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CHARACTERISTICS OF A STANDARD TUBE

By
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September 30, 1944

Hanford Works
Richland, Washington

Technical Information Extension, Oak Ridge, Tennessee

AEC RESEARCH AND DEVELOPMENT REPORT

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September 30, 1944

CHARACTERISTICS OF A STANDARD TUBE

Transmitted herewith are three charts showing the temperatures attained at various points of the slug in a typical tube of a flat ended pile:

- Chart I: Characteristics of Standard Tube at Standard Water Rate - 21.0 g.p.m.
- Chart II: Same - Enlargement of the lower fourth of Chart I
- Chart III: Value and location of Maximum Temperature

These charts are based on the latest information available to us on September 15, 1944. They are valid for any power load when the water rate is 21.0 g.p.m., whatever may be the inlet temperature of the cooling water. A simple method is provided for correcting the curves for deviations in water rate from 21 g.p.m. (cf. Appendix III).

There is appended a detailed explanation of their derivation and of the evaluation of the constants involved in their construction. The current discovery that the pile will be self-poisoned by transient fission products means that the true temperature curves will be somewhat flatter than those here presented.

Fifteen copies of each of the charts have already been issued to P. W. Cross for the use of the Technical Department.

TECHNICAL DIVISION
THOMAS B. RICH

Thomas B. Rich

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~~UNCLASSIFIED~~**I. DERIVATION OF GENERAL FORMULAE****II. EVALUATION OF CORRECTIONS**

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III. EFFECT OF DEVIATION FROM THE STANDARD WATER RATE**DISCLAIMER**

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I. DERIVATION OF GENERAL FORMULAR.

According to elementary pile theory in which self-poisoning is neglected², the local rate of power generation in a flat ended pile varies along the length of a tube as $\cos \pi z / 2L$, where z is distance measured, in the direction of water flow, from the mid-plane of the loading and L is the effective half-length of the pile. In consequence, if temperatures are measured above the inlet water temperature, the temperature of the cooling water at distance z from the midpoint of a tube is

$$t_w = (T_w/2)(1 + \frac{\sin \theta}{\sin \theta_0}) \quad (1)$$

where

- T_w = outlet temperature of the water
- θ = $\pi z / 2L$
- θ_0 = $\pi L / 2L$
- L = effective half-length of tube
- $2L$ = length loaded with active slugs

In general the elevation Δt of the temperature of any point of a slug above the local water temperature is given by a formula of the type

$$\begin{aligned} \Delta t &= A P \cos \theta & (2A) \\ &= B P_m \cos \theta & (2B) \\ &= \Delta t_{max} \cos \theta & (2C) \end{aligned}$$

where P = power load per tube, W/tube

P_m = maximum power evolved in metal and graphite per unit length of active metal

Δt_{max} = maximum value of Δt for the class of points considered, and A and B are constants characteristic of the point considered. It is here assumed that the thermal resistances do not vary with distance along the tube. This assumption is slightly in error because the co-efficient of heat transfer from the surface of the aluminum jackets to the water increases slowly with temperature and therefore increases as one follows the tube in the direction of flow. Actually the error is of little significance, especially in view of the fact that variation in the extent of film deposits along the length of the tube certainly occurs and is unpredictable. The effect of such deposits on the co-efficient is expected to be greater than that of temperature. Variation of thermal resistances with z is, therefore, neglected.

* Self-poisoning by transient fission products will result in a power distribution somewhat flatter than the cosine curve.

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The quantities T_w , P , and P_m are related to each other as follows.
Let

- v = water rate in g.p.m. per tube
- L_a = length of a finished active slug
- L_m = length of heavy metal rod in each slug
- N = number of slugs in active length of tube

Then, if temperatures are in degrees Centigrade and powers in MW:

$$P = \frac{500 v T_w}{1896} \quad (3)$$

$$P_m = \frac{P}{L_m L \sin \theta_0} = \left(\frac{L_a}{L_m}\right) \left(\frac{P}{2L}\right) \left(\frac{2L}{\sin \theta_0}\right) \quad (4)$$

$$= \frac{500 v T_w L_a}{1896 N L_m \sin \theta_0} \quad (5)$$

The factor $L_a/\sin \theta_0$ is the ratio of maximum power per unit length to the lengthwise mean power per unit length.

