

# Dynamics of Placement of Underwater Concrete - Partnership Between Ohio Dept of Transportation and University of Toledo

**James Kamm**

College of Engineering  
University of Toledo  
Toledo, Ohio

Email: [james.kamm@utoledo.edu](mailto:james.kamm@utoledo.edu)

## Abstract

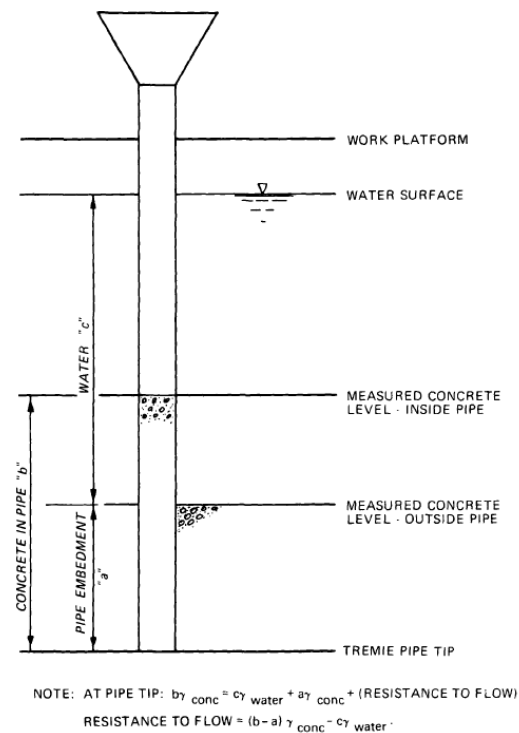
Little is known about the dynamics of placement of underwater concrete or grout using the tremie method. This paper documents a study by the University of Toledo requested by the Ohio Department of Transportation, Wood County, Ohio which creates a method of evaluating certain aspects of underwater concrete placement. The methodology is typical of a second course of engineering fluid mechanics.

## Introduction

There are many situations in the construction of bridges and dams when it would be ideal to place wet concrete in position underwater. By the chemical nature of the curing process of concrete, it can be placed underwater and still cure to a substantial strength. The placement of the concrete however must be done very ‘quietly’ and without disturbance or else it will mix with surrounding water and lose its curing ability. Therefore the placement of the concrete is usually done through a vertical pipeline with open end at the submarine location of the concrete placement. Concrete is then poured down the pipe in a controlled manner to assure that the velocity of exit at the bottom is sufficiently low to avoid substantial mixing with the surrounding water.

The process is initiated by prefilling the vertical pipe with concrete using a plug at the bottom of the pipe and a hopper (tramoggia or tremie) at the top. Once the plug is released, the concrete is allowed to free-fall to a balance point (see *Figure 1* labeled ‘b’) in the pipe. The balance point can be determined from hydrostatics as

$$b = c \frac{\gamma_{H_2O}}{\gamma_{concrete}} + a$$



*Figure 1 Geometry of the Liquid/Mixtures  
in a Tremie Placement<sup>1</sup>*

Notice that a certain amount of concrete is allowed to build-up around the base of the tremie pipe (distance 'a') as the concrete is laid. This is required to keep a seal so that no water will get into the tremie pipe while pouring concrete. It is called the *immersion depth* of the tremie pipe.

To get the concrete to flow through the tremie pipe, additional concrete must be poured into the tremie. The additional build-up of concrete over the balance point causes a similar amount to pour out of the bottom of the pipe. The additional level of concrete in the tremie pipe required to keep concrete flowing is determined by the friction of movement in the tremie pipe itself plus the additional pressure at the exit of the tremie required to move the previously laid concrete into place. It is this last pressure which is the topic of this paper.

## Flow Dynamics Outside the Tremie

Figure 2 is one concept of the flow from the base of the tremie pipe. The red bubble or 'ballon' at the base of the tremie pipe is a reminder that the pressure of the concrete stream as it exits the base of the tremie has two components. The first is the hydrostatic pressure of the two exterior liquids: water and concrete. This pressure is equal to the local hydrostatic pressure of the water head plus the liquid concrete head .

$$P_{\text{local}} = \gamma_{\text{water}} W + \gamma_{\text{grout}} C$$

According to the dimensions identified in the diagram right, this amounts to  
The second component (the red bubble) of the pressure at the base of the tremie pipe is the additional pressure needed to move the placed grout/concrete to its final resting place. In this illustration it appears that the flow has a preference to move upwards as it is pushed away from the pipe exit however there doesn't seem to be any physical

