x) \ge 4$, we get: $x\cdot y = 1$

-- If $0<y'<2$ and $x>0.5$, i.e. $0< (y'/x) <4$, we get: $x+y/4 = 1$

So,

-- When $SR \ge 4$, i.e. $(y'/x) \ge 4$, we get:

$x\cdot y' = 1$

$\Rightarrow x = 1/y'$

$\Rightarrow x^2 = 1/(y'/x) = 1/SR$

$\Rightarrow v^2 = 1/SR$

$\Rightarrow v = 1/SR^{0.5}$

-- When $0< SR < 4$, i.e. $0< (y'/x) <4$, we get:

$x+y'/4 = 1$

$\Rightarrow 1+y'/4x = 1/x$

$\Rightarrow x = 1/(1+y'/4x) = 1/(1+SR/4)$

$\Rightarrow v = 1/(1+SR/4)$

b) Considering the 2nd relation (parabolic) of RCC-M, We have:

-- If $0<y'\le 2.002$ and $0.615\le x<1$, so $0< (y'/x) \le 3.2553$, i.e. $0< SR \le 3.2553$, we get:

$y' = 5.2\cdot(1-x)$

$\Rightarrow x = 1/(1+y'/5.2x)$

$\Rightarrow v = 1/(1+SR/5.2)$

-- If $y'>2.002$ and $0< x<0.615$, so. $(y'/x) >3.2553$, i.e. $SR>3.2553$, we get:

v = 0.3 0.4 0.5
SR = 15.5 8.875 5.4

So far, the RCC-M method can also be interpreted by SR and v. Hence, we can easily compare the previous two methods by defining SR as abscissa and v as ordinate and plotting two curves of them.

According to previous equations, we obtain data in table 1 and curves in figure 1.

Tab. 1 Comparisons of efficiency index, RCC-M(Linear) and RCC-M(Parabolic)

SR	**V(RCC-MR)**	**RCCM(Parabolic)**	**RCCM(Linear)**
0	1	1	1
0.1	1	0.981132075	0.975609756
0.46	1	0.918727915	0.896860987
0.5	0.990111111	0.912280702	0.888888889
0.6	0.96278125	0.896551724	0.869565217
0.7	0.93599654	0.881355932	0.85106383
0.8	0.91008642	0.866666667	0.833333333
0.9	0.885227147	0.852459016	0.816326531
1	0.8615	0.838709677	0.8
1.29	***0.79915423***	***0.801232666***	0.756143667
1.5	0.75964	0.776119403	0.727272727
1.9	0.695513674	0.732394366	0.677966102
2	0.681444444	0.722222222	0.666666667
3	0.572125	0.634146341	0.571428571
4	***0.5***	0.578252033	***0.5***
5	0.447213595	0.522357724	0.447213595
5.4	0.430331483	0.5	0.430331483
6	0.40824829	0.482733813	0.40824829
7	0.377964473	0.453956835	0.377964473
8	0.353553391	0.425179856	0.353553391
8.875	0.335672543	0.4	0.335672543
9	0.333333333	0.398113208	0.333333333
10	0.316227766	0.383018868	0.316227766
15.5	***0.254000254***	***0.3***	***0.254000254***
20	0.223606798	**	0.223606798
30	0.182574186	**	0.182574186
40	0.158113883	**	0.158113883
50	0.141421356	**	0.141421356
60	0.129099445	**	0.129099445
70	0.119522861	**	0.119522861
80	0.111803399	**	0.111803399
90	0.105409255	**	0.105409255
100	0.1	**	0.1

