ChE classroom

LUBRICATION FLOWS

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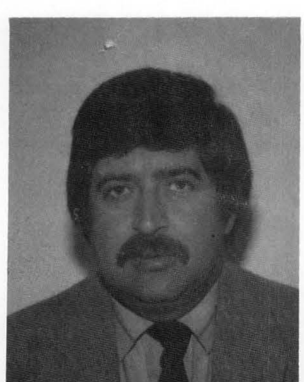
Lubrication flows are perhaps the most applicable material of fluid mechanics at both the undergraduate and the graduate levels. At the undergraduate level, important one-dimensional approximations such as channel, film, and coating flow equations can be derived and studied from simplified mass and momentum balances by means of the control volume principle or else by simplifying the general equations of change (Navier-Stokes). This leads to the celebrated Reynolds equation [1]

$$\mathbf{R}(h, p, Ca) = 0 \qquad (1)$$

where h is the thickness of the narrow channel or of the thin film, p is a generalized pressure, $p = P - St\, g$ where $St = \rho g D^2/\mu V$ is the Stokes number and g the gravity acceleration in the direction of fluid motion. The capillary number, $Ca = \mu V/\sigma$, usually enters through the balance of the normal stresses at a free surface.



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Eq. (1) can be solved:

- **To find the pressure distribution and relative quantities (load capacity, friction and wear, cavitation, *etc.*) when the thickness h(x) is known. The most typical application is journal-bearing lubrications.**
- **To find the thickness h(x) when the pressure is known. The most typical applications are formation of thin films and coating applications.**

Eq. (1) is not always solvable analytically. In some extreme cases it is solvable by simplified perturbation techniques. By the time the student reaches the solution, he/she must have dealt with

- **Derivation of governing differential equations by mass and momentum balances on appropriately chosen control volumes (or alternatively, the Navier-Stokes equations).**
- **Order of magnitude analysis to derive the lubrication equations.**
- **The solution of the differential lubrication equations subject to boundary conditions, to find the velocity profile.**
- **The integral mass conservation equation to derive the Reynolds equation.**
- **The surface tension and the curvature of a thin film, to find the pressure distribution.**
- **The solution of the Reynolds equation, to find the film thickness or the pressure distribution.**
- **Simplified perturbation techniques to find limiting solutions to the Reynolds equation.**

Thus, lubrication flows cover most of the material taught in undergraduate fluid mechanics and at the same time are attractive to the student because they deal with practical problems.

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The most important applications of the thin film lubrication equations are films falling under surface tension, nonisothermal films, dip and extrusion coating, and wetting and liquid spreading. A similar class of problems includes centrifugal spreading, common in bell sprayers and in spin coating.

INTRODUCTION

The lubrication approximation for flows in *nearly* rectilinear channels or pipes, of *nearly* parallel walls, can be derived intuitively from the equations of flow in rectilinear channels and pipes. The equations that govern flows in rectilinear channels and pipes are the continuity or mass conservation which demands constant flow rate

$$\frac{\partial u_x}{\partial x} = 0; \qquad u_z = 0; \qquad u_x = f(z) \tag{2}$$

and the equation of conservation of linear momentum in the flow direction

$$\frac{dP}{dx} = \mu \frac{\partial^2 u_x}{\partial z^2} \tag{3}$$

which under constant presure gradient, dP/dx, predicts linear shear stress and parabolic velocity profiles. The gradient, dP/dx, is usually imposed mechanically and, since the channel is rectilinear and the motion steady, it is constant along the channel (see Figure 1a), equal to $\Delta P/\Delta L$, where ΔP is the pressure difference over distance ΔL. Thus, the mechanism of motion is simple; flow of material from regions of high pressure to regions of low pressure. This is Poiseuille flow.