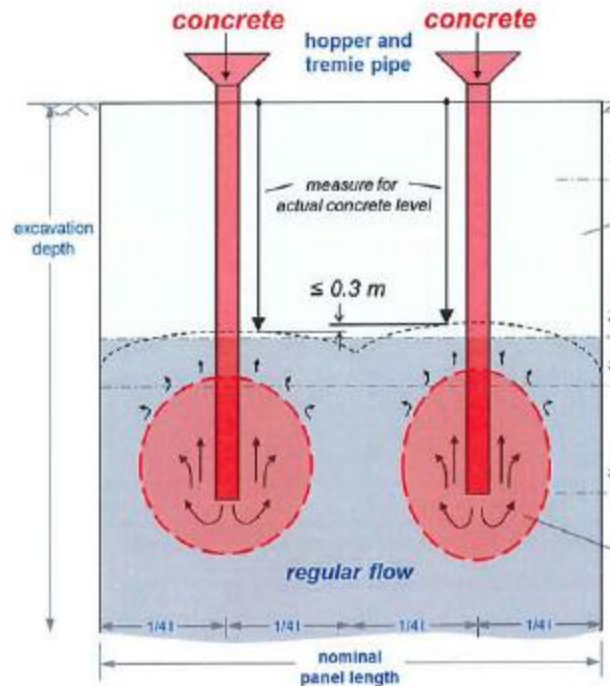


Figure 2 One Concept for Tremie Placement<sup>2</sup>

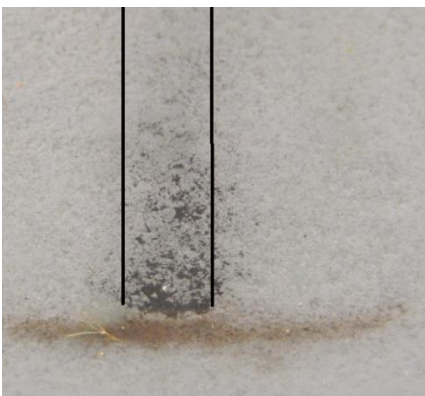


Figure 3 Brown Grout Placed in Silica Sand by Tremie Pipe

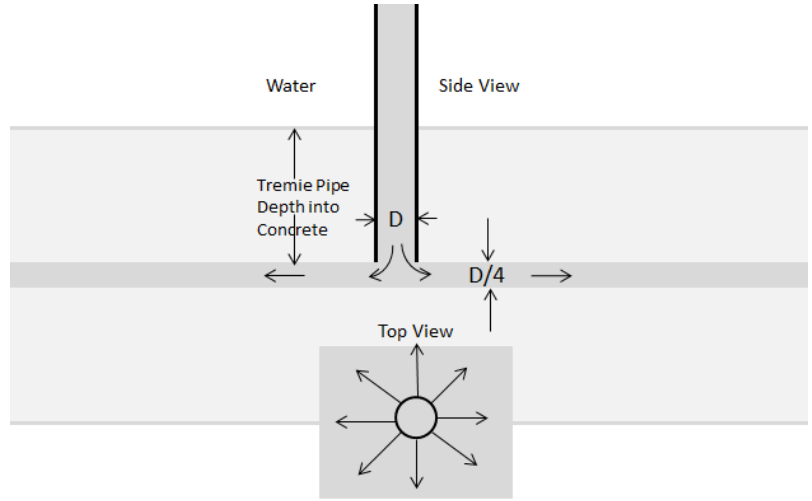
From: University of Toledo Engineering Lab, October, 2015.

support for this hypothesis. In fact, it seems that the direction of minimal resistance would be horizontal. To move downward upon exit, the flow would have to overcome the compressive strength of the previously laid concrete and to move upward it would have to overcome the concrete head of the mixture above it. To move horizontally, it *only* needs to overcome the shear resistance to move to its final resting place.

Therefore, a better model (as least to begin with) is to assume the flow is horizontal. In fact, in a small experiment in the laboratory, with a tremie pipe immersed in dry white silica sand and filled with a brown dry grout powder, when the grout was

forced out of the tremie pipe it gave a brown trace as shown in *Figure 3*. Notice that the horizontal movement is quite prominent in the experiment.