By adding Eqs (1) and (2B) and using Eq (5), the general formula for the temperature of any point of a slug is obtained.

$$t = (T_w/2)(1 + b \sin \theta + c \cos \theta) \quad (6)$$

$$\text{where } b = 1/\sin \theta_0 \quad (7)$$

$$c = \frac{v L_a}{1.896 N L_m \sin \theta_0} \quad (8)$$

If T_0 is some nominally agreed upon standard value of T_w , then for each water rate there is obviously a corresponding value P_0 of P and P_{m0} of P_m . Other values of T_w , P , and P_m may therefore be expressed as $F T_0$, $F P_0$, and $F P_{m0}$, where F is the fraction of the standard value of T_0 which obtains.

Equation (6) then becomes

$$t/F = (T_0/2)(1 + b \sin \theta + c \cos \theta) \quad (9)$$

This is the general equation of the curves plotted in Charts I and II.

It may be readily seen from Eq (9) that the maximum value of t/F is

$$\begin{aligned} t_{m}/F &= (T_0/2)(1 + \sqrt{b^2 + c^2}) \\ &= (T_0/2)(1 + b\sqrt{1 + (c/b)^2}) \end{aligned} \quad (10)$$

$$= (T_0/2)(1 + b\sqrt{1 + K^2}) \quad (10a)$$

where

$$K = (c/b)^2 = \left(\frac{v L_a}{1.896 N L_m}\right)^2$$

Equation (10a) is the equation of the graph of $\frac{t_w}{T}$ versus B in Chart III. The value of β at which the maximum occurs is

$$\beta = \frac{2 T_0}{\pi} \sin^{-1} \left(\frac{1}{\sqrt{1 + K F^2}} \right) \quad (11)$$

if the inverse sine is expressed in radians, or

$$\beta = \frac{2 T_0}{90} \sin^{-1} \left(\frac{1}{\sqrt{1 + K F^2}} \right) \quad (11a)$$

if the inverse sine is expressed in degrees. Equation (11a) is plotted as β versus B in Chart III.

II. EVALUATION OF THE CONSTANTS

A. Definition of Full Load for a Tube.

Full load cannot be unambiguously stated for the pile as a whole because, within the limits of the available water supply, the maximum permissible power output of the pile may be widely varied by varying the scheme of loading and poisoning. Full load for a tube may be conveniently specified as the power that may be evolved by that tube at the highest permissible water rate without exceeding some agreed upon temperature at some point of the tube wall or slugs. Since the temperatures of points on the slugs cannot be measured readily or accurately it is more convenient to use the maximum temperature of the tube wall as a basis; this temperature is substantially that of the exit water. It has been generally agreed that until experience demonstrates a higher temperature to be safe, the maximum operating temperature for the outlet water will be taken as 60°C. If the inlet temperature of the cooling water at its lowest is taken as 5°C, this leads to a Full Load Temperature Rise, T_0 , of 60°C.

The actual power evolved per tube when operated with a rise of 60°C varies directly with the water rate as shown by Eq (3). Tests have shown that the highest water rate allowable without exceeding the nominal safe operating pressure in the aluminum tubes (200 lb/sq. in.) is about 21 g.p.m. The exact value cannot be known in advance of operation under power because the resultant non-uniform contraction of the annulus by thermal expansion could not be reproduced in the tests. Further, slight changes in the arrangement of dunnies affect the rate somewhat. Since the divergence from 21 g.p.m. is expected to be small and the use of this value will maintain consistency with many earlier computations, it has been adopted as the Standard Water Rate, w_s . Correction of the chart readings for deviation from the standard water rate proves to be simple. From Eq (3), it then follows that the Standard Full Load Power is

$$P = \frac{500 w_s T_0}{1006} = 332.26 \text{ KW/tube}$$

B. Standard Tube Loading.

For the purpose of the charts the tube is supposed to contain 32 active slugs, each containing an 8" length of heavy metal and having aluminum end caps 0.370" long. Thus