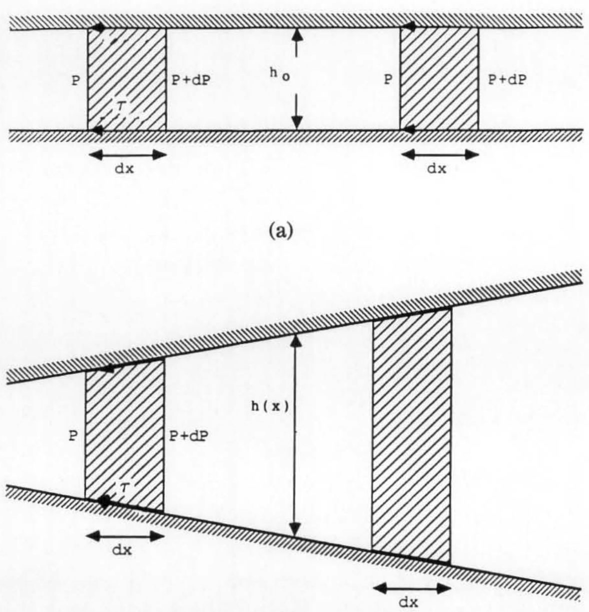

FIGURE 1. Force balance in a rectilinear flow, $h_o dP = 2\tau dx$, and in lubrication flow, $h(x)\, dP(x) = 2\tau(x) dx$.

When one or both walls are in slight inclination, α, to the midplane of symmetry, the same governing equations are expected to hold which may now be locally weak functions of x, of order α. The most obvious difference is the pressure gradient, dP/dx. In the case of a lubrication flow which may be accelerating or decelerating, in a converging or diverging channel, respectively, dP/dx is not constant along the channel because the pressure forces needed to move two cones of liquid of the same height dx at two different positions along the channel are different (see Figure 1b). Thus, dP/dx is a function of x and so is the velocity in the governing equations

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z} = 0 \tag{4}$$

$$\frac{dP(x)}{dx} = \mu \frac{\partial^2 u_x}{\partial z^2} \tag{5}$$

Both Eqs. (3) and (5) express conservation of linear momentum or the Newton's law of motion that there is no accumulation of momentum in a control volume because there is no substantial net convection, and the forces capable of producing momentum are in equilibrium. According to Newton's law of motion there is no acceleration (actually the acceleration is vanishingly small in lubrication flows) because there is no net force acting on a control volume. The forces on the control volume, of height Δx, are net pressure force (dP/dx)A(x) and shear stress force $A(x)dx\tau_{xy}$ (Figure 1b). The underlying mechanism is more complex than in the Poiseuille flow. First, the moving wall on one side sweeps fluid into a narrowing passage through the action of viscous shear forces, which gives rise to a local velocity profile of Couette-type $u_x = Vy/h$, with flow rate, $Q = Vh/2$. Because Q is constant by continuity and h(x) is diminishing, the flow sets up a pressure gradient to supply a Poiseuille component that redistributes the fluid and maintains a constant flow rate (Figure 2).

Derivation of Lubrication Equations by the Navier-Stokes Equations

Alternatively, the lubrication equation can be derived by order of magnitude and dimensionless analysis of the full, two-dimensional, Navier-Stokes equations

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z} = 0$$

$$\rho\left[\frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_z \frac{\partial u_x}{\partial z}\right] = -\frac{\partial P}{\partial x} + \mu\left[\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial z^2}\right] \quad (6)$$

$$\rho\left[\frac{\partial u_z}{\partial t} + u_x \frac{\partial u_z}{\partial x} + u_z \frac{\partial u_z}{\partial z}\right] = -\frac{\partial P}{\partial z} + \mu\left[\frac{\partial^2 u_z}{\partial z^2} + \frac{\partial^2 u_z}{\partial x^2}\right] \quad (7)$$

where x- is the direction of flow and z- the gapwise direction. The geometry of the flow is shown in Figure 2.

There are several good reasons to work with dimensionless equations and variables: to reduce the dependence of the solution to minimum dimensionless numbers; to simplify the equations judging from the relative magnitude of a dimensionless number to one; and to scale-up experiments to real applications of the same dimensionless number.

To achieve these goals

- The dimensionless variable, say u*, must be of the order of one. By using the boundary velocity V, then $u_x^* = u_x/V$ may at most vary between zero and one, and so u* is of order one.
- If the problem lacks the characteristic dimensional variable, V, in the previous paragraph, then it is made-up by combining other characteristic variables. For example, for time, $t^* = t/(L/V)$. The characteristic dimensional variable for pressure is $P = \mu V/\alpha L$, because viscous forces, which resist the motion, are in equilibrium with the pressure forces, as shown by Figure 1.