**: no data in this range in RCC-M

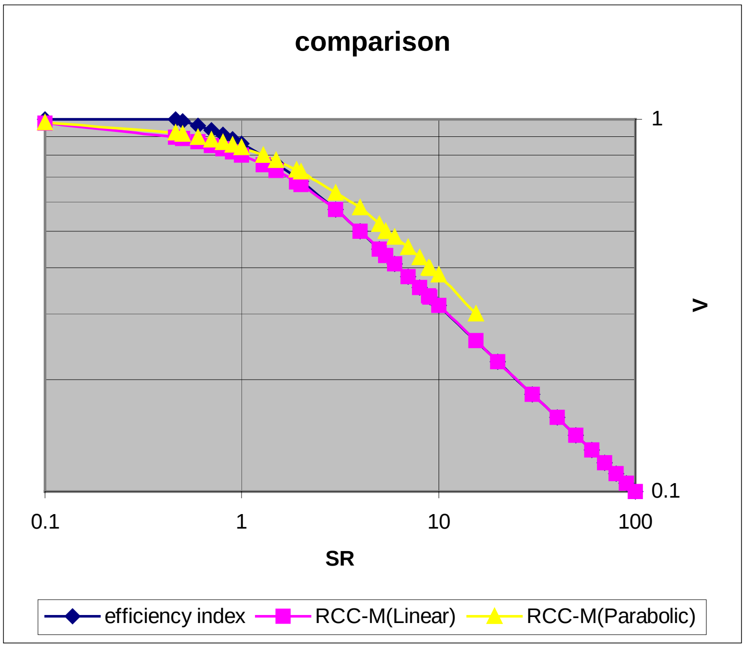

Fig. 1 Comparisons of efficiency index, RCC-M(Linear) and RCC-M(Parabolic)

From Table 1 and Figure 1, we conclude as follows:

a) When 0< SR ≤ 15.5, RCC-M 1st method (Linear) is more conservative than RCC-M 2nd method (Parabolic)

b) When 0< SR ≤ 4, RCC-M 1st method (Linear) is more conservative than RCC-MR method (efficiency curve)

c) When SR> 4, RCC-M 1st method (Linear) is identical with RCC-MR method (efficiency curve)

d) When 0< SR ≤ 1.29, RCC-M 2nd method (Parabolic) is more conservative than RCC-MR method (efficiency curve)

e) When 1.29< SR ≤ 15.5, RCC-M 2nd method (Parabolic) is less conservative than RCC-MR method (efficiency curve)

f) When SR> 15.5, RCC-M 2nd method (Parabolic) does not present detail data.

3. COMPARISONS OF RCC-MR AND ASME, WITH SIGNIFICANT CREEP

In this part, comparisons of the efficiency curve in RCC-MR RB3262.11(edition 2002) and methods in ASME-NH APPENDIX T(edition 2001) are investigated, with significant creep.

In RCC-MR RB3262.11, the thermal ratcheting method is:

Firstly, determine the Secondary Ratio SR:

1) Determine secondary ratio in relation to the primary membrane stress, SR_1,

$SR_1 = Q/P_m$

2) Determine secondary ratio in relation to the sum of primary stresses, SR3,

$SR_3 = Q/(P_L+\Phi P_b)$

To apply this rule, the primary bending stress is multiplied by factor Φ taking account of the effect of creep on this stress category.

Secondly, determine the Efficiency index v. Once the secondary ratios are known in relation to the primary membrane stress and in relation to the sum of primary stresses, for each of these values, an efficiency index is obtained using an efficiency diagram as given in figure RB 3261.113a. The relation between the secondary ratio SR and the efficiency index v is the same as that listed in part 2 of this paper.

Thirdly, determine Effective primary stress intensity P:

a) Determine effective primary membrane stress, P_1,

$P_1 = P_m/v_1$

b) Determine effective primary membrane stress + bending stress, P_3,

$P_3 = (P_L+\Phi P_b)/v_3$

At last, check the following limits of Level A criteria:

a) $P_1 \le 1.3Sm$; $P_3 \le 1.5 \times 1.3Sm$.

b) The plastic strain + associated creep strain at 1.25 times the effective primary membrane stress intensity P_1 should not exceed 1%.

c) The plastic strain + associated creep strain at 1.25 times the effective primary stress intensity of the sum of primary stresses corrected by the effect of creep P_3 should not exceed 2%.

In ASME-NH APPENDIX T (edition 2001), the thermal ratcheting method is (in this paper, only the elastic analysis and simplified inelastic analysis method are considered):

For elastic analysis, there are three tests presented in ASME T-1320,

--Test No. A-1,

$X+Y \le S_a/S_y$

$X \equiv (P_L+P_b/K_t) \div S_y$

$Y \equiv Q/S_y$

Sy=the average of the S_y values at the maximum (S_{yh}) and minimum (S_{yL}) wall averaged temperatures during the cycle being evaluated

Q=the maximum range of the secondary stress intensity during the cycle being considered

K_t, coefficient considering the effect of creep

S_a, the detail determination refers to ASME T-1322.