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$$\begin{aligned}
 N &= 32 \\
 L_m &= 8/12 = 0.6667 \text{ ft.} = 20.32 \text{ cm.} \\
 L_n &= 8.7/12 = 0.7250 \text{ ft.} = 22.098 \text{ cm.} \\
 L &= (16)(0.7250) = 11.60 \text{ ft.} = 353.57 \text{ cm}
 \end{aligned}$$

The effective incremental length due to the end reflector is taken as 41 cm at each end. Thus

$$L_0 = 394.57 \text{ cm} = 17.875 \text{ along lengths} = 12.95 \text{ ft.}$$

C. Derived Quantities.

$$\theta_0 = \frac{\pi L}{2 L_0} = \frac{(90)(16)}{17.875} = 80.649^\circ = 1.4076 \text{ radians}$$

$$\sin \theta_0 = 0.98761$$

$$\cos \theta_0 = 0.16246$$

$$D = 1/\sin \theta_0 = 1.01347$$

$$\theta_0/\sin \theta_0 = 1.4266$$

For Full Load Temperature Rise, $T_0 = 60^\circ\text{C}$ and Standard Water Rate, $w_0 = 21.0 \text{ G.P.M.}$:

$$\begin{aligned}
 P_m &= \frac{P}{N L_m} = \frac{(132.26)(1.4266)}{(32)(0.6667)} \\
 &= 22.22 \text{ KW/ft of heavy metal}
 \end{aligned}$$

$$C = \frac{(21)(1.4266 B)}{(1.838)(32)(0.6667)} = 0.74067 B$$

where B is in $^\circ\text{C}/(\text{KW/ft.})$

$$K = 0.53411$$

Hence Eq (9) becomes

$$t/r = 30 (1 + 1.01347 \sin \theta + 0.74067 B \cos \theta) ^\circ\text{C} \quad (12)$$

Eq (10a) becomes

$$t_m/r = 30(1 + 1.01347 \sqrt{1 + 0.53411 B^2}) ^\circ\text{C} \quad (13)$$

and Eq (11a) becomes

$$\beta = 0.19839 \sin^{-1} \left(\frac{1}{\sqrt{1 + 0.53411 B^2}} \right) \quad (14)$$

if β is measured in along lengths.

D. Values of B.

The quantity B is defined by the formula

$$\Delta t_{\text{max}} = B P_m$$

for the maximum elevation above the local water temperature of a given class of points on the slugs. The values of B given below are those appropriate when p_m is expressed in Btu/ft. of heavy metal and Δt_{max} is in degrees Centigrade. In deriving these values, it has been assumed, as has been customary, that 94% of the heat picked up by the water comes from the metal and 6% from the graphite. Since p_m is defined to include the heat reaching the water from both sources, the factor 0.94 will be contained in all the B 's below since the accompanying charts cover points on the slugs only and not in the graphite.

In general, temperature differences between pairs of points in the same cross section are directly proportional to the power load per unit length at that cross section. Therefore B in the above formula may usually be regarded as a sum

$$B = B_0 + B_1 + B_2 + \dots$$

where B_0 is the coefficient in the formula if Δt_{max} refers to the elevation of the coating temperature above that of the cooling water locally and B_1, B_2 , etc. are coefficients in similar formulas for the temperature differences between conveniently chosen pairs of points in the cross section. In general, of the components of B , only B_0 , which is inversely proportional to the coefficient of heat transfer between the slug and the water, is significantly affected by water rate, water temperature, and film deposits. The curves on Charts I and II, with one exception which is noted, and the values of B (except in the case of B_0 itself, Section I) are given for $h_v = 1.1820$ which corresponds to a heat transfer coefficient from slug to water of 4000 pou/(hr)(sq.ft.)(°C) = 0.542 cal/(sec)(sq. cm.)(°C). Should the results for a different value of the coefficient be desired, subtract 1.1820 from the values of B given below and add the appropriate value of B_0 , computed as explained in Section 1. To show the effect of changing the coefficient, lines for the coating temperature have been given on Charts I and II both for $h_v = 4000$ ($B_0 = 1.1820$) and for $h_v = 6000$ ($B_0 = 0.7877$). The vertical distance between these two curves shows for each abscissa the amount by which all curves except that for the water temperature are simultaneously lowered when the coefficient is increased from 4000 to 6000. The curve for the water temperature remains fixed in position.

