

Gases, water, alcohol, and benzene are examples of Newtonian fluids. In fact, all liquids with a simple chemical formula are Newtonian. Also, most solutions of simple compounds, such as sugar and salt, are Newtonian. For a more viscous fluid, the straight line will be closer to the  $\tau$  axis (i.e., the slope will be higher). (See Fig. 1.5.) For low-viscosity fluids, the straight line will be closer to the  $dv/dy$  axis (i.e., the slope will be lower).

*Pseudoplastic fluids* (muds, motor oils, polymer solutions, natural gums, and most slurries) exhibit viscosities that decrease with an increasing velocity gradient. Such fluids present no serious pumping problems.

*Plastic materials*, such as tomato catsup, behave similarly to pseudoplastic fluids once movement begins; that is, their viscosities decrease with agitation. However, a finite force must be applied before any fluid movement occurs.

*Bingham fluids* (Bingham plastics), typified by toothpaste, jellies, bread dough, and some slurries, are capable of indefinitely resisting a small shear stress but move easily when the stress becomes large—that is, Bingham fluids ~~become pseudoplastic when the stress increases.~~

*Dilatant fluids* are rare but include clay slurries, various starches, some paints, milk chocolate with nuts, and other candy compounds. They exhibit viscosities that increase with increasing agitation (i.e., with increasing velocity gradients), but they return rapidly to their normal viscosity after the agitation ceases. Pump selection is critical for dilatant fluids because these fluids can become almost solid if the shear rate is high enough.

Viscosity can also change with time (all other conditions being constant). If viscosity decreases with time during agitation, the fluid is said to be a *thixotropic fluid*. If viscosity increases (usually up to a finite value) with time during agitation, the fluid is a *rheopectic fluid*. Viscosity does not change in time-independent fluids. *Colloidal materials*, such as gelatinous compounds, lotions, shampoos, and low-temperature solutions of soaps in water and oil, behave like *thixotropic liquids*—their viscosities decrease as the agitation continues. However, viscosity does not return to its original state after the agitation ceases.

Molecular cohesion is the dominating cause of viscosity in liquids. As the temperature of a liquid increases, these cohesive forces decrease, resulting in a decrease in viscosity.

In gases, the dominant cause of viscosity is random collisions between gas molecules. This molecular agitation increases with increases in temperature. Therefore, viscosity in gases increases with temperature.

Although viscosity of liquids increases slightly with pressure, the increase is insignificant over moderate pressure ranges. Therefore, the absolute viscosity of both gases and liquids is usually considered to be essentially independent of pressure.<sup>14</sup>

The units of absolute viscosity, as derived from Eq. 1.23, are lbf-sec/ft<sup>2</sup>. Such units are actually used in the English engineering system.<sup>15</sup> Absolute viscosity is measured in pascal-seconds (Pa·s) in SI units. Another common unit used throughout the world is the *poise* (abbreviated P), equal to a dyne·s/cm<sup>2</sup>. These dimensions are the same primary dimensions as in the English system,  $F\theta/L^2$  or  $M/L\theta$ , and are functionally the same as a g/cm·s. Since the poise is a large unit, the *centipoise* (abbreviated cP) scale is generally used. The viscosity of pure water at room temperature is approximately 1 cP.

### Example 1.4

A liquid ( $\mu = 5.2 \times 10^{-5}$  lbf-sec/ft<sup>2</sup>) is flowing in a rectangular duct. The equation of the symmetrical facial velocity distribution (in ft/sec) is approximately  $v = 3y^{0.7}$  ft/sec, where  $y$  is measured in inches from the wall. (a) What is the velocity gradient at  $y = 3.0$  in from the duct wall? (b) What is the shear stress in the fluid at that point?