*Figure 4* illustrates the consequences of horizontal planar flow. Since the flow is submerged, it ideally flows between two fixed disk plates; the lower plate being the stationary concrete in place below the tremie pipe exit and the upper plate the layer of stationary concrete above the tremie exit. Therefore the velocity of flow is radial and diminishes as the square of the distance from the pipe exit. The idealized flow from the tremie pipe is what fluid mechanics would call *flow from a source* (pipe exit, see Top View, *Figure 4*). The distance between upper and lower 'plates' is  $D/4$ , based on continuity of flow (mass flow rate) exiting the tremie pipe ( $\gamma V_{\text{pipe}} A_{\text{pipe}}$ ) and the flow rate exiting the source cylinder between the plates ( $\gamma V_o \pi DH$ ).



*Idealized Flow from a Tremie Pipe*

*Figure 4 The Assumptions of Source Flow from the Tremie Pipe*

Actually the result of  $D/4$  also assumes the velocity exiting the tremie pipe and the initial velocity if the radial flow is the same, which is an assumption that seems reasonable but has no fluid mechanic justification.

If  $Q$  is the flow rate of concrete in the tremie pipe ( $\text{ft}^3/\text{sec}$ ), then the average velocity of flow at any distance  $r$  from the center of the tremie pipe is given by

$$V = Q / [(D/4)(\pi r^2)] \quad \text{Eq 1}$$

Furthermore the pressure needed at the base of the tremie pipe to push the concrete to its ultimate destination is

$$P_o = \frac{1}{\pi DH} \int_0^R \tau dA$$

where

$P_o$  is the pressure required at the base of the tremie pipe, over and above the local pressure

$\tau$  is the shear force at any distance  $r$  from the center of the tremie pipe,  
 $\tau = \mu dV/dH$  ( $H$  is the vertical direction between plates)

$A$  is the area the shear force is applied to, as a function of  $r$ ,  $A = \pi r^2$   
 $dA = 2 \pi r dr$

$R$  is the distance from the tremie pipe that the grout/concrete is pushed

If the velocity distribution between the plates is assumed linear for simplicity (over parabolic), then for a Bingham fluid that has a zero velocity stress

$$\tau = \tau_o + \mu 4V/H$$

where V is a function of r as in Eq 1.

Therefore

$$P_o = \frac{1}{\pi DH} \int_0^R \tau dA$$

$$= \frac{1}{\pi DH} \int_0^R \left( \tau_o + \frac{16\mu Q}{\pi DH r^2} \right) \pi r dr = \frac{1}{\pi DH} \left( \pi \tau_o \frac{R^2}{2} + \frac{16\mu Q}{DH} \ln \left[ \frac{D}{2R} \right] \right)$$

or if  $H = D/4$  
$$P_o = 2\tau_o(R/D)^2 + 64 \gamma \mu Q/D^2 \ln (2R/D) \quad \text{Eqn 2}$$

R in this equation is the distance to the final resting place of the concrete grout. If the placement is within a casing, a caisson, or a cofferdam, then the value of R is well defined. If the placement is without a form, as in the filling of a mine, the concrete/grout does not push forever but rather has a tendency to stack or create a cone, see *Figure 6*. This is particularly true if the tremie pipe is raised periodically during the pour.

If the placement is in a cone, then the immersion depth of the tremie pipe and the slope of the cone are both determiners for R. The slope of this cone is affected by a variety of characteristics of the concrete/grout and of the rate of placement, however, it is a good assumption that the slope of the cone is the same as the slope of the cone made from a slump measurement. *Figure 7* shows a slump test cone with standard dimensions 12 inches high, 4 inch diameter at the top and 8 inch base diameter, for a total volume of 352 in<sup>3</sup>. After the cone is removed, the shape that the sample assumes varies according to the amount of slump, but for slump between 5 and 10 inches, which is typical for underwater placement, the end result is approximately