Accordingly, define

$$x^* = \frac{x}{L}; \quad z^* = \frac{z}{\alpha L}; \quad t^* = \frac{tV}{L}; \quad h^* = \frac{h}{\alpha L};$$
$$u_x^* = \frac{u_x}{V}; \quad u_z^* = \frac{u_z}{\alpha V}; \quad P^* = \frac{P}{\mu \frac{V}{\alpha^2 L}}; \quad (8)$$

which upon substitution in the N-S equations, yields

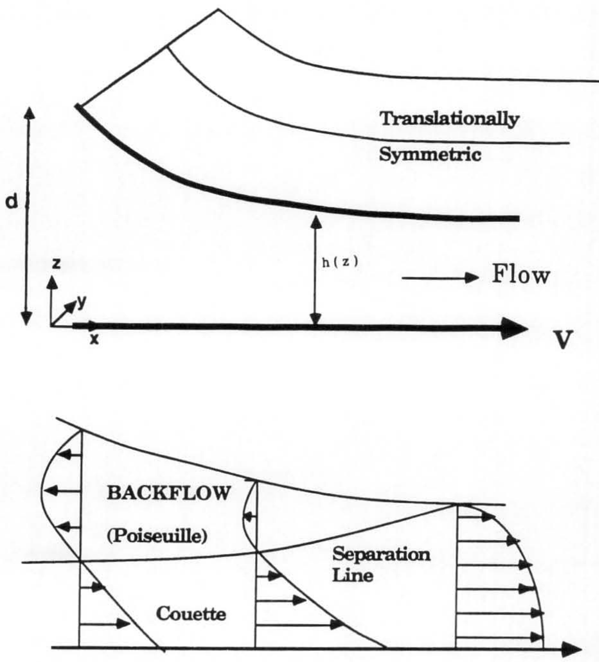

FIGURE 2. Geometry of a two-dimensional lubrication flow. The velocity profiles along the channel are mixtures of Couette and Poiseuille.

(with asterisk suppressed hereafter)

$$\alpha \mathrm{Re}\left(\frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_z \frac{\partial u_x}{\partial z}\right) = \left(-\frac{\partial P}{\partial x} + \alpha^2 \frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial z^2}\right) \quad (9)$$

$$\alpha^3 \mathrm{Re}\left(\frac{\partial u_z}{\partial t} + u_x \frac{\partial u_z}{\partial x} + u_z \frac{\partial u_z}{\partial z}\right) = \left(-\frac{\partial P}{\partial z} + \alpha^4 \frac{\partial^2 u_z}{\partial x^2} + \alpha^2 \frac{\partial^2 u_z}{\partial z^2}\right) \quad (10)$$

The lubrication equation holds in geometries where $\alpha << 1$. Since all the dimensionless terms and derivatives in these two equations are of order one, the resulting lubrication dimensionless equations are in the limit of $\alpha = 0$ and $\alpha \mathrm{Re} = 0$,

$$-\frac{\partial P}{\partial x} + \frac{\partial^2 u_x}{\partial z^2} = 0 \quad (11)$$

$$-\frac{\partial P}{\partial z} = 0 \quad (12)$$

These equations are similar to those derived intuitively from channel flow [*e.g.*, Eqs. (2) and (3)]. Notice that high Reynolds numbers are allowed as far as the product αRe is vanishingly small and the flow remains laminar.

The appropriate boundary conditions to Eqs. (5) and (11) are

At $z = 0$, $u_x = V$ (no-slip boundary condition)
At $z = h$, $u_x = 0$ (Slit Flow), (no slip boundary condition)
or $z = h$, $\tau_{zx} = 0$ (Thin Film), (zero shear stress at free surface)

Under these conditions the solution to Eq. (5) is

$$u_x = -\frac{1}{2\mu}\frac{dP}{dx}(zh - z^2) + V - \frac{z}{h}V \quad \text{(Slit Flow)} \qquad (13)$$

$$u_x = -\frac{1}{2\mu}\frac{dP}{dx}(2zh - z^2) + V \quad \text{(Film Flow)} \qquad (14)$$