--Test No. A-2,

$X+Y \le 1$

--Test No. A-3,

For Test Number A-3, the limits of NB-3222.2(3Sm criteria), NB-3222.3(expansion stress intensity criteria), and NB-3222.5(thermal stress ratcheting criteria same as those of RCC-M described previously) shall be met and, in addition, other requirements shall be satisfied. The details refer to ASME T-1324.

For simplified inelastic analysis, other three tests are presented in ASME T-1330 to satisfy the strain limits：

--Test Nos. B-1 and B-2

First step, determine σ_c,

$\sigma_c = Z \cdot S_{yL}$

Z= X·Y, in regimes S2 and P for Test B-1

$Z = Y+1-2\sqrt{(1-X)Y}$, in regime S1 for Test B-1

Z=X, in regime E for Test B-1

σ_c ,effective creep stress which is used to determine a total ratcheting creep strain.

Z, dimensionless effective creep stress parameter for any combination of loading.

The regimes E, S1, S2 , P and effective creep parameter Z for test Nos. B-1 and B-3 are shown in Fig.2 (i.e.Fig.T-1332-1 of ASME Appendix T).

The determination of Z for Test B-2 is shown in Fig.3 (i.e.Fig.T-1332-2 of ASME Appendix T).

APPENDIX T

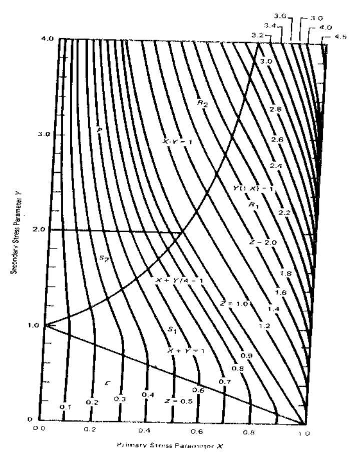

FIG. T-1332-1 EFFECTIVE CREEP STRESS PARAMETER Z FOR SIMPLIFIED INELASTIC ANALYSIS USING TEST NOS. B-1 AND B-3
[For Use Only When the Restrictions of T-1331(a) for Test No. B-1 Are Met]

Fig.2 the regimes E, S1, S2, P and effective creep parameter Z for test Nos. B-1 and B-3

Fig. T-1332-2 2001 SECTION III, DIVISION 1 - NH

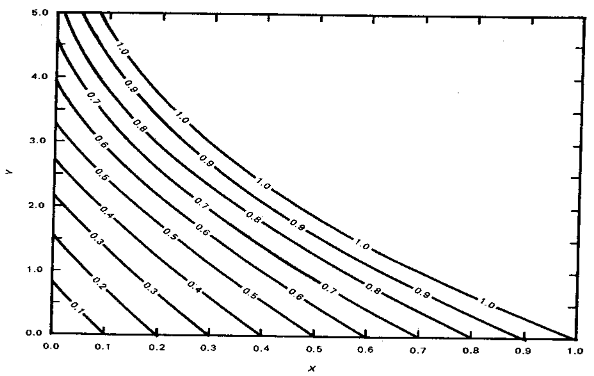

FIG. T-1332-2 EFFECTIVE CREEP STRESS PARAMETER *Z* FOR SIMPLIFIED INELASTIC ANALYSIS USING TEST NO. B-2
(Applicable to General Structures)

Fig.3 The determination of Z for Test B-2

Second step, determine creep ratcheting strain and verify the strain limits. The creep ratcheting strain is determined by multiplying σ_c by 1.25 and evaluating the creep strain associated with the 1.25 σ_c stress held constant throughout the temperature-time history of the entire service life. The resulting value shall be limited to 1% for parental metal and ½% for weld metal.

Note that, Test B-1 can be used only for:

a) Axisymmetric structures subjected to axisymmetric loadings and away from local structural discontinuities; or

b) General structures in which the peak through-the-wall thermal stress is negligible (i.e., the thermal stress distribution is linear through the wall).

Test B-2, which is more conservative, is applicable to any structure and loading.

