Abstract
The equations governing the upward, one-dimensional diffusion of a flammable gas that is heavier than air have been solved numerically as an aid to safety personnel and accident investigators. A method is provided to determine the time required to reach the lower explosion limit at any elevation above the floor level. Results are presented graphically and a sample calculation is provided.

Introduction
In most cases of flammable gas leaks inside buildings the spread of the gas and its mixing with air is largely caused by air currents. However, there are situations where the leaking gas enters a quiescent environment. Examples are underground industrial facilities not normally occupied and not containing devices that cause air circulation. Unoccupied, metal skin recreational vehicles and mobile homes with no operating appliances and thus no significant air circulation may also be approximated by the present theory. In such situations the spread of the flammable gas is primarily controlled by diffusion. It is the purpose of this study to provide information on this spread. Such information is of frequent interest to accident investigators who are concerned about whether the lower explosion limit (LEL) could have been attained at the location of an ignition source during the time period that a leak was known to exist. These calculations also provide a lower bound on the spread of a flammable gas since any air currents present will increase this spread.

The model analyzed here is the case of a leaking flammable gas forming a mixture with air at the floor level. This mixture at floor level is assumed to be very thin and to have a constant composition as time passes. The assumption of constant composition at floor level with the passage of time is somewhat restrictive. From a practical standpoint it
would be achieved by a balance between the fuel entering at floor level due to the leak and the diffusion of fuel upward from floor level. This balance can take place at various values of $X_\phi$, thus five values of this variable are considered (0.1, 0.3, 0.5, 0.7, and 0.9). The flammable gas from this floor-level mixture gradually spreads vertically via diffusion. The flammable gas is assumed to be denser than air, thus removing buoyancy-induced mixing.

While a fairly well-sealed enclosure is required to meet the assumptions of this analysis, it is also assumed that the enclosure is porous enough and the leak small enough so that the flammable gas leaking into the enclosure does not cause a pressure increase.

When a large volume of a heavy gas is suddenly released at the lower boundary of a volume containing a lighter gas, the early spread of this heavier gas is called a gravity wave. It has been investigated for example by Meroney and Lohmeyer\textsuperscript{1} as well as Huppert and Simpson.\textsuperscript{2} Such gravity waves are not included here.

There are multiple driving forces causing the spread of one gas into another. Examples are concentration or ordinary diffusion as well as pressure diffusion, forced diffusion, and thermal diffusion. Certainly concentration diffusion must be included here. Pressure diffusion may be important when great heights are considered or when large pressure gradients are imposed, for example, via centrifugation. Clearly such diffusion can be neglected here.

Forced diffusion is the result of applying different forces to different particles in a mixture, thus promoting mixing or separation. Forced diffusion can be accomplished when an electric field is applied to a mixture of particles having different ionic charges. This is not the case here and thus this diffusion mechanism is neglected.

Thermal diffusion is caused by a temperature gradient. It is neglected here since the effect is small and the system considered here is assumed to be isothermal.

Thus the only diffusion mechanism that need be considered is that due to the concentration gradient. Note that since these other diffusion mechanisms are negligible and since the effect of concentration diffusion is to reduce the concentration gradient, there is no mechanism to cause settling or stratification once the system reaches a uniform concentration throughout.

**Method of Analysis**

For unsteady, binary diffusion, Bird, Stewart, and Lightfoot\textsuperscript{3} provide the following equation, valid in the absence of thermal, pressure, and forced diffusion.