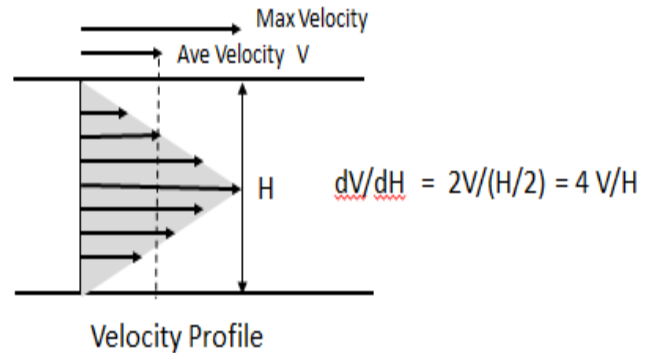


Figure 5 Velocity profile for  $dV/dH = 4V/H$

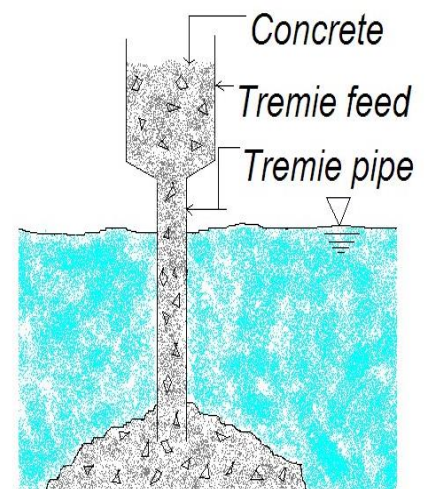


Figure 6 Concrete placed in a cone shape<sup>3</sup>

cone shaped. The geometry of this cone is:

$$\text{Height} = 12 - \text{slump} \quad (\text{inches})$$

$$\begin{aligned} \text{Volume} &= 352 \text{ in}^3 = 1/3 \pi r^2 \text{ height} \\ &= 1/3 \pi r^2 (12 - \text{slump}) \end{aligned}$$

or 
$$r = \frac{3(352)}{\pi(12 - \text{slump})}$$

and

$$\text{slope} = \frac{r}{h} = \frac{\sqrt{\frac{3(352)}{\pi(12 - \text{slump})}}}{12 - \text{slump}} = \frac{18.3}{(12 - \text{slump})^{3/2}}$$

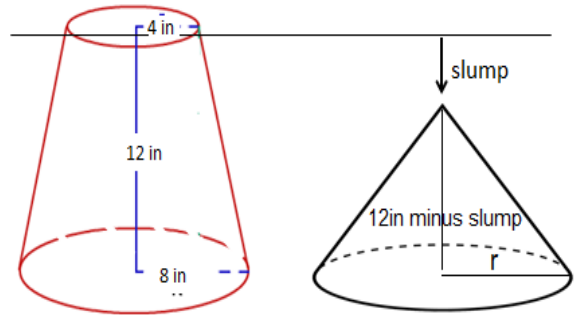


Figure 7 Converting slump test into cone angle

According to the graph of Figure 7, this implies a 6.5:1 slope for slump = 10 inch and a 3.5:1 slope for a slump = 9 inch.

The relationship between R and slope then is

$$R = \text{slope (immersion depth)}$$

As to Eqn 2, the other parameters that require discussion are  $\tau_o$  and  $\mu$ . Typical values for wet concrete can be found in Figure 9.

Figure 9 Fluid properties of wet concrete/grout<sup>4</sup>

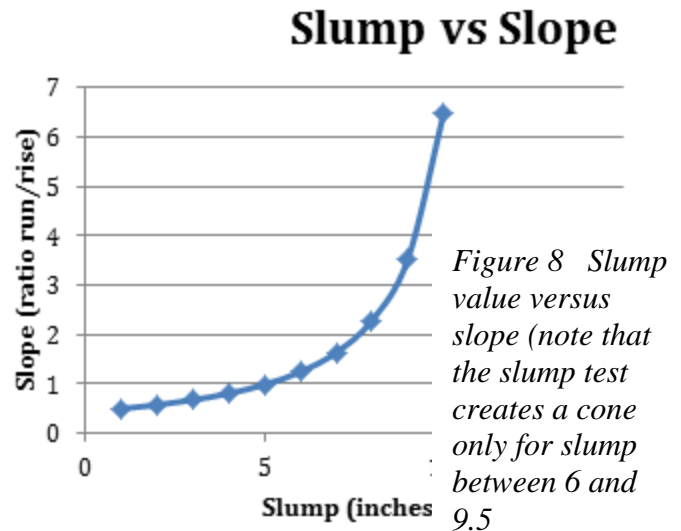


Table 1. Rheology of cement paste, mortar and concrete

Material	Cement paste, grout	Mortar	Flowing concrete	Self-compacting concrete	Concrete
Yield stress N/m <sup>2</sup>	10–100	80–400	400	50–200	500–2000
Plastic viscosity Ns/m <sup>2</sup>	0.01–1	1–3	20	20–100	50–100
Structural breakdown	Significant	Slight	None	None	None