*Solution*

(a) The velocity is not a linear function of  $y$ , so  $dv/dy$  must be calculated as a derivative.

$$\begin{aligned}\frac{dv}{dy} &= \frac{d}{dy} 3y^{0.7} \\ &= (3)(0.7y^{-0.3}) \\ &= 2.1y^{-0.3}\end{aligned}$$

At  $y = 3$  in,

$$\frac{dv}{dy} = (2.1)(3)^{-0.3} = 1.51 \text{ ft/sec-in}$$

(b) From Eq. 1.23, the shear stress is

#### Stress, Pressure, and Viscosity

$$\begin{aligned}\tau &= \mu(dv/dy) \\ &= \left(5.2 \times 10^{-5} \frac{\text{lbf-sec}}{\text{ft}^2}\right) \left(1.51 \frac{\text{ft}}{\text{sec-in}}\right) \left(12 \frac{\text{in}}{\text{ft}}\right) \\ &= 9.42 \times 10^{-4} \text{ lbf/ft}^2\end{aligned}$$

<sup>14</sup>This is not true for kinematic viscosity, however.

<sup>15</sup>Units of lbf/ft-sec are also used for absolute viscosity in the English system. These units are obtained by multiplying lbf-sec/ft<sup>2</sup> units by  $g_c$ .

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Customary U.S. Solution

From Eq. 1.50(b),

$$\begin{aligned} \Delta P &= (\rho_m h_m - \rho_w h_w) \times \frac{g}{g_c} \\ &= \frac{\left(848 \frac{\text{lbm}}{\text{ft}^3}\right)(17 \text{ in}) - \left(62.4 \frac{\text{lbm}}{\text{ft}^3}\right)(120 \text{ in})}{\left(12 \frac{\text{in}}{\text{ft}}\right)^3} \\ &\quad \times \left(\frac{32.2 \frac{\text{ft}}{\text{sec}^2}}{32.2 \frac{\text{lbm-ft}}{\text{lb-ft-sec}^2}}\right) \\ &= 4.01 \text{ lbf/in}^2 \quad (4.01 \text{ psig}) \end{aligned}$$

**23. HYDROSTATIC PRESSURE**

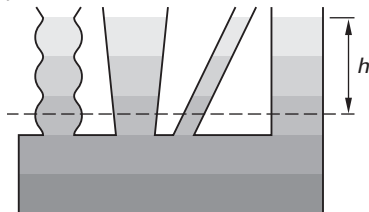
Hydrostatic pressure is the pressure a fluid exerts on an immersed object or container walls.<sup>34</sup> Pressure is equal to the force per unit area of surface.

$$P = \frac{F}{A} \tag{1.51}$$

Hydrostatic pressure in a stationary, incompressible fluid behaves according to the following characteristics.

- Pressure is a function of vertical depth (and density) only. The pressure will be the same at two points with identical depths.
- Pressure varies linearly with (vertical and inclined) depth.
- Pressure is independent of an object’s area and size and the weight (mass) of water above the object. Figure 1.15 illustrates the *hydrostatic paradox*. The pressures at depth *h* are the same in all four columns because pressure depends on depth, not volume.

Figure 1.15 Hydrostatic Paradox



- Pressure at a point has the same magnitude in all directions (*Pascal’s law*). Therefore, pressure is a scalar quantity.
- Pressure is always normal to a surface, regardless of the surface’s shape or orientation. (This is a result of the fluid’s inability to support shear stress.)
- The resultant of the pressure distribution acts through the *center of pressure*.
- The center of pressure rarely coincides with the average depth.

**24. FLUID HEIGHT EQUIVALENT TO PRESSURE**

Pressure varies linearly with depth. The relationship between pressure and depth (i.e., the *hydrostatic head*) for an incompressible fluid is given by Eq. 1.52.

$$P = \rho gh \tag{SI} \quad 1.52(a)$$

$$P = \frac{\rho gh}{g_c} = \gamma h \tag{U.S.} \quad 1.52(b)$$

Since  $\rho$  and  $g$  are constants, Eq. 1.52 shows that  $p$  and  $h$  are linearly related. Knowing one determines the other.<sup>35</sup> For example, the height of a fluid column needed to produce a pressure is

$$h = \frac{P}{\rho g} \tag{SI} \quad 1.53(a)$$

$$h = \frac{Pg_c}{\rho g} = \frac{P}{\gamma} \tag{U.S.} \quad 1.53(b)$$

Table 1.13 lists six common fluid height equivalents.<sup>36</sup>

Table 1.13 Approximate Fluid Height Equivalents at 68°F (20°C)

liquid	height equivalents	
water	0.0361 psi/in	27.70 in/psi
water	62.4 psf/ft	0.01603 ft/psf
water	9.81 kPa/m	0.1019 m/kPa
water	0.4329 psi/ft	2.31 ft/psi
mercury	0.491 psi/in	2.036 in/psi
mercury	133.3 kPa/m	0.00750 m/kPa

<sup>34</sup>The term *hydrostatic* is used with all fluids, not only with water.

