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Department of Environmental Engineering

MEMBRANE BIOREACTORs

Week 13th: DESIGN of MBR

Part II

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CEV4362 MEMBRANE BIOREACTORS

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Week 13th: DESIGN of MBR

6.5. Membrane System Design

6.6. Design Example

- Checking Design SRT Based on Nitrification Kinetics
- Determining the Solids Production Associated with Biological Reactions
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- Determining the Internal Recycling Rate
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6.5. Membrane System Design

It is desirable to set water flux as high as possible to reduce the cost associated with membrane modules, but high flux rates may result in a low stability MBR system. The transmembrane pressure (TMP) increases with time and exponentially increases with flux. Determining the design flux should consider the flow rate peaking factor (i.e., the ratio of hourly peak flow to daily average flow) and the pausing time due to filtration cycle and backwashing. Membranes should be stably operated at peak flow conditions. Therefore, the design flux should be determined based on the peak flow condition not daily average flow rate. If the peaking factor is >1.5, it is strongly recommended to install a flow equalization tank instead of increasing the number of membrane modules for a cost-effective solution.

The pausing time due to the filtration cycle and backwashing reduces the design flux. Chemical cleaning periods during which filtration is not underway also contribute to a decrease in design flux.

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6.5. Membrane System Design (Cont.)

Design flux can be determined as the following equation:

$$\text{Design flux} = \frac{(\text{Maximum operating flux})(\text{Filtration ratio})(\text{Operating ratio})}{\text{Peaking factor}}$$

where
Maximum operating flux = critical flux, $L/m^2/h$
Filtration ratio = (filtration time)/(filtration + backwash + pausing times), unitless
Operating ratio = (operating time)/(operating + cleaning times), unitless
Peaking factor = (hourly peak flow)/(daily average flow), unitless

The number of membrane modules installed in an MBR can be determined based on the design flux.

$$\text{Number of modules} = \frac{\text{Daily average flowrate}}{(\text{Design flux})(\text{Membrane area per module})}$$

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Example 6.8:

Permeate water is withdrawn with 30 LMH in an MBR plant. In order to minimize membrane fouling, 30 s of backwashing is practiced every 5 min of filtration cycle (i.e., 4.5 min of permeation and 0.5 min of backwashing). In addition to backwashing, maintenance cleaning is performed for 30 min every day. What is the net water flux considering backwashing and maintenance cleaning?

Solution 6.8:

$$\text{Net flux} = (\text{instant flux})(\text{filtration ratio})(\text{operating ratio})$$

$$= (30\ \text{LMH})\left(\frac{4.5\ \text{min}}{5\ \text{min}}\right)\left(\frac{23.5\ \text{h}}{24\ \text{h}}\right) = 26.4\ \text{LMH}$$

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6.6. Design Example

The challenge is to design the bioreactor and membrane systems for a newly built MBR plant treating municipal wastewater. The bioreactor consists of an anoxic tank and an aerobic tank, and the mixed liquor in the aerobic tank is recycled into the anoxic tank (i.e., internal recycle) to facilitate biological nitrogen removal via nitrification and denitrification. The anoxic and aerobic tanks are assumed to be operated by completely stirred tank reactor.

Designing should include

1. The volume of two completely mix tank reactors (i.e., anoxic and aerobic tanks),
2. Flow rates for internal recycle,
3. Aeration rates for biological treatment and membrane cleaning,
4. The number of membrane modules installed in the aerobic tank.

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6.6. Design Example (Cont.)

The target MLSS concentration in the bioreactor and SRT is 8000 g MLVSS/m^3 and 20 days, respectively. In this example, the membrane system will be designed based on the GE-Zenon's ZeeWeed 500d immersed membranes. The ZeeWeed 500d cassette has maximum 48 modules and each module has 31.6 m^2 of membrane surface area (i.e., 1516.8 m^2/cassette).