On Charts I and II a scale of B has been provided to assist in the interpolation of curves for values of B not represented on the chart. Chart III serves for the rapid estimation of the value and location of the maximum temperature for any point of the slug cross-section for which B is known. The same information can be secured from Charts I and II, but with less accuracy.

1. Surface of Coating ($B = B_0$)

$$\Delta t_{max} = \frac{(0.94)(1896) B_m}{2\pi R h_v} \quad ^\circ\text{C}$$

where

R = radius of slug = 0.720 in. = 0.0600 ft.
 h_v = coefficient of heat transfer between slug and water, Btu/(hr)(sq.ft.)(°C)

Therefore

$$B = R_0 = 4727.8/h_w \quad ^\circ\text{C}/(\text{m}/\text{ft.})$$

whence the following table results:

h_w	$B = R_0$
3000	1.576
3500	1.351
4000*	1.182*
4500	1.0506
5000	0.94756
5500	0.85960
6000*	0.78797

Curves are given for the starred values.

The quantity h_w as used here is an overall coefficient between the surface of the slug and the water. If h denotes the coefficient from the surface of a perfectly clean slug to the water and r_s is the scale or dirt resistance

$$h_w = \frac{1}{\frac{1}{h} + r_s}$$

Values of h are not known with high precision because of the difficulty of maintaining perfectly deposit free conditions in experimental work. It has, however, been found that the true values are somewhat higher than those estimated from Madison's formula (Eq 11, p.103 Madison's Heat Transmission). His formula reduces for the present circumstances to

$$h = 2244(1.35 + 0.02 t_1 + 0.6F)(\frac{V}{21})^{0.8}$$

where t_1 is the inlet water temperature in $^\circ\text{C}$. For the Standard Water Rate ($v = 21$) and full load ($F = 1$) one finds the following results for typical inlet temperatures if this equation is used as a basis:

Inlet Water Temp., t_1 $^\circ\text{C}$	0	2	10	20
h , Fou/(sq.ft.)($^\circ\text{C}$)	4380	4600	4830	5080
Corresponding R_0 , clean	1.0794	1.0276	0.9787	0.8978
1000/ h	0.2283	0.2174	0.2070	0.1999
Allowable 1000 r_s :				
If h_w is to be 4000	0.0217	0.0326	0.0430	0.601
If h_w is to be 3500	0.0974	0.0683	0.0787	0.0958

The actual values of h_w under operating conditions will have to be deduced from data covered by the Flow Laboratory or from accurate measurements of the temperature at the side of a slug. If 90°C is the highest temperature which can withstand to contemplate for the temperature of the coating at a rib or at the end of the slug, the minimum allowable value of h_w is about 3000.

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2. Surface of Heavy Metal

The maximum temperature drop through the aluminum jacket if 35 mils thick is

$$\Delta t_{al} = \frac{(1896)(0.035)(.94) P_m}{(2\pi)(0.000)(120)(12)} = 0.1149 P_m$$

that of the solder layer is assumed to correspond to an apparent coefficient of 20,000 Btu/(hr)(sq.ft.)(°F):

$$\Delta t_{solder} = (4727.8/20000) P_m = 0.2364 P_m$$

Assuming $h_g = 4000$,

$$B = 0.1149 + 0.2364 + 1.1820 = 1.533$$

3. Axis of Metal.

The maximum temperature difference between the axis of the heavy metal and its surface is

$$t_{axis} - t_{surface} = \frac{0.94 P_m [I_0(uR) - 1]}{2\pi R k u I_1(uR)}$$

where R = radius of heavy metal rod = $0.680/12 = 0.0566$ ft.

k = thermal conductivity of heavy metal
= 12 Btu/(hr)(sq.ft.)(°F/ft.) approximately