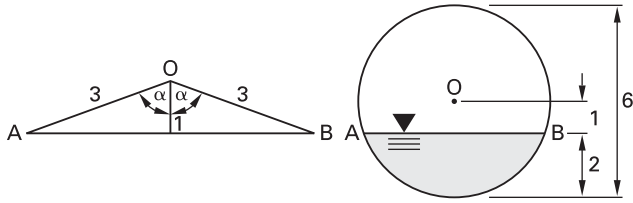
<sup>35</sup>In fact, pressure and height of a fluid column can be used interchangeably. The height of a fluid column is known as *head*. For example: “The fan developed a static head of 3 in of water,” or “The pressure head at the base of the water tank was 8 m.” When the term “head” is used, it is essential to specify the fluid.

<sup>36</sup>Of course, these values are recognized to be the approximate specific weights of the liquids.

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**Example 2.4**

A pipe (internal diameter = 6) carries water with a depth of 2 flowing under the influence of gravity. Calculate the hydraulic radius analytically.



*Solution*

The equations for a circular segment must be used. The radius is  $6/2 = 3$ .

Points A, O, and B are used to find the central angle of the circular segment.

$$\begin{aligned} \phi &= 2\alpha = 2 \arccos \frac{1}{3} = (2)(70.53^\circ) \\ &= 141.06^\circ \end{aligned}$$

$\phi$  must be expressed in radians.

$$\phi = 2\pi \left( \frac{141.06^\circ}{360^\circ} \right) = 2.46 \text{ rad}$$

The area of the circular segment (i.e., the area in flow) is

**Mensuration of Areas and Volumes: Circular Segment**

$$\begin{aligned} A &= [r^2(\phi - \sin\phi)]/2 \\ &= \frac{(3)^2(2.46 \text{ rad} - \sin(2.46 \text{ rad}))}{2} \\ &= 10.876 \end{aligned}$$

The arc length (i.e., the wetted perimeter) is

$$P = r\phi = (3)(2.46 \text{ rad}) = 7.38$$

The hydraulic radius is

$$R_H = \frac{A}{P} = \frac{10.875}{7.38} = 1.47$$

**10. HYDRAULIC DIAMETER**

Many fluid, thermodynamic, and heat transfer processes are dependent on the physical length of an object. This controlling variable is generally known as the *characteristic dimension*. The characteristic dimension in evaluating fluid flow is the *hydraulic diameter* (also known as the *equivalent hydraulic diameter*).<sup>9</sup> The hydraulic diameter for a full-flowing pipe is simply its inside diameter. The hydraulic diameters of other cross sections in flow are given in Table 2.1. If the hydraulic radius is known, it can be used to calculate the hydraulic diameter.

$$D_H = 4R_H \quad 2.19$$

**Table 2.1** Hydraulic Diameters for Common Conduit Shapes

conduit cross section	$D_H$
<i>flowing full</i>	
circle	$D$
annulus (outer diameter $D_o$ , inner diameter $D_i$ )	$D_o - D_i$
square (side $L$ )	$L$
rectangle (sides $L_1$ and $L_2$ )	$\frac{2L_1L_2}{L_1 + L_2}$
<i>flowing partially full</i>	
half-filled circle (diameter $D$ )	$D$
rectangle ( $h$ deep, $L$ wide)	$\frac{4hL}{L + 2h}$
wide, shallow stream ( $h$ deep)	$4h$
triangle, vertex down ( $h$ deep, $L$ broad, $s$ side)	$\frac{hL}{s}$
trapezoid ( $h$ deep, $a$ wide at top, $b$ wide at bottom, $s$ side)	$\frac{2h(a + b)}{b + 2s}$

<sup>9</sup>The engineering community is very inconsistent, but the three terms *hydraulic depth*, *hydraulic diameter*, and *equivalent diameter* do not have the same meanings. Hydraulic depth (flow area divided by exposed surface width) is a characteristic length used in Froude number and other open channel flow calculations. Hydraulic diameter (four times the area in flow divided by the wetted surface) is a characteristic length used in Reynolds number and friction loss calculations. Equivalent diameter ( $1.3(ab)^{0.625}/(a + b)^{0.25}$ ) is the diameter of a round duct or pipe that will have the same friction loss per unit length as a noncircular duct. Unfortunately, these terms are often used interchangeably.