General information, wastewater characteristics, kinetic parameters, aeration parameters, and operating conditions of the membrane system are presented in Tables 6.4 through 6.8. Following is a desktop approach adapted from the procedure introduced in Wastewater Engineering (Tchobanoglous et al., 2003).

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Table 6.4. General Information for the Design

Constituent	*Value*
Average influent wastewater flow rate (m^3/day)	1000
Peaking factor for wastewater flow[a]	1.5
Solids retention time of the aerobic tank (day)	20
Average wastewater temperature during summer (°C)	25
Average wastewater temperature during winter (°C)	12
Maximum permeate biodegradable COD (g/m^3)	5.0
Maximum permeate ammonia (g N/m^3)	0.5
Maximum permeate nitrate (g N/m^3)	25.0
DO concentration of aerobic tank (g/m^3)	2.0

[a] Peaking factor is defined as the average daily flow per hourly peak flow. And the duration of peaking factor is assumed to be 2 h.

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Table 6.5. Influent Wastewater Characteristics

Constituent	*Concentration (mg/L)*
Biodegradable COD	230
Nonbiodegradable soluble COD	20
TKN	50
Nitrate	0
Nonbiodegradable VSS	20
Alkalinity (as $CaCO_3$)	150

Table 6.7. Influent Wastewater Characteristics

Parameter	*Unit*	*Value*
Alpha (α)	Unitless	0.45
Beta (β)	Unitless	1.0
DO in aeration basin (DO)	mg/L	2.0
Diffuser oxygen transfer rate (E)	%	30

6.6. Design Example (8/25)

Table 6.6. Activated Sludge Kinetic Parameters

Parameter	*Unit*	*Value*
μ_m	g VSS/(g VSS/day)	6.0
K_s	g bCOD/m³	20.0
Y	g VSS/g bCOD	0.40
k_d	g VSS/(g VSS/day)	0.12
f_d	Unitless	0.15
$\mu_{m,N}$	g VSS/(g VSS/day)	0.75
K_N	g N/m³	0.74
K_{DO}	g DO/m³	0.5
Y_N	g VSS/g N	0.12
$k_{d,N}$	g VSS/(g VSS/day)	0.08
θ values		
μ_m or $\mu_{m,N}$	Unitless	1.07
k_d or $k_{d,N}$	Unitless	1.04
K_s	Unitless	1.00
K_N	Unitless	1.05
SDNR	Unitless	1.08

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6.6.1. Checking Design SRT Based on Nitrification Kinetics

Initially, it is necessary to check whether the design SRT value is greater than the minimum SRT required to achieve full nitrification in the aerobic tank.

Table 6.8. Parameters of Membrane System Operation

Parameter	*Unit*	*Value*
Maximum operating flux[a]	L/m² h	40
Permeation cycle		
Filtration	min	15
Backwash	min	0.5
Maintenance cleaning		
Frequency	times/week	3
Duration	min	60
Coarse bubble aeration		
SAD	$m^3/m^2/h$	0.54
Aeration/pause	s	10/10

[a] Maximum operating flux indicates critical flux. And the flux condition over the maximum operating flux should be limited to <1 h.

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6.6.1. Checking Design SRT Based on Nitrification Kinetics (Cont.)

The minimum SRT for nitrification can be determined from the specific growth rate of AOB using the following equations:

$$\mu_{AOB} = \left(\frac{\mu_{m,AOB} \cdot NH_3}{K_N + NH_3}\right)\left(\frac{DO}{K_{DO} + DO}\right) - k_{d,AOB}$$

$$\mu_{m,AOB}(T) = \mu_{m,AOB}(20°C) \cdot \theta^{(T-20)}$$

$$K_N(T) = K_N(20°C) \cdot \theta^{(T-20)}$$

$$k_{d,AOB}(T) = k_{d,AOB}(20°C) \cdot \theta^{(T-20)}$$

At winter temperature conditions (i.e., 12°C),

$$\mu_{m,AOB}(12°C) = 0.75 \times 1.07^{(12-20)} = 0.44 \text{ g VSS/g VSS day}$$

$$K_N(12°C) = 0.74 \times 1.05^{(12-20)} = 0.50 \text{ g N/m}^3$$

$$k_{d,AOB}(12°C) = 0.08 \times 1.04^{(12-20)} = 0.06 \text{ g VSS/g VSS day}$$

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6.6.1. Checking Design SRT Based on Nitrification Kinetics (Cont.)