$u = 22.31$ ft.⁻¹

$I_0(x)$, $I_1(x)$ are the Bessel functions $I_0(ix)$, $-iI_1(ix)$

$I_0(uR) = 1.4411$
 $I_1(uR) = 0.7669$

Whence

$$t_{axis} - t_{surface} = 10.754 P_m$$

and, assuming $h_g = 4000$,

$$B = 10.754 + 1.533 = 12.287$$

4. Coating near Unbonded Spot (Salted Area in Front Test)

An unbonded spot on a sling is surrounded by a region where the temperature of the coating is abnormally high. This results from the fact that the partial blockage of the heat flux which would normally flow through the spot forces the heat to escape through the adjacent portions of the bonded area. Consequently the temperature of the coating immediately over the spot will be abnormally low although if the spot is of considerable size the defect of temperature will occur chiefly near its boundaries. The metal directly under the spot will assume an abnormally high temperature; for very large spots this temperature will be high enough near the center to drive the normal heat flux into the coating so that the central region on the coating over such a spot will be at the same temperature as that which it would assume over a bonded area.

Numerically no more than rough estimates can be given for the magnitudes of these effects because the relative thermal resistances of bonded and unbonded areas can only be guessed. They are neither experimentally reproducible nor calculable. From the computations of Quinn (MUC-EDGE #173, 3/27/44; also teletype Quinn to Simon-Worthington, 5/22/44) and of Karush and Young (MUC-GY 6, 3/7/44) it is estimated that, for a heat evolution within the slug of 22.4 KW/ft. of heavy metal, the peak elevation of the coating above the normal temperature varies with spot diameter as follows when the heat transfer coefficient from the coating to the water is 3000:

Diameter	°C
1/4"	4
1/2"	10
1"	14

Within the precision here possible it would make no difference if the coefficient h_w was 4000 or 6000 instead of 3000. For a half-inch spot

$$B = 1.1820 + \frac{10}{(22.4/3000)} = 1.602$$

3. Temperature Elevation at a Rib.

Where the slug rests on the ribs, the cooling water evidently has very imperfect access to the surface of the slug, so the heat which would normally be removed from the surface at that point must largely flow laterally in the coating to point at either side of the rib. Actually some of the heat flows into the rib across a film of water and enters the main water stream from the walls of the tube, but the amount is likely to be small because of the high thermal resistance of the stagnant water layer. It follows that the temperature of the coating at a rib will be abnormally high.

If it is supposed that no heat whatever is lost from the part of the coating directly over the rib, that the heat transfer coefficient is uniform over all other parts of the coating, and that no lateral heat flow takes place except through the coating, it is found (cf. W. K. Woods to Worthington 9/21/43) that

$$\frac{\Delta t_{rib}}{\Delta t_w} = 1 + A + \frac{A^2}{2}$$

- where Δt_{rib} = temperature difference between the water and the coating at the rib
 Δt_w = normal elevation of temperature of coating above that of water
 $A = \sqrt{h_w a^2 / k L}$
 h_w = coefficient of heat transfer between slug surface and water
 a = half width of rib
 k = thermal conductivity of the coating
 L = thickness of coating

Here,

$$\begin{aligned} h &= 4000 \text{ Btu/(hr)(sq.ft.)(}^\circ\text{C)} \\ e &= 0.12/2 \text{ inch (effectively)} = 0.005 \text{ ft.} \\ k &= 120 \\ L &= 40 \text{ mile if allowance is made for some conduction} \\ &\quad \text{in the bond layer and in the heavy metal} \end{aligned}$$

Thus, $A = 0.5$, and

$$\frac{\Delta t_{\text{rib}}}{\Delta t_w} = 1.625$$

Therefore, for $h_o = 4000$

$$B = 1.1820 \times 1.625 = 1.921$$

It should be noted that in this case, B is directly proportional to h_o for the coating.

As a matter of fact h_o falls off in the vicinity of the rib (CP 1311, p. 32; CP 1576, p. 34; CP 1723, p. 1728). However, more elaborated computations (loc. cit., also CP 935, CP 1152, CP 1318) lead ultimately to results substantially the same as that given above. The worst effect is in any case rendered uncertain by the fact that there will be an indeterminate accumulation of deposits in the crevices between the plug and the ribs.