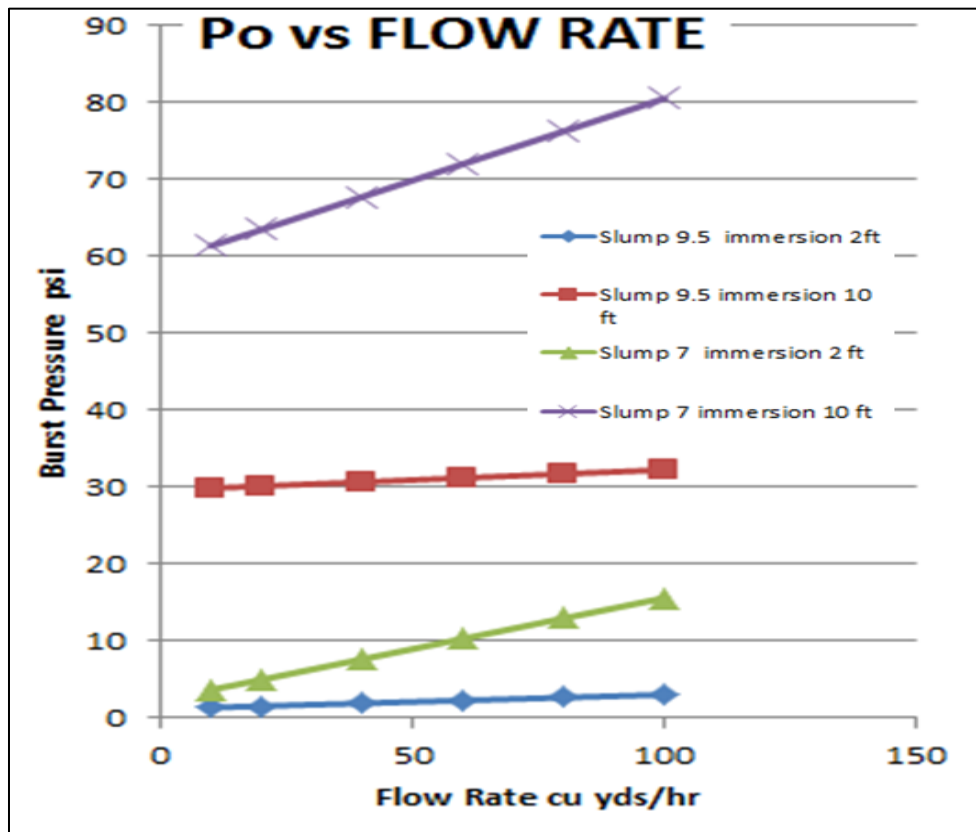


Figure 10: Pressures at the base of the tremie pipe to deliver concrete/grout to final placement

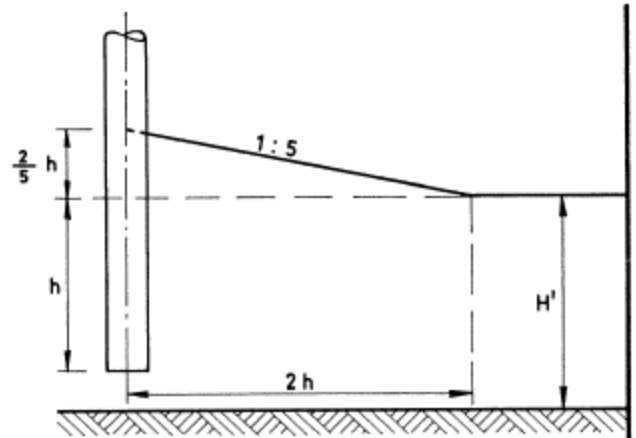
A numerical evaluation of the required placement pressure versus slump, immersion depth, and volume flow rate is shown in *Figure 10*. This graph is interesting from the viewpoint that these ‘burst pressures’ must be supported by the weight of concrete over the tremie pipe base, that is, if these placement pressures are greater than the concrete hydrostatic pressure due the immersion of the pipe, then the concrete/grout will not flow underneath the layer but instead burst through the layer and flow over the top of the ‘stack’. With a concrete/grout specific weight of typically 150 lb/ft<sup>3</sup>, the pressure that can be sustained per foot of immersion is about 1 psi. Therefore the maximum placement pressure without bursting for 2 ft immersion is 2 psi and for 10 ft immersion is 10 psi. On *Figure 10*, the two lowest lines represent immersion of 2 feet. In both cases, the placement pressures are almost always greater than 2 psi, meaning that the deposit of concrete/grout is almost always by bursting through the top of the previously laid mixture. In fact, for the 9.5 inch slump, only placement rates less than 40 cu yds/hr with immersion depth of 2 feet will keep the placement flow below the previously laid concrete level. For immersion levels greater than 2 feet, and for slumps less than 9 inches, the flow will always burst through the top and flow over the previously laid concrete.