Test B-3, has two main characters:

a) Only applicable to axisymmetric loadings and away from local structural discontinuities.

b) The procedure of it may be used for cycles in regimes R1 and R2. This procedure may also be applied to cycles in the s1 and s2, and P regimes in order to minimize the conservatism in the calculated strains when there are a few relatively severe cycles.

The total inelastic strains accumulated in the lifetime of the component are given by:

$\Sigma\varepsilon = \Sigma\nu + \Sigma\eta + \Sigma\delta$

Where

$\Sigma\delta$ = the enhanced creep strain increments due to relaxation of the [σ_c]stresses.

$\Sigma\eta$ = the plastic ratchet strain increments for cycles in regimes S1, S2, P, R1, and R2.

$\Sigma\nu$ = the inelastic strains obtained from the isochronous curves as in the test No.B-1, ignoring the increase of σ_c stress for cycles evaluated using T-1333 in ASME-NH Appendix T and detailed inelastic analyses.

According to the previous methods presented in RCC-MR and ASME Appendix T, Two practical evaluations are performed here to show the comparisons of aforementioned methods in the following paragraphs.

1st evaluation is:

For mod 9Cr-1Mo steel (material data are given in RCC-MR A3-18S). Case of a vessel submitted to internal pressure P and to a linear thermal gradient T in the thickness. The mean temperature in the thickness is $_{mean}$, *and the life time is t.*

One load cycle includes 2 extreme states (have same Tmean):

a) Structure at Tmean(=400°C,450°C,500°C), DT=0

b) Structure at Tmean(=400°C,450°C,500°C), DT=60

We consider that the pressure induces only membrane stress P_m, *and that the stress due to the linear thermal gradient T is: E.α. T/(2.(1-)).*

Perform the analyses for:

$_{mean}$: 400, 450, 500°C

P_m: $0.8S_m$, $0.9S_m$, S_m

T: 60°C, 80°C, 100°C

t: 1E5h, 4E5h

In order to simplify the comparison, the material properties data and formulas for creep strain calculations, which come from RCC-MR A3.18S, are used both for ASME Tests and RCC-MR criterions in Tab.2.

Tab.2 Comparison of ASME and RCC-MR with significant creep for 1st evaluation

$_{mean}$ (°C)	P_m (MPa)	Q (MPa)	t(h)	ASME Test Safety margin							RCC-MR Safety margin	
				3Sm	A-1	A-2	A-3	B-1	B-2	B-3	1.3Sm	ε (Total)
400	101.12	139.47	*1E5*	0.46	0.84	0.71	**	0.015	0.024	//	0.66	0.022
			4E5	0.46	0.84	0.71	**	0.021	0.035	//	0.66	0.033
400	156.91	134.82	*1E5*	0.56	**1.02**	0.86	**	0.028	0.043	//	0.77	0.053
			4E5	0.56	**1.02**	0.86	**	0.042	0.064	//	0.77	0.079
400	174.34	168.54	1E5	0.66	**1.20**	**1.05**	**	0.052	0.12	//	0.88	0.12
			4E5	0.66	**1.20**	**1.05**	**	0.076	0.18	//	0.88	0.17
450	129.95	101.46	*1E5*	0.47	0.93	0.72	**	0.065	0.096	//	0.67	0.10
			4E5	0.47	0.93	0.72	**	0.099	0.15	//	0.67	0.16
450	146.20	135.28	*1E5*	0.58	**1.13**	0.88	**	0.12	0.20	//	0.79	0.23
			4E5	0.58	**1.13**	0.88	**	0.20	0.43	//	0.79	0.50
450	162.44	169.1	1E5	0.68	**1.33**	**1.04**	**	0.20	0.65	//	0.90	0.56
			4E5	0.68	**1.33**	**1.04**	**	0.42	**1.94**	//	0.90	**1.59**
500	117.09	102	*1E5*	0.50	**1.18**	0.75	**	0.32	0.72	//	0.69	0.71
			4E5	0.50	**1.18**	0.75	**	0.91	**2.41**	//	0.69	**2.35**
500	131.72	136	*1E5*	0.61	**1.44**	0.92	**	0.73	**1.93**	//	0.81	**2.56**
			4E5	0.61	**1.44**	0.92	**	**2.43**	**7.10**	//	0.81	**9.54**
500	146.36	170	1E5	0.72	**1.70**	**1.08**	**	**1.74**	**10.2**	//	0.93	**8.40**
			4E5	0.72	**1.70**	**1.08**	**	**6.36**	**39.9**	//	0.93	**32.7**

**: Test A-3 is not suitable here since all of the values of 1.5Sy|T are above St.

//: Test B-3 is not suitable for regime E.