Using the calculated values given, other kinetic parameters, and the design conditions, the specific growth rate of AOB can be calculated as follows:

$$\mu_{AOB} = \left(\frac{\mu_{m,AOB} \cdot NH_3}{K_N + NH_3}\right)\left(\frac{DO}{K_{DO} + DO}\right) - k_{d,AOB}$$

$$= \left(\frac{(0.44\ g/g\ day)(0.5\ g/m^3)}{(0.50 + 0.5)\ g/m^3}\right)\left(\frac{2.0\ g/m^3}{(0.5 + 2.0)\ g/m^3}\right) - 0.06\ g/g\ day$$

$$= 0.12\ g/g\ day$$

The minimum SRT required in the aerobic tank can be calculated as follows:

$$SRT = \frac{1}{\mu_{AOB}} = \frac{1}{0.12\ g/g\ day} = 8.3\ days$$

Even though we applied a safety factor (i.e., the ratio of peak influent TKN to average influent TKN concentration) of two, the calculated minimum SRT is shorter than the predetermined SRT of 20 days. Therefore, it is not necessary to reset the design SRT.

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6.6.2. Determining the Solids Production Associated with Biological Reactions

Total solids production associated with biological reactions ($P_{X,bio}$, unit: mass per time). $P_{X,bio}$ can be calculated by subtracting solids production originated from inert material in influent wastewater from total solids production (P_{XT}). To obtain $P_{X,bio}$, first it is required to estimate the permeate COD concentration and oxidizable ammonia concentration. Permeate COD can be determined as follows:

$$S = \frac{K_S(1 + k_d SRT)}{SRT(\mu_m - k_d) - 1} = \frac{(20\ \text{g COD/m}^3)\left[1 + (0.09\ \text{g VSS/g VSS day})(20\ \text{days})\right]}{20\ \text{days}\left[(3.50 - 0.09)\ \text{g VSS/g VSS day}\right] - 1}$$

$$= 0.83\ \text{g COD/m}^3$$

$$k_d(12°C) = k_d(20°C) \cdot \theta^{(T-20)} = 0.12 \times 1.04^{(12-20)} = 0.09\ \text{g VSS/g VSS day}$$

$$\mu_m(12°C) = \mu_m(20°C) \cdot \theta^{(T-20)} = 6.0 \times 1.07^{(12-20)} = 3.50\ \text{g VSS/g VSS day}$$

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6.6.2. Determining the Solids Production Associated with Biological Reactions (Cont.)

Note that the permeate COD concentration is less than the design permeate biodegradable COD (5.0 g/m^3). The oxidizable ammonia concentration (N_{ox}) can be determined by iterative calculations of $P_{X,bio}$ and N_{ox}. Initially, we assume N_{ox} as 35 g N/m^3 (70% of influent TKN concentration) and calculate $P_{X,bio}$ as follows:

$$P_{X,bio} = \frac{QY(S_0 - S)}{1 + k_d SRT} + \frac{QY_n N_{ox}}{1 + k_{d,AOB} SRT} + f_d k_d \frac{QY(S_0 - S)}{1 + k_d SRT} SRT$$

$$= \frac{(1{,}000\ m^3/day)(0.40\ g/g)\left[(230 - 0.83)\ g/m^3\right]}{\left[1 + (0.09\ g/g\ day)(20\ days)\right]}$$

$$+ \frac{(1{,}000\ m^3/day)(0.12\ g/g)(35\ g/m^3)}{\left[1 + (0.06\ g/g\ day)(20\ days)\right]}$$

$$+ \frac{(0.15\ g/g)(0.09\ g/g\ day)(1{,}000\ m^3/day)(0.40\ g/g) \times \left[(230 - 0.83)\ g/m^3\right](20\ days)}{\left[1 + (0.09\ g/g\ day)(20\ days)\right]}$$

$$= 43{,}487\ g\ VSS/day$$

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6.6.3. Determining the Volume of an Aerobic Tank