The volume flux and the pressure distribution in the lubricant layer can be calculated when the flow rate Q, and the inclination α, are known. A lubrication layer will generate a positive pressure and thus load capacity, normal to this layer, only when the layer is so arranged that the relative motion of the two surfaces tends to drag fluid by viscous stresses from the wider to the narrower end of the layer [2]. The load, W, supported by the pressure is

$$W = \int_0^L (P - P_o)\,dx = \frac{6\mu V}{\alpha^2}\left[\log\frac{d}{d - \alpha L} - 2\left(\frac{\alpha L}{2d - \alpha L}\right)\right] \qquad (15)$$

Thus, the inclination α, is responsible for the pressure build-up by decelerating the flow and transmitting momentum and thus load capacity to the upper boundary.

Reynolds Equation for Lubrication

Mass conservation on an infinitesimal volume yields

$$-Q_{x+dx} + Q_x = dx\frac{dh}{dt} \qquad (16)$$

which states that the net mass convection in the control volume is being used to increase the volume at rate d/dt (dxdh) where dx and dh are the width in the flow direction and the height of the volume, respectively. Rearrangement yields

$$-\frac{dQ}{dx} = \frac{dh}{dt} \qquad (17)$$

which for confined and film flows reduces to

$$\frac{d}{dx}\left[-\frac{1}{2\mu}\frac{dP}{dx}\frac{h^3}{6} + \frac{hV}{2}\right] = -\frac{dh}{dt} \quad \text{(Slit Flow)} \qquad (18)$$

and

$$\frac{d}{dx}\left[-\frac{1}{\mu}\frac{dP}{dx}\frac{h^3}{3} + hV\right] = -\frac{dh}{dt} \quad \text{(Film Flow)} \qquad (19)$$

respectively.

Solution of Steady Reynolds Equation for Slit Flow

The steady-state form of Eq. (18)

$$\frac{d}{dx}\left[-\frac{1}{2\mu}\frac{dP}{dx}\frac{h^3}{6} + \frac{hV}{2}\right] = 0$$

is integrated to

$$-\frac{1}{2\mu}\frac{dP}{dx}\frac{h^3}{6} + \frac{hV}{2} = Q$$

and one proceeds according to Batchelor [2] and Denn [3] to the calculation of pressure

$$P(x) = P_0 + 6\mu V\int_0^x \frac{dx}{h^2(x)} - 12\,\mu Q\int_0^x \frac{dx}{h^3(x)} \qquad (19a)$$

where

$$Q = \frac{P_0 - P_L}{12\,\mu\int_0^L h^{-3}(x)dx} + \frac{V}{2}\,\frac{\int_0^L h^{-2}(x)dx}{\int_0^L h^{-3}(x)dx} \qquad (19b)$$

Then one can proceed to the evaluation of load capacity

$$W = \int_s \left[P_0 - P(x)\right]ds \qquad (19c)$$

and of shear or friction

$$F = \int_s \tau_{zx}\,ds \qquad (19d)$$

on the surface, S. It is easy to show that the load capacity is of order α^{-2} whereas the shear or friction is of order α^{-1}. Thus the ratio load/friction increases with α^{-1}.

The most important application of the lubrication theory for confined flows in journal-bearing [4] and piston-ring [5] systems of engines. Other flows that can be studied at the undergraduate level by means of the lubrication equations, include wire coating [3], forward roll coating [6], and many polymer applications [7]. The solution to these problems follows the procedure outlined above, starting from Eq. (17). The flow rate is usually given by

$$Q = V\,h_f \qquad (20)$$

where V is the speed of production and h_f the final thickness. The boundary condition on the pressure at the outlet may vary [8]. $P(L) = 0$, $dP(L)/dx = 0$, or $P(L) = 2/(h_f)^2$.

Solution of Steady, Reynolds Equations for Film Flow

In confined lubrication flows there is pressure build-up due to inclination, α, and backflow of some of the entering liquid. The pressure is then usefully used to support loads. In thin film lubrication flows, any pressure build-up is due to surface tension, and in fact if the surface tension is negligible the pressure gradient is zero.