What has been described here are two types of flow patterns, each existing if certain conditions hold true. Therefore we call these patterns different *flow regimes* and name them *laminar sublayer flow* – for placement that is moved below the static layer of preplaced concrete, and *burst flow* – placement that flows to the top of the preplaced layer.

## Comparison with the Literature

In a 1999 study done for the US Army Corps of Engineers<sup>5</sup>, a study of flow pattern of concrete placed underwater into a cofferdam, and with some experience this report used a stack slope pattern of 5:1 (Figure 11). Compared to this study (Figure 8), that would be consistent with a slump = 9.5, typical for tremie pipe placement.

There are several references of best management practices for tremie placement of concrete that suggest, for a variety of reasons that moving concrete.



The following is an excerpt from a US Army Corps of Engineers study<sup>5</sup>

Figure 11: Assume slope of 5:1 in the literature<sup>5</sup>

*Tremie concrete, with or without the antiwashout admixture, should always be discharged into and beneath the already placed concrete. Specifications should require that the tip of tremie be always embedded in fresh concrete by at least 0.6 m (2 ft). This requirement not only helps to prevent a loss of the seal, but also improves the concrete flow pattern.*

Figure 2, from the Deep Foundations Institute, suggests that the flow pattern for concrete placement may not be subsurface, and the diagram suggests a type of burst flow pattern. Indeed, in the document, it states

*“Concrete flow patterns are not well understood”.*

Later in the document it contradicts itself, *“It is generally recognized that there are two principle flow types involving regular... flow patterns. Regular flow patterns involve ‘plug flow’ or ‘volcanic flow’:*

*‘Plug’ flow where the upper region of already placed concrete is lifted upwards by the fresh concrete exiting the tremie pipe*

*‘Volcano’ flow where the upper regions of already placed concrete rolls upwards and sideways due to higher resistance to flow ...”*

Without any evidence or analysis, this description is precisely what in this document is called the *laminar flow regime* and the *burst regime*.

## Conclusion

Equation 2 is a critical evaluation tool for determining the flow pattern for the placement of concrete from a tremie pipe. It is also valuable to determine the minimum placement pressures required at the base of the tremie pipe. The analysis is typical of an honors project for a second level fluid mechanics course in an engineering science or engineering technology program.

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## Biographical Information

### James Kamm

Dr. Kamm is Professor of Engineering Technology at the University of Toledo. He has been the lead thermodynamics and fluid mechanics instructor in the Department and wholly responsible for the Thermodynamics and Fluids Laboratory. He is the author of a textbook in thermodynamics: HEAT AND POWER THERMODYNAMICS (Prentice Hall) which has been used for both introductory and advanced courses of thermodynamics for engineering technology. His text has been converted to a digital book and with streaming media. He has been honored on several occasions for his excellence in the classroom. In 1991, the Outstanding Teaching Award was presented by the National Institute for Staff and Organizational Development, University of Texas. In 2002, he was cited in Who's Who Among America's Teachers, and in 2009, we received the Outstanding Teaching Award from the University of Toledo.

Dr. Kamm has established a rapport with the HVAC industry and became a member of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) in 1976. He has served on various local ASHRAE chapter committees and in 1980 was nominated for a three year term as Regional Chairman of Educational Activities. In 1983, he was elected Regional Chairman. During his three year term, he was responsible for overseeing all the activities of 13 mid-western ASHRAE chapters and serving on the Society Board of Directors. After retiring from the ASHRAE Board, he served as chairman of the Toledo ASHRAE for four years, culminating in President in 1994. Dr. Kamm is a Life Member of ASHRAE and is the author of the ASHRAE on-Line learning course, *Fundamentals of Psychrometrics*. He has published many papers and has been interviewed numerous times on his research in energy related topics. Much of this comes from his constant involvement in undergraduate research through the Senior Technology Design capstone course. He has received a grant from the Ohio Biomass Energy Program (PUCO) to propose a new biofeedstock. His paper 'A New Class of Plants for a Biofuel Feedstock Energy Crop' appeared in APPLIED BIOCHEMISTRY and BIOTECHNOLOGY, (2004) Humana Press.