The volume of the aerobic tank can be calculated based on the estimation of the total solids mass and the design total solids concentration. It is thus necessary to calculate daily solids production (P_{X_T}) for the estimation of the total solids mass in the aerobic tank.

$$P_{X_T} = P_{X,bio} + QX_{0,i} = 43{,}990\,g/day + (1{,}000\,m^3/day)(20\,g/m^3)$$

$$= 63{,}990\,g\,VSS/day$$

$$V = \frac{\text{Mass of solids in a bioreactor}}{\text{Total solids concentration in a bioreactor}}$$

$$= \frac{(63{,}990\text{ g VSS/day})(20\text{ days})}{8{,}000\text{ g VSS/m}^3} = 160\text{ m}^3$$

The volume of the aerobic tank corresponds to 3.8 h of HRT (=160 m^3/(1000 m^3/day)(24 h/day)).

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6.6.4. Estimating the Volume of an Anoxic Tank (Cont.)

Estimating the required volume of anoxic tank begins with estimating the solids concentration in the anoxic tank (X_{ax}), which is used to calculate the F/M ratio in the anoxic tank (F/M_{ax}). The SDNR is a function of F/M_{ax} and is used for the amount of biomass required for denitrification. Assuming the ratio of recycle activated sludge from aerobic tank to anoxic tank is high enough, X_{ax} is assumed to be equivalent to the solids concentration in the aerobic tank (X) (e.g., 8000 g VSS/m^3). F/M_{ax} is now calculated based on the assumption of 2 h of HRT for the anoxic tank volume (e.g., 83.3 m^3) by following equation:

$$\frac{F}{M_{ax}} = \frac{QS_0}{V_{ax}X_{ax}} = \frac{(1000\ m^3/day)(230\ g/m^3)}{(83.3\ m^3)(8000\ g/m^3)} = 0.345\ g/g\ day$$

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6.6.4. Estimating the Volume of an Anoxic Tank (Cont.)

SDNR can be calculated as follows:

$$SDNR(20°C) = 0.019\left(\frac{F}{M_{ax}}\right) + 0.029 = 0.019(0.345\ g/g\ day) + 0.029$$

$$= 0.036\ g\ NO_3^- - N/g\ VSS\ day$$

$$SDNR(12°C) = SDNR(20°C)\cdot\theta^{(12-20)} = (0.036\ g/g\ day)(1.08)^{(12-20)}$$

$$= 0.019\ g\ NO_3^- - N/g\ VSS\ day$$

As previously determined, the nitrogen concentration to be oxidized (N_{ox}) is 44.2 g NO_3^-–N/m^3 and the nitrate discharge limit is 25 g NO_3^-–N/m^3. Therefore, the amount of nitrogen to be denitrified is 19,200 g NO_3^-–N/day (=(44.2 − 25) g/m^3×1,000 m^3/day) and the amount of biomass required for denitrification is 1,010,526 g VSS (=(19,200 g/day)/(0.019 g/g day)).

$$V_{ax} = \frac{\text{Solids required for denitrification}}{\text{Solids concentration in the anoxic tank}} = \frac{Q\left(N_{ox} - NO_{3,p}\right)/SDNR}{X}$$

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6.6.4. Estimating the Volume of an Anoxic Tank (Cont.)