Table 10.6 Typical Characteristics of Non-Aerated Stabilization Ponds

characteristic	aerobic				
	algae-growth maximizing (high rate)	oxygen-transfer maximizing (low rate)	facultative	facultative with surface agitation	anaerobic
size (cell)	0.5–2.5 ac (0.25–1 ha)	<10 ac (<4 ha)	2.5–10 ac (1–4 ha)	2.5–10 ac (1–4 ha)	0.5–2.5 ac (0.25–1 ha)
depth	1.0–1.5 ft (0.3–0.45 m)	3.0–5.0 ft (1–1.5 m)	3.0–7.0 ft (1–2 m)	3.0–8.5 ft (1–2.5 m)	8.0–15 ft (2.5–5 m)
BOD <sub>5</sub> loading	75–150 lbm/ac-day (80–160 kg/ha-d)	25–100 lbm/ac-day (40–120 kg/ha-d)	12–70 lbm/ac-day (15–80 kg/ha-d)	45–175 lbm/ac-day (50–200 kg/ha-d)	175–450 lbm/ac-day (200–500 kg/ha-d)
BOD <sub>5</sub> conversion	80–90%	80–90%	80–90%	80–90%	50–85%
residence time	4–6 days	10–40 days	7–30 days	7–20 days	20–50 days
temperature	40–85°F (5–30°C)	32–85°F (0–30°C)	32–120°F (0–50°C)	32–120°F (0–50°C)	40–120°F (5–50°C)
algal concentration	100–250 mg/L	40–100 mg/L	20–80 mg/L	5–20 mg/L	0–5 mg/L
suspended solids in effluent	150–300 mg/L	80–140 mg/L	40–100 mg/L	40–60 mg/L	80–160 mg/L
cell arrangement	series	parallel or series	parallel or series	parallel or series	series
minimum dike width			8 ft (2.5 m)		
maximum dike wall slope			1:3 (vertical:horizontal)		
minimum dike wall slope			1:4 (vertical:horizontal)		
minimum freeboard			3 ft (1 m)		

(Multiply lbm/ac-day by 1.12 to obtain kg/ha-d.)  
 (Multiply ft by 0.3048 to obtain m.)  
 (Multiply ac by 0.4 to obtain ha.)  
 (Multiply mg/L by 1.0 to obtain g/m<sup>3</sup>.)

above the anaerobic zone. Molecular oxygen is not available in the region at all times. Generally, the zone is aerobic during the daylight hours and anaerobic during the hours of darkness.

An aerobic zone with molecular oxygen present at all times exists above the facultative zone. Some oxygen is supplied from diffusion across the pond surface, but the majority is supplied through algal photosynthesis.

General guidelines are used to design facultative ponds. Ponds may be round, square, or rectangular. Usually, there are three cells, piped to permit operation in series or in parallel. Two of the three cells should be identical, each capable of handling half of the peak design flow. The third cell should have a minimum volume of one-third of the peak design flow.

### 11. AERATED LAGOONS

An *aerated lagoon* is a stabilization pond that is mechanically aerated. Such lagoons are typically deeper and have shorter residence times than nonaerated

ponds. In warm climates and with floating aerators, one acre can support several hundred pounds (a hundred kilograms) of BOD per day.

The basis for the design of aerated lagoons is typically the organic loading and/or residence time. Other factors that must be considered in the design process are solids removal requirements, oxygen requirements, temperature effects, and energy for mixing.

Equation 10.1 is the design equation for an aerated lagoon.

**BOD<sub>5</sub> for Mixed Lagoons in Series**

$$\frac{S}{S^0} = \frac{1}{1 + k_p \theta} \tag{10.1}$$

In Eq. 10.1,  $S$  is the effluent total BOD<sub>5</sub> concentration, and  $S^0$  is the influent total BOD<sub>5</sub> concentration.  $k_p$  is the *kinetic constant*, also called the first-order BOD *removal rate constant*. The kinetic constant is a measure of the rate at which BOD is reduced in the lagoon.