The steady-state form of Eq. (19)

$$\frac{d}{dx}\left[-\frac{1}{\mu}\frac{dP}{dx}\frac{h^3}{3} + Vh\right] = 0$$

is integrated to

$$-\frac{1}{\mu}\frac{dP}{dx}\frac{h^3}{3} + Vh = Q = Vh_f \tag{21}$$

The film thickness, h, is not known. However, the pressure drop, dP/dx, can be deduced from the surface tension by means of the Young-Laplace equation under the lubrication requirement that the slope, dh/dx, must be much less than unity

$$-P = \frac{\sigma \frac{d^2h}{dx^2}}{\left[1 + \left(\frac{dh}{dx}\right)^2\right]^{\frac{1}{2}}} \approx \sigma \frac{d^2h}{dx^2} \tag{22}$$

Here h(x) is the elevation of the free surface from the x-axis, and σ the surface tension of the liquid. Then

$$-\frac{dP}{dx} = \sigma \frac{d^3h}{dx^3} \tag{23}$$

and substitution of dP/dx in Eq. (21) yields

$$\frac{\sigma}{\mu}\frac{h^3}{3}\frac{d^3h}{dx^3} + hV = Vh_f \tag{24}$$

which is rearranged to

$$h^3\frac{d^3h}{dx^3} + 3\,Ca\left(h - h_f\right) = 0 \tag{25}$$

The capillary number $Ca = \mu V/\sigma$ is another dimensionless number and measures the viscous to surface tension forces. Eq. (24) is highly nonlinear and cannot be solved analytically.

The most important applications of the thin film lubrication equations are films falling under surface tension, nonisothermal films, dip and extrusion coating, and wetting and liquid spreading. A similar class of problems includes centrifugal spreading, common in bell sprayers and in spin coating. A rich collection of lubrication problems from polymer processing can be found in Pearson [7, 9] and from coating in several theses under Scriven [10].

CONCLUSIONS

Lubrication flows are ideal for undergraduate students to cover and learn a significant amount of fluid mechanics material. This material includes the differential Navier-Stokes equations, dimensional analysis and simplified dimensionless numbers, control volume principles, the Reynolds lubrication equation for confined and free surface flows, capillary pressure, and simplified perturbation techniques. Problems and solutions can be easily chosen from practical and interesting applications such as journal bearing, expanding pipe flow, film flow, and several polymer and coating operations.

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APPENDIX

Vertical Dip Coating

An example of thin lubrication film under gravity, surface tension, and viscous drag arises in dip coating, shown in Figure 3. This method of coating is practiced to cover metals with anticorrosion layers and to laminate paper and polymer films. The substrate is being withdrawn at speed V from a liquid bath of density ρ, viscosity μ, and surface tension σ. The analysis will predict the final coating thickness as a function of the processing conditions (withdrawal speed) and of the physical characteristics of the liquid (ρ, μ, and σ).

Solution

The governing momentum equation, with respect to the shown cartesian system of coordinates is

$$-\frac{dP}{dz}+\mu\frac{\partial^2 u_z}{\partial y^2}-\rho g=0 \quad (A1)$$

The boundary conditions are

$$u_z(y=0)=V \quad (A2)$$

and

$$\tau_{zy}(y=H)=\mu\frac{du_z}{dy}=0 \quad (A3)$$

The particular solution is

$$u_z=\frac{1}{\mu}\left(\frac{dP}{dz}+\rho g\right)\left(\frac{y^2}{2}-Hy\right)+V \quad (A4)$$

The resulting Reynolds equation is

$$-\frac{1}{\mu}\left(\frac{dP}{dz}+\rho g\right)\frac{H^3}{3}+VH=Q=VH_f \quad (A5)$$

where H_f is the final coating thickness.

The pressure gradient

$$\frac{dP}{dz}=-\sigma\frac{d^3H}{dz^3} \quad (A6)$$

is replaced in Eq. (A5) to yield the final Reynolds equation

$$\frac{1}{\mu}\left(\sigma\frac{d^3H}{dz^3}-\rho g\right)\frac{H^3}{3}+V(H-H_f)=0 \quad (A7)$$

which is rearranged to the form

$$\frac{H^3}{3}\frac{d^3H}{dz^3}-\frac{\rho g}{\sigma}\frac{H^3}{3}+\frac{V\mu}{\sigma}(H-H_f)=0 \quad (A8)$$