2nd evaluation is:

For mod 9Cr-1Mo steel (material data are given in RCC-MR A3-18S). case of a vessel submitted to internal pressure P and to a linear thermal gradient T in the thickness. The mean temperature in the thickness is θ_{mean}, *and the life time is t.*

One load cycle includes 2 extreme states (have different Tmean):

a) Structure at Tmean(=20°C), DT=0

b)Structure at Tmean(=400°C,450°C,500°C), DT=60

We consider that the pressure induces only membrane stress P_m, and that the stress due to the linear thermal gradient T is: $E.\alpha.$ $T/(2.(1-\nu))$.

Perform the analyses for:

$_{mean}$: 400, 450, 500°C

P_m: $0.8S_m$, $0.9S_m$, S_m

T: 60°C, 80°C, 100°C

t: 1E5h, 4E5h

The results of the comparisons using ASME Tests and RCC-MR criterions are listed in Tab.3.

Tab.3 Comparison of ASME and RCC-MR with significant creep for 2nd evaluation

mean (°C)	P_m (MPa)	Q (MPa)	t(h)	ASME Test Safety margin							RCC-MR Safety margin	
				3Sm	A-1	A-2	A-3	B-1	B-2	B-3	1.3Sm	ε (Total)
400	101.12	139.47	*1E5*	0.46	0.84	0.65	**	0.015	0.027	//	0.59	0.022
			4E5	0.46	0.84	0.65	**	0.021	0.045	//	0.59	0.033
400	156.91	134.82	*1E5*	0.56	**1.02**	0.79	**	0.028	0.079	//	0.69	0.053
			4E5	0.56	**1.02**	0.79	**	0.042	0.12	//	0.69	0.079
400	174.34	168.54	1E5	0.66	**1.20**	0.93	**	0.052	0.14	//	0.79	0.12
			4E5	0.66	**1.20**	0.93	**	0.076	0.21	//	0.79	0.17
450	129.95	101.46	*1E5*	0.47	0.93	0.64	**	0.065	0.14	//	0.58	0.10
			4E5	0.47	0.93	0.64	**	0.099	0.26	//	0.58	0.16
450	146.20	135.28	*1E5*	0.58	**1.13**	0.78	**	0.12	0.32	//	0.68	0.23
			4E5	0.58	**1.13**	078	**	0.20	0.78	//	0.68	0.50
450	162.44	169.1	1E5	0.68	**1.33**	0.92	**	0.20	0.68	//	0.78	0.56
			4E5	0.68	**1.33**	0.92	**	0.42	**2.04**	//	0.78	**1.59**
500	117.09	102	*1E5*	0.50	**1.18**	0.63	**	0.32	**1.16**	//	0.56	0.71
			4E5	0.50	**1.18**	0.63	**	0.91	**4.10**	//	0.56	**2.35**
500	131.72	136	*1E5*	0.61	**1.44**	0.77	**	0.73	**2.81**	//	0.66	**2.56**
			4E5	0.61	**1.44**	0.77	**	**2.43**	**10.5**	//	0.66	**9.54**
500	146.36	170	1E5	0.72	**1.70**	0.91	**	**1.66**	**14.0**	//	0.76	**8.40**
			4E5	0.72	**1.70**	0.91	**	**6.03**	**55.1**	//	0.76	**32.7**

**: Test A-3 is not suitable here since all of the values of 1.5Sy|T are above St.
//: Test B-3 is not suitable for regime E.

From Tab.2 and Tab.3, some conclusions are made here:

a) ASME Test A-1 is more conservative than A-2;

b) ASME Test B-2 is more conservative than B-1, but suitable for more general case.

c) Basically, Test A-1 and A-2 are easily to apply, but more conservative than B-1 and B-2;

d) RCC-MR is very close to ASME Test B-2; meanwhile, these two methods both are suitable for more general case.

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