# 19

## Potable Water Residuals Management

Content in blue refers to the *NCEES Handbook*.

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### 1. RESIDUAL MATERIALS FROM WATER TREATMENT

The treatment of potable water can produce various residual materials. Depending on the processes used, these materials can consist of gases, liquids, and solids.

Gases are produced only in the minority of treatment plants that employ processes to strip volatile organics from the source water. The production of gases may occur where the source water is a contaminated groundwater such that processes of natural aeration have prevented volatilization of the chemicals before treatment.

Liquid wastes may be produced by treatment plants that employ ion exchange for softening and by those that employ membrane processes for pathogen, salt, and potentially organics removal. Ion exchange produces a relatively small amount of wastewater from media regeneration. Membrane processes produce substantial amounts of waste reject water, potentially accounting for 25% or more of the total flow.

However, the vast majority of water treatment plants in the United States employ the coagulation-precipitation-filtration sequence or combine coagulation-precipitation-filtration with precipitation softening. In these cases, the primary residual is a solid.

The solid waste that is generated from coagulation-precipitation-filtration and, where applied, precipitation softening is a dilute suspension of about 1–3% solids in 99–97% water. The treatment and management of this material involves reducing the sludge volume by removing as much of the water as feasible to allow disposal. Disposal methods vary, depending on the individual circumstances at each treatment facility. A dewatered sludge will typically contain 15–25% solids.

In most cases, the dewatered sludge does not contain a substantial amount of organic material and does not require stabilization. Depending on the quantities involved and the proximity of other treatment facilities, undeveloped land, and landfills, the final disposition of the sludge may include discharge without thickening to an on-site lagoon or to a publicly owned treatment works; land application as a soil amendment, assuming favorable climate, topographic, and hydrologic conditions; or placement in a sanitary landfill.

### 2. SLUDGE QUANTITIES

*Sludge* is the watery waste that carries off the settled floc and the water softening precipitates. The sludge volume produced is given by Eq. 19.1, in which  $s$  is the gravimetric fraction of solids. The gravimetric solids for coagulation sludge, when expressed as a fraction, is generally less than 0.02. For water softening sludge, it is on the order of 0.10. In Eq. 19.1,  $W_s$  can be either a specific quantity or a rate of production per unit time.

Specific Gravity for a Solids Slurry

$$V = \frac{W_s}{(s/100)\gamma_S} = \frac{W_s}{[(100 - p)/100]\gamma_S} \quad 19.1$$

The most accurate way to calculate the mass of sludge is to extrapolate from jar or pilot test data. There is no absolute correlation between the mass generated and other water quality measurements. However, a few generalizations are possible.

- Each unit mass (lbm, mg/L, etc.) of alum produces 0.46 unit mass of floc.
- 100% of the reduction in suspended solids (expressed as substance) shows up as floc.
- 100% of any supplemental flocculation aids is recovered in the sludge.

Suspended solids in water may be reported in turbidity units. There is no easy way to calculate total suspended solids (TSS) in mg/L from turbidity in NTU. The ratio of TSS to NTU normally varies from 1.0–2.0, and can be as high as 10. A value of 1 or 1.5 is generally appropriate.

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Calculate the mass of carbon required for 1,1,1-TCA.

$$\begin{aligned} \frac{C_0 - C_e}{M} &= KC_e^{1/n} \\ M &= \frac{C_0 - C_e}{KC_e^{1/n}} \\ &= \frac{0.9 \frac{\text{mg}}{\text{L}} - 0.2 \frac{\text{mg}}{\text{L}}}{\left(2.5 \frac{\text{mg}}{\text{g}}\right) \left(0.2 \frac{\text{mg}}{\text{L}}\right)^{0.34}} \\ &= 0.49 \frac{\text{g GAC}}{\text{L water treated}} \end{aligned}$$

For TCE, the mass of carbon required is

$$\begin{aligned} M &= \frac{C_0 - C_e}{KC_e^{1/n}} \\ &= \frac{0.4 \frac{\text{mg}}{\text{L}} - 0.005 \frac{\text{mg}}{\text{L}}}{\left(28 \frac{\text{mg}}{\text{g}}\right) \left(0.005 \frac{\text{mg}}{\text{L}}\right)^{0.62}} \\ &= 0.38 \frac{\text{g GAC}}{\text{L water treated}} \end{aligned}$$