The volume of anoxic tank (V_{ax}) can, therefore, be calculated as follows:

$$V_{ax} = \frac{\text{Activated sludge required for denitrification}}{\text{Activated sludge concentration in the anoxic tank}}$$

$$= \frac{1{,}010{,}526\ \text{g}}{8{,}000\ \text{g/m}^3} = 126.3\ \text{m}^3$$

The calculated volume of the anoxic tank (126.3 m^3) is larger than our initial assumption (83.3 m^3). The calculated value needs to be equalized to that of the initial assumption. Similar to the determination of $P_{X,bio}$ and N_{ox}, V_{ax} can be estimated by iterative calculation. Iterative calculation has resulted in the following values:

$$\frac{F}{M_{ax}} = 0.21\ \text{g COD/g VSS day}$$

$$\text{SDNR}(20°\text{C}) = 0.0331\ \text{g NO}_3^-\text{–N/g VSS day}$$

$$\text{SDNR}(12°\text{C}) = 0.0179\ \text{g NO}_3^-\text{–N/g VSS day}$$

$$\text{Activated sludge required for denitrification} = 1{,}074{,}754\ \text{g VSS}$$

$$V_{ax} = 134.3\ \text{m}^3\ (=3.2\ \text{h of HRT})$$

6.6.6. Checking the Alkalinity Requirement

As discussed previously, alkalinity is consumed during nitrification (7.14 mg $CaCO_3$ per mg NH_3–N oxidized) and recovered during denitrification (3.60 mg $CaCO_3$ per mg NO_3^-–N reduced). It is thus necessary to check whether supplemental alkalinity is needed or not. Alkalinity consumed during nitrification:

$$= \left(7.14 \frac{\text{mg CaCO}_3}{\text{mg NH}_3 - \text{N}}\right)(44.2\ \text{mg/L}) = 316\ \text{mg/L as CaCO}_3$$

Alkalinity saved during denitrification

$$= \left(3.60 \frac{\text{mg CaCO}_3}{\text{mg NH}_3 - \text{N}}\right)(19.2\ \text{mg/L}) = 69\ \text{mg/L as CaCO}_3$$

Considering influent alkalinity (150 mg $CaCO_3$/L) and minimum residual alkalinity (50 mg $CaCO_3$/L), it is necessary to supplement 147 mg $CaCO_3$/L of alkalinity to the bioreactor.

$$\text{Supplemental alkalinity} = \text{Influent alkalinity} - \text{Consumed alkalinity}$$

$$+ \text{Saved alkalinity} - \text{Minimum alkalinity}$$

$$= (150 - 316 + 69 - 50)\ \text{mg/L} = -147\ \text{mg CaCO}_3/\text{L}$$

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6.6.7. Determining the Waste Activated Sludge

As discussed previously, the waste activated sludge rate is equivalent to the daily solids production rate (P_{XT}). Because P_{XT} was estimated using mass units, it is necessary to convert it into a volume unit for determining the waste activated sludge rate using the solids concentration in the aerobic tank. Note that, in practice, there is no thickening facility such as secondary sedimentation tanks in MBR plants. Therefore, the concentration of waste activated sludge is the same as the MLVSS concentration of the aerobic tank where activated sludge wasting is performed.

$$P_{X_T} = 63{,}990 \text{ g VSS/day}$$

$$\text{Waste activated sludge} = \frac{63{,}990 \text{ g/day}}{8{,}000 \text{ g/m}^3} = 8.0 \text{ m}^3\text{/day}$$

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6.6.8. Determining the Aeration Requirements for Biological Reactions