By identifying the dimensionless numbers

$$Ca=\frac{V\mu}{\sigma} \quad (A9)$$

and

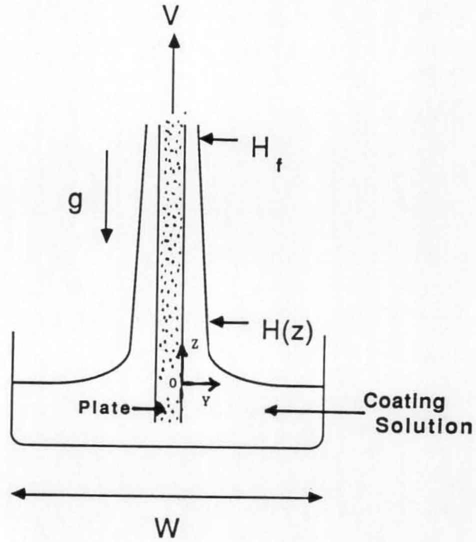

FIGURE 3. Dip Coating: A coated plate is being withdrawn from a coating solution. A final thin film or coating results on the plate under the combined action of gravity, surface tension, and drag by the moving substrate.

$$St=\frac{\rho g H_f^2}{\mu V} \quad (A10)$$

Eq.(A8) becomes

$$\frac{H^3}{Ca}\frac{d^3H}{dz^3}-St\frac{H^3}{H_f^2}+3(H-H_f)=0 \quad (A11)$$

which can be solved directly for the following limiting cases:

1. Negligible surface tension ($Ca \to \infty$)

Eq. (A11) reduces to the third-order algebraic equation

$$H^3-\frac{3H_f^2}{St}H+\frac{3H_f^3}{St}=0 \quad (A12)$$

In the limit of infinite St (*i.e.*, very heavy liquid!), the only solution is H = 0, *i.e.*, no coating. In the limit of zero St (*i.e.*, horizontal arrangement), $H = H_f$, *i.e.*, plain Couette (plug) flow. For finite values of St the solution is independent of z, which predicts a flat film throughout.

2. Infinitely large surface tension ($Ca \to 0$)

Eq. (A10) reduces to

$$\frac{d^3H}{dz^3}=0 \quad (A13)$$

with general solution

$$H(z)=C_1\frac{z^2}{2}+C_2z+C_3 \quad (A14)$$

along with the boundary conditions

$$H(z=0) = W/2, \quad H(z=L) = H_f, \quad (dH/dz)_{z=L} = 0$$

The solution is

$$H(z) = \left(\frac{W - 2H_f}{L^2}\right)\left(\frac{z^2}{2} - zL\right) + \frac{W}{2} \tag{A15}$$

which is a parabolic film thickness.

<u>3. Finite surface tension ($0 < Ca < k$)</u>

Eq. (A11) is cast in the form

$$H^3\left(\frac{d^3H}{dz^3} - \frac{St\,Ca}{H_f^2}\right) + 3Ca\left(H - H_f\right) = 0 \tag{A16}$$

with no apparent analytic solution. For a special case of horizontal coating ($St = 0$), and since usually $H_f / W << 1$, the transformation

$$H^* = \frac{H}{W}, \qquad z^* = \frac{z}{W} \tag{A17}$$

reduces Eq. (A16) to

$$H^{*3}\frac{d^3H^*}{dz^{*3}} + 3Ca\left(H^* - \frac{H_f}{W}\right) = 0 \tag{A18}$$

which predicts that near the inlet, where $H^* \approx 1$, the film decays with rate depending on the Ca. Near the other end, where $H^* \approx 2H_f/W$, the film becomes flat, surface tension becomes unimportant, and therefore the slope is zero. Eq. (A18) can be solved asymptotically by perturbation techniques. ❐

CHEATING

Continued from page 17.

this paper. Perhaps these considerations will motivate us to develop innovative ethics curricula and to improve monitoring of course activities, so that our disciplines may be able to better safeguard (and perhaps even increase) their already high levels of excellence.

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2. Return from News Agents	-0-	-0-
G. TOTAL *(Sum of E, F1 and 2—should equal net press run shown in A)*	2365	2080

11. I certify that the statements made by me above are correct and complete	Signature and Title of Editor, Publisher, Business Manager, or Owner

PS Form 3526, Dec 1987 *(See instructions on reverse)*