The mass is greater for 1,1,1-TCA, so 1,1,1-TCA will control design. Because TCE is present, its concentration must be accounted for, but how this is done is left primarily to the judgment of the engineer. For example, a safety factor could be applied to increase the carbon required, the carbon required for each chemical could be added together, or the overall concentration of contaminants in the water could be adjusted to let them be “as 1,1,1-TCA.” One way this might be done is

$$\begin{aligned} 900 \frac{\mu\text{g}}{\text{L}} + \left(400 \frac{\mu\text{g}}{\text{L}}\right) \left(\frac{0.49}{0.38}\right) \\ = 1416 \frac{\mu\text{g}}{\text{L}} \text{ as 1,1,1-TCA} \\ \frac{1.416 \frac{\text{mg}}{\text{L}} - 0.2 \frac{\text{mg}}{\text{L}}}{\left(2.5 \frac{\text{mg}}{\text{g}}\right) \left(0.2 \frac{\text{mg}}{\text{L}}\right)^{0.34}} \\ = 0.84 \frac{\text{g GAC}}{\text{L water treated}} \end{aligned}$$

This will provide a conservative estimate of GAC use. By adding GAC required for each chemical, the use rate would be 0.87 mg of GAC per liter of water treated. Using 1.14 mg GAC per liter would provide a safety factor of 0.87/0.87 or 1.0. This seems reasonable and is supported by adding together the GAC required for each chemical.

The daily GAC mass required to remove 1,1,1-TCA and TCE is

$$\begin{aligned} &\left(25 \frac{\text{gal}}{\text{min}}\right) \left(3.785 \frac{\text{L}}{\text{gal}}\right) \left(1440 \frac{\text{min}}{\text{day}}\right) \\ &\times \left[\left(0.84 \frac{\text{g GAC}}{\text{L}}\right) \left(10^{-3} \frac{\text{kg}}{\text{g}}\right)\right] \\ &\times \left(2.204 \frac{\text{lbm}}{\text{kg}}\right) \\ &= 252 \text{ lbm GAC/day} \end{aligned}$$

For two standard sizes of adsorption vessels, the number of days to saturation would be

$$\begin{aligned} \frac{10,000 \text{ lbm GAC}}{252 \frac{\text{lbm GAC}}{\text{day}}} &= 40 \text{ days} \\ \frac{20,000 \text{ lbm GAC}}{252 \frac{\text{lbm GAC}}{\text{day}}} &= 80 \text{ days} \end{aligned}$$

An operating period before change-out of more than about 30 days may lead to problems from calcium carbonate precipitation due to water hardness. Therefore, choose the 10,000 lbm vessel operated in a two-in-series, lead-follow mode. From Table 51.2, a 10,000 lbm vessel typically has a 357 ft<sup>3</sup> bed volume with a 7.5 ft diameter. Using these specifications, calculate the empty bed contact time and the hydraulic loading rate.

$$\begin{aligned} \text{EBCT} &= \frac{(357 \text{ ft}^3) \left(7.5 \frac{\text{gal}}{\text{ft}^3}\right)}{25 \frac{\text{gal}}{\text{min}}} \\ &= 107 \text{ min } [ > 10 \text{ min, so OK}] \\ \text{HLR} &= \frac{25 \frac{\text{gal}}{\text{min}}}{(7.5 \text{ ft})^2 \left(\frac{\pi}{4}\right)} \\ &= 0.57 \text{ gal/min-ft}^2 \left[ < 2 \text{ gal/min-ft}^2, \text{ so not OK; recirculate} \right] \end{aligned}$$

Try a recirculation ratio of 4.0 for HLR<sub>recirc</sub>. Check the recirculated flow rate and empty bed contact time.

$$\begin{aligned} \text{HLR}_{\text{recirc}} &= (4.0) \left(0.57 \frac{\text{gal}}{\text{min-ft}^2}\right) \\ &= 2.28 \text{ gal/min-ft}^2 \\ &[ > 2 \text{ gal/min-ft}^2, \text{ so OK}] \end{aligned}$$