OD_{theory} for COD removal and nitrification in the aerobic tank can be obtained as follows:

$$OD_{theory} = Q(S_0 - S) + 4.32QN_{ox} - 2.86Q(N_{ox} - NO_{3,e}) - 1.42P_{X,bio}$$

$$= (1{,}000\ m^3/day)\left[(230 - 0.83)\ g/m^3\right] + 4.32(1{,}000\ m^3/day)(44.2\ g/m^3)$$

$$- 2.86(1{,}000\ m^3/day)\left[(44.2 - 25)\ g/m^3\right] - 1.42(43{,}487\ g/day)$$

$$= 303{,}450\ g\ O_2/day$$

Oxygen demand at field conditions (OD_{field}) can be estimated based on the net OD_{theory}, wastewater characteristics, and mixing conditions can be calculated as:

$$OD_{field} = \left(\frac{OD_{theory}}{E}\right)\left(\frac{DO_{S,20}}{\alpha \cdot (\beta DO_S - DO) \cdot \theta^{T-20}}\right)$$

$$= \left(\frac{303\ kg/day}{0.3}\right)\left(\frac{8.51\ g/m^3}{0.6(0.95 \times 10.10\ g/m^3 - 2.0\ g/m^3) \cdot 1.024^{(12-20)}}\right)$$

$$= 2280\ kg/day$$

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6.6.9. Designing the Membrane System

The design of the membrane system includes determining the design flux, required number of membrane modules, and aeration requirement for coarse bubble aeration.

First, the design flux can be determined based on wastewater flow characteristics and the membrane filtration cycle as follows:

$$\text{Design flux} = \frac{(\text{Maximum operating flux})(\text{Filtration ratio})(\text{Operating ratio})}{\text{Peaking factor}}$$

$$= \frac{(40\ \text{L/m}^2\ \text{h})(0.968)(0.982)}{1.5} = 25.35\ \text{L/m}^2\ \text{h}$$

where

Peaking factor=(hourly peak flow)/(daily average flow) = 1.5

Filtration ratio=(filtration time)/(filtration time+backwash time)=(15 min)/ (15 + 0.5 min) = 0.968

Operating ratio=(operating time)/(operating time+cleaning time)=[1 week − (3 times)(60 min/time)(1 week/10,080 min)]/(1 week) = 0.982

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6.6.9. Designing the Membrane System (Cont.)

Second, the number of membrane modules can be estimated based on the design flux and daily average flow:

$$\text{Number of modules} = \frac{\text{Daily average flow}}{(\text{Design flux})(\text{Membrane area per module})}$$

$$= \frac{(1000\ \text{m}^3/\text{day})(1000\ \text{L/m}^3)(1\ \text{day}/24\ \text{h})}{(25.35\ \text{L/m}^2\ \text{h})(31.6\ \text{m}^2/\text{module})} = 52\ \text{modules}$$

ZeeWeed 500d cassettes can hold maximally 48 modules. Therefore, two cassettes are required with each cassette holding 26 modules.

Third, the coarse bubble aeration requirement for membrane scouring can be estimated based on the SAD and cyclic aeration strategy as follows:

$$\text{Aeration requirement for coarse bubble aeration}$$

$$= (\text{SAD}_m)(\text{Membrane area})\frac{\text{Aeration time}}{\text{Aeration time} + \text{Pause time}}$$

$$= (0.54\ \text{m}^3/\text{m}^2/\text{h})(52\ \text{modules} \times 31.6\ \text{m}^2/\text{module})\frac{10\ \text{s}}{(10 + 10\ \text{s})}$$

$$= 443.7\ \text{m}^3/\text{h} = 7.39\ \text{m}^3/\text{min}$$

6.6.10. Summary of Design

Design Parameter	*Unit*	*Value*
Aerobic tank		
Volume	m^3	160
HRT	h	3.8
Anoxic tank		
Volume	m^3	134
HRT	h	3.2
Internal recycle		
Flow rate	m^3/day	800
Ratio to influent flow rate	Q	0.8
Alkalinity addition	mg $CaCO_3$/L	147
Wastage activated sludge		
Mass rate	kg VSS/day	64.0
Volumetric rate	m^3/day	8.0
Aeration		
Biological reactions	m^3/min	5.86
Coarse bubble aeration	m^3/min	7.39
Membrane system		
Number of modules	ea	52
Number of cassettes	ea	2

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Thank you…