6. Center of End Cap.

By the use of electrical model, Paschke (Dept. of the Heat Transfer Laboratory, Columbia University, March 17, 1944) determined the temperature distribution in aluminum caps of various designs and thicknesses on heavy metal slugs generating heat uniformly throughout their volume. Subsequently Wilkins (CP 2071, CP 1954) found that the heat generation near the end of the heavy metal in such a capped slug was enhanced because the aluminum cap served as a neutron window. The result is to multiply the difference in temperature between the water and the center of the end of a capped slug as found by Paschke by $1 + L/6$ where L is the cap thickness in centimeters. The Paschke results, so corrected, lead to the following figures:

Cap thickness inches	Δt_{max} for $P_n = 22.2 \text{ MW/ft}$	B
0.1772	65.8	2.961
0.250	54.0	2.430
0.266	51.1	2.300
0.300	46.8	2.106
0.350	41.1	1.850

III. EFFECT OF DEVIATIONS FROM THE STANDARD WATER RATE (21.0 G.P.M.)

A deviation of w from the Standard Rate, 21 G.P.M., has no effect on the curves for the water temperature. Full load has been defined with respect to the total temperature rise of the water as that, whatever

the actual water rate, the total rise in water temperature in a tube operating at $F = 1$ is $T_0 = 60^\circ\text{C}$. Variations in water rate have no effect on the shape of the water temperature curve.

The other curves on Charts I and II are raised when the water rate is increased. In Eq (9), Part I, only the coefficient c involves w , and by reference to Eq (8) it is seen that c is directly proportional to w . Since the difference at any abscissa between the local water temperature and any of the other curves is proportional to c any curve may be corrected to a new water rate w by raising its ordinate by $(\frac{w - 21}{21}) \times (\text{local elevation above water temperature})$.

TECHNICAL PART

I: CHARACTERISTICS of STANDARD TUBE at STANDARD WATER RATE ~ 21.0 g.p.m.

3-717,
9/14/44

TBD 8/5/44
REV. 3/15/44

3-745,
9/18/44

Distance from midplane
0 40 80 120 160 200 240 280 320

Temperature above inlet
Water temp.
Full load °C. Half load

Full load °C.	Half load	P/Im Relative Loss Power
110		
100	50	1.5
90		
80	40	
70		
60	30	
50		
40	20	
30		
20	10	
10		
0	0	

This scale valid for midplane temp. 190 °C where P is from Fig. 14-154

II: CHARACTERISTICS of STANDARD TEST

It is tested at WATER RATE = 21.0 gpm.
 P = 110.332.5 KW/t at 30.0 °C.
 It is a 30.0 gpm test with 1350 caps
 for which the maximum power is $P_m = 22.22$ KW
 and test is done with a 94% efficiency
 heat transfer rate to cooling water $h_w = 4000$ sec/c
 as noted.

Distance from midplane 0 40 80 120 160 200 240 280 320

152154

310

300

290

280

270

260

250

240

230

220

210

200

190

180

170

160

150

140

130

120

110

100

90

80

70

60

 t_m/F °C. $\frac{t_m}{F}$ vs. B $\bar{\theta}$ vs. B $B, ^\circ\text{C}/(\text{KW}/\text{ft})$

9

8

7

6

5

4

3

2

1

0

III: CHARACTERISTICS OF STANDARD TUBE VALUE & LOCATION of MAXIMUM TEMPERATURE

$\bar{z}$

Distance of maximum temperature downstream from middle of tube

t_m = maximum temperature measured above inlet water temperature, °C

F = fraction of full load

B = coefficient in $\Delta t = B P_m \cos \theta$

where

Δt = local temperature elevation above water, °C

P_m = max. power KW per foot or action per gram of metal.

$$\theta = \frac{\pi \bar{z}}{2 Z_e}$$

$\bar{z}$ = distance from midplane

Z_e = effective half length

Slug Lengths	Feet
16	12
15	11
14	10
13	9
12	8
11	7
10	6
9	5
8	4
7	3
6	2
5	1
4	0
3	0
2	0
1	0
0	0

Basis: 32 unit loading.

Full load = 21 g.p.m heated from 5°C to 65°C = 352.3 KW per tube.

-END-

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