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PHYSICAL MODELLING OF FORTY CUBIC METER LNG SPILLS AT CHINA LAKE, CALIFORNIA

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INTRODUCTION

In many parts of the world there is the perception that current and planned liquid natural gas (LNG) operations and facilities present an unacceptable risk to the public. Hence, the Division of Environmental Control Technology, Department of Energy, and the Gas Research Institute, USA have supported a series of tests on liquid natural gas spilled in amounts of five and forty cubic meters onto a pond at China Lake Naval Weapons Center, California. A parallel wind tunnel model program has been performed in the meteorological wind tunnels of Colorado State University to provide field test planning information, to extend the value of a limited set of field measurements, and to validate the concept of physical modeling of LNG plume dispersion as a predictive hazard analysis tool. The measurement results described herein provided a foundation for instrument placement and interpretation of terrain effects during the 40 m^3 field experiments. Wind tunnel laboratory measurements permit a degree of control of safety, meteorological, source and site variables not often feasible or economic at full scale.

Past studies have demonstrated that the cold LNG vapor plume will remain negatively buoyant for most of its lifetime (Meroney and Neff, 1977). A hazardous mixture will extend downwind at ground level until

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the atmosphere has diluted the LNG vapor below the lower flammability limit, LFL, (a local concentration for methane of 5 % by volume). During the fall of 1978 four experiments were performed where 5 m^3 of LNG were released through a 20 cm pipe onto a pond of water at a rate of about 5 m^3/min. (Koopman, et. al., 1979). Wind tunnel simulations were also performed before and after the field tests by Meroney and Neff (1980). Comparison of the measured concentration data with model predictions was significantly hindered by fluctuations in the wind speed and direction during the field experiments. Even when averaged over 10 second intervals, the wind speed varied by as much as a factor of three and the wind direction by as much as 60° during a single test. Nonetheless for the one case where conditions were reasonably stationary the laboratory concentrations were within 4 to 25 % of field measurements.

During the fall of 1979 a series of model tests were performed at Colorado State University to simulate 40 cubic meter spills at the China Lake site. A new set of instrumentation, data handling procedures, and model were prepared (Meroney et. al., 1980). The results are the subject of this paper. During the summer of 1980 field spills have been performed at the China Lake facility. This data is currently being tabulated for distribution by the Lawrence Livermore Laboratory, California.

LABORATORY SIMULATION OF DENSE PLUMES RESULTING FROM CRYOGENIC SPILLS

Physical modeling in wind tunnels requires consideration of the physics of the atmospheric surface layer as well as the dynamics of the plume motion. Reliable criteria for simulating the pertinant physical properties of the atmospheric boundary layer have been demonstrated by several investigators (Cermak, 1975, 1979). Frequently partial simulation suffices when the test domain is limited in time and space (i.e. Cariolis accelerations are neglected). Specific problems associated with the dispersion of cold natural gas plumes have been previously discussed by Meroney et. al. (1978, 1979). Prior experience with dense gas plume simulation has also been summarized in Meroney et. al., (1980).

Partial Simulation Criteria

When one considers the dynamics of gaseous plume behavior, exact similitude requires the simultaneous equivalence of mass, momentum and volume flux ratios, densimetric Froude number, Reynolds number, and specific gravity. Consideration of variable property, non-ideal gas, and thermal behaviour of the plume mixture introduces additional constraints on specific heat capacity variations (Neff and Meroney, 1979).

For a plume whose temperature, molecular weight, and specific heat are all different from that of the ambient air, i.e., a cold natural gas plume, equality in the variation of the specific gravity upon mixing must be relaxed slightly if one is to model utilizing a gas different from that of the prototype. In most situations this deviation from exact similarity is very small.

A reasonably complete simulation may be obtained in some situations even when a modified initial specific gas ratio is stipulated. By increasing the specific gravity of the model gas compared to the prototype gas, one increases the reference velocity over the model. It is difficult to generate a flow which is similar to that of the atmospheric boundary layer in a wind-tunnel run at very low wind speeds. Thus the effect of modifying the models specific gravity extends the range of flow situations which can be modeled accurately. Meroney et al. (1974) and Isyumov and Tanaka (1979) found that Froude number and volume flux equality provided conservative ground-level concentrations for buoyant plumes. Skinner and Ludwig (1978) and Kothari and Meroney (1980) obtained similar plume trajectories when Flux Froude number and momentum ratio equivalence are specified.

Scaling of the effects of heat transfer by conduction, convection, radiation, or latent heat release from entrained water vapor cannot be reproduced when the model source gas and environment are isothermal. Fortunately, in a large majority of industrial plumes the effects of heat transfer by conduction, convection, and radiation from the environment are small enough that the plume buoyancy essentially remains unchanged. The influence of latent heat release by moisture upon the plume's buoyancy is a function of the quantity of water vapor present in the plume and the humidity of the ambient atmosphere. Such phase change effects on plume buoyancy can be very pronounced in some prototype situations. Fortunately the China Lake site humidity is extremely low.

The modeling of the plume Reynolds number is relaxed in all physical model studies. This parameter is thought to be of small importance since the plume's character is normally dominated by background atmospheric turbulence soon after its emission. But, if one was interested in plume behavior near the source, then steps should be taken to assume that the model's plume is fully turbulent.

Simulation of the China Lake LNG Spill Plume

The buoyancy of a plume resulting from an LNG spill is a function of both the mole fraction of methane and temperature. If the plume entrains air adiabatically, then the plume would remain negatively buoyant for its entire lifetime. A release of an isothermal high molecular weight gas will behave in a similar manner to a cold plume entraining adiabatically within small corrections for differences between specific heat capacity of source gas and air. Hence, to simplify laboratory procedures the equality of model and prototype specific gravity was relaxed so that pure Argon could be used for the source gas. The equivalence of momentum flux ratio is not physically significant for a ground source released at low flow rates over a large area (LNG boiling on China Lake test pond); hence, model conditions were stipulated on the basis of equivalence between densimetric Froude number and volume flux ratio.

Argon provides almost eight times the detection sensitivity for instantaneous concentration measurements as the carbon dioxide used in previous studies. Over the concentration range where the buoyancy forces are dominant the variation of the Froude number is properly simulated. Undistored scaling of velocity components was maintained, which implies the undistorted scaling of source strength.

Since the thermally variable prototype gas was simulated by an isothermal simulation gas, the concentration measurements observed in the model must be adjusted to equivalent concentrations that would be measured in the field. This relationship which is derived in Neff and Meroney (1979) is:

$$X_p = \frac{X_m}{X_m + (1 - X_m)\frac{T_s}{T_a}}$$

where

X_m = volume or mole fraction measured during the model tests

T_s = source temperature of LNG during field conditions

and T_a = ambient air temperature during field conditions.

The actual source condition, boiloff rate per unit area over the time duration of the spill, for a spill of LNG on water is highly unpredictable. As there was no data on the variable area and variable volume of the different LNG tests conducted at China Lake, the source conditions were approximated by assuming a steady boiloff rate for the duration of the spill over a constant area.

LABORATORY METHODOLOGY

Simulation methods required to produce a model atmospheric boundary layer have been described in some detail by Cermak (1975). Special procedures and equipment required for dense plume measurements are considered by Meroney et al. (1978, 1979).

Wind-Tunnel Facility

The Environmental Wind Tunnel (EWT) at Colorado State University was used for the LNG spill test series. This wind tunnel, designed to study atmospheric flow phenomena, incorporates special features such as adjustable ceiling, rotating turntables, transparent boundary walls, and a long test section (3.6 m wide x 2.1 m tall x 17.4 m long) to permit reproduction of micrometeorological behavior at large scales. Mean wind speeds of 0.15 to 12 m/s can be obtained in the EWT. Boundary-layer depths one meter thick over the downstream six meters can be obtained with the use of vortex generators at the test-section entrance and surface roughness on the floor. The flexible test-section roof of the EWT is adjustable in height to permit the longitudinal pressure gradient to be set at zero. The vortex generators at the tunnel's entrance were followed by 10 m of open cardboard corrugation which produced a physical height variation of 3 mm, and a 3 m approach ramp to the 1:240 scale topography at the China Lake site.

Model

A 1:240 scale model of the China Lake topography was constructed for the use in the Environmental Wind Tunnel. The topography of the China Lake site was simulated by a layered model, each layer (1.3 mm thick) was equivalent to 0.3 m in the field. The model and concentration probes are shown in Figure 1. A cylindrical plenum manufactured with perforated upper plate was centered in the middle of the test site pond. The source gas, Argon, stored in a high-pressure cylinder was directed through a solenoid valve, a flowmeter, and onto the circular area source mounted in the model pond. All source release conditions were step functions; thus, their profiles can be recreated from the data in Table 1.

Wind Profiles and Turbulence Measurements

Velocity profile measurements and reference wind speed conditions were obtained with a Thermo-Systems, Inc. (TSI) 1050 anemometer and a TSI model 1210 hot-film probe. Turbulence measurements were made with this system for the longitudinal velocity component and with a TSI split-film probe connected to two TSI 1050 anemometers for both longituninal and vertical component measurements. Since the voltage response of these anemometers is nonlinear with respect to velocity, a multi-point calibration of system response versus velocity was utilized for data reduction.

Concentration Measurements

The concentrations of methane produced during a LNG spill are inherently time dependent. It was necessary to have a frequency response to concentration fluctuations of at least 50 Hz to isolate peaks of methane concentrations above 5 % (the lower flammability limit of methane in air, LFL); hence, a set of eight aspirating hot-film probes were used for this study.

The basic principles governing the behavior of such probes have been discussed by Meroney et al. (1980, 1978). The hot-wire aspirating probes were constructed with 0.1 mm diameter platinum wire sensors monitored by an eight-channel Thermal System Inc. hot wire anemometer. The signals were conditioned for input to a Preston analog to digital converter operated by a Hewlett Packard System 1000 computer. The effective sampling area of the probe inlet is a function of the probe's aspiration rate and the distribution of approach velocities of the gas sampled. The effective sampling area over the model was 0.5 cm^2, or resolution at full scale would be 2.9 m^2. The errors caused by a linearity assumption during data reduction, temperature drift, and calibration uncertainities is estimated to be 5 to 15 % of the measured methane concentrations.

TEST PROGRAM RESULTS

A summary of the equivalent prototype test conditions selected for the pre-field test series performed in the EWT are presented in Table 1. All dimensions reported for measured results are equivalent full scale values. The coordinate origin for all figures is the pond center of LNG spill point. The positive x axis is in the direction of the prevailing wind.

Characteristics of the Modeled Boundary Layer

Measurements of the approach flow characteristics were obtained for the modeled flow over the China Lake scale topography. In the absence of field data the characteristic velocity and length scales have been compared to values recommended by Counihan (1975) for a site of equivalent surface roughness. Table 2 compares such values as cited by Counihan and values scaled up from the model tests.

Test Series Results

The China Lake boiloff rate, duration, and wind speed for LNG spills were simulated as noted in Table 1. Concentrations were measured versus time at specified distances and heights. A digitized record of concentration time history was recorded on computer system disk files. Each test configuration was replicated several times to examine the statistics expected due to turbulence variability. Three such time history replications are presented in Figure 3 for three different ground level points downwind of spill configuration Number 7 as described in Table 1. From time history records such as these peak concentrations, times of 5 % arrival, 15 % arrival, 15 % departure, 5 % departure and the total dosage were evaluated.

Table 3 summarizes data for the maximum longitudinal downwind distance over which concentrations of 15, 10, and 5 % persisted for each test. The data suggest that for similar orientations and wind speeds a higher spill rate may result in slightly longer transport distance. On the other hand an increase in wind speed for constant orientation and spill rate will result in longer transport distances, yet for higher windspeeds the turbulence increases and the distance to LFL decreases.

Figures 4, 5 and 6 display maximum concentration isopleths when the plume moves up over a hill, along the side of a hill, and over flat ground respectively. As might be expected the hill delays and spreads the plume laterally resulting in shortest downwind distances to LFL. The plume moving over flat ground travels further with smaller lateral spreading. The longest distance to LFL appears to occur for test Number 6 when the plume moves along the hill edge. Apparently the gravitational effect on the hill slope decreases lateral spreading permitting the plume to exist undilluted for longer times. The same effects are apparent in the data in Table 3.

For health safety purposes the data may be plotted in terms of the maximum limits of the flammable zone as a function of distance and time. Figure 7 displays plume flammable zones for test Number 1. Apparently flammable gases may persist near the source even 10 minutes after the spill for almost all cases studied. Finally Figure 8 suggests the typical time progression of the LFL contour over the terrain. Until 300 seconds the plume progresses downwind; subsequently the LFL retreats toward the source. For an idealized instantaneous release over flat terrain one might expect the gases to retreat inward, but not necessarily toward the source.

CONCLUSIONS

The laboratory data await correlation and comparison with equivalent field tests; nonetheless a number of interesting phenomena are discernable in the test results. Topographical effects are significant. Modest hill slopes of 1:10 can detain dense plumes and reduce longitudinal distances to LFL. Shallow valleys or gorges may channel the plume and sustain high concentrations. Accelerated boiloff rates of a finite amount of gas may result in slightly modified LFL distances; however, the effect of a factor of 2 variations in boiloff rate is barely discernable in these results. An increased travel distance to a given concentration with increased wind speed was clearly apparent for winds between 3 and 5 m/sec. As Fay (1980) notes, this is in marked contrast to the passive dispersion of clouds where there is an inverse dependence on wind speed.

ACKNOWLEDGEMENT

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Table 1: Summary of Tests: China Lake Spills

Test Number	Wind Speed 10m (m/sec)	Spill Size (liquid) (m^3)	Spill Rate (m^3/min)	Wind Direction (Angle)
1	3	40	15	225°
2	3	40	30	225°
3	5	40	15	225°
4	5	40	30	225°
5	5	40	30	195°
6	5	40	30	255°
7	5	40	30	285°
8	7	40	15	225°
9	7	40	30	225°

Table 2: Summary of Approach Flow Characteristics

Description	Atmospheric Data*	Modeled Values
z_o (m)	(0.01 - 0.15) 0.045	0.043
$1/n$	(0.14 - 0.17) 0.15	0.180
u_*/u_{10}	(0.04 - 0.05) 0.045	0.078
Λ_x (m)	(12.0 - 30.0)	31 - 62
Λ_y (m)	(1 - 2)	–
$(u'/u)_{30\ m}$	(0.11 - 0.18) 0.14	0.13

* Counihan, 1975

Table 3: Maximum Longitudinal Distances to UFL and LFL

Test Number	Wind Speed (m/sec)	Wind Direction (angle °)	Spill Rate (m^3/min)	Longitudinal Distances (m) to		
				15 % UFL	10 %	5 % LFL
1	3	225	15	80	120	320
2	3	225	30	90	150	270
3	5	225	15	100	190	350
4	5	225	30	120	180	350
5	5	195	30	115	225	400
6	5	255	30	180	225	400
7	5	285	30	145	245	400
8	7	225	15	100	150	320
9	7	225	30	140	235	355

Figure 1: China Lake Naval Weapons Center Spill Site Model; Scale 1:240

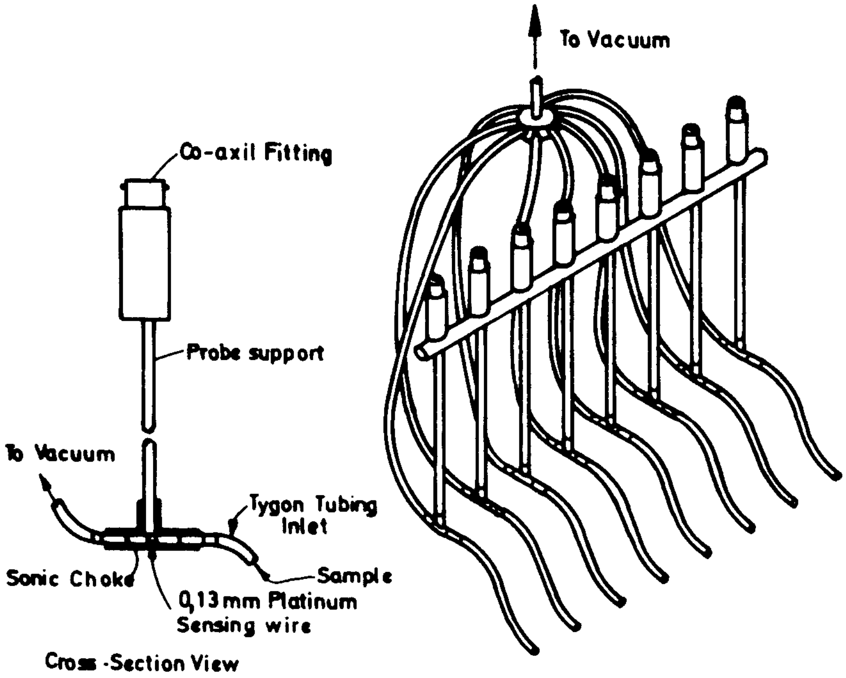

Figure 2: Hot-wire Katharometer Probes

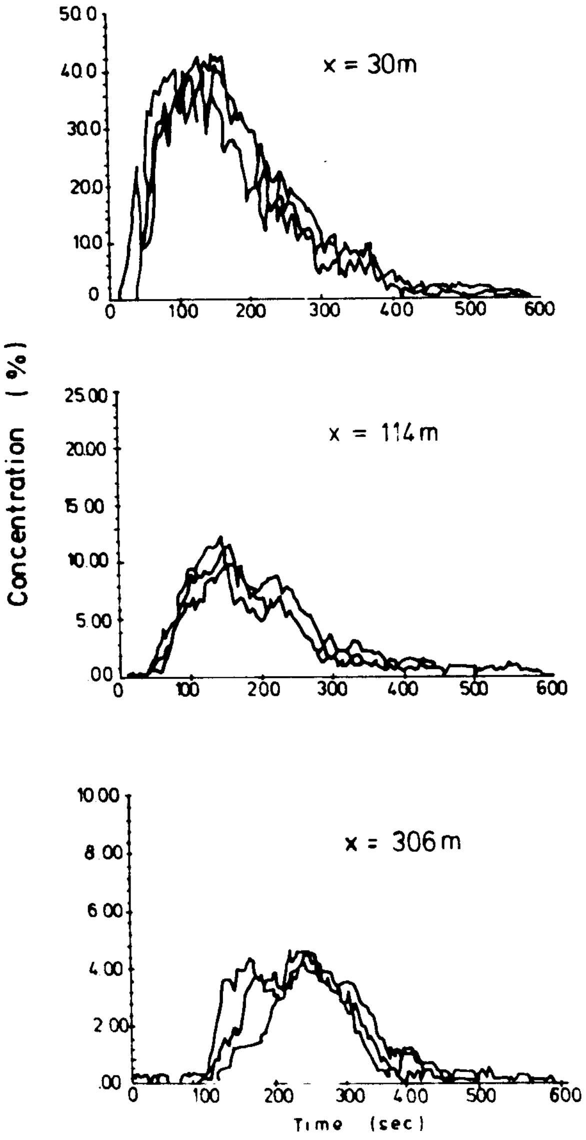

Figure 3: Concentration Time Histories (Run Number 7)

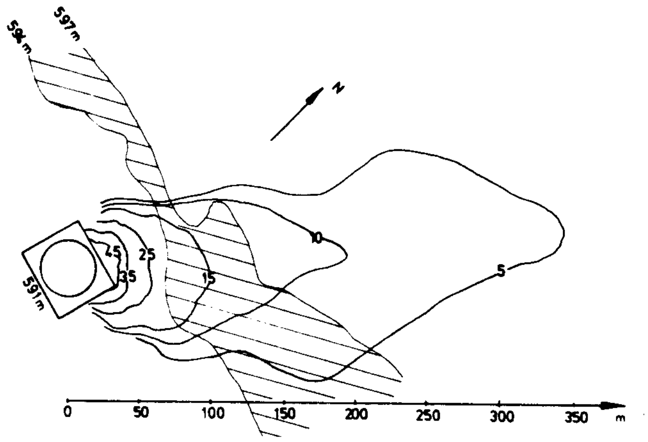

Figure 4: Ground Level Peak Concentration Contours (Run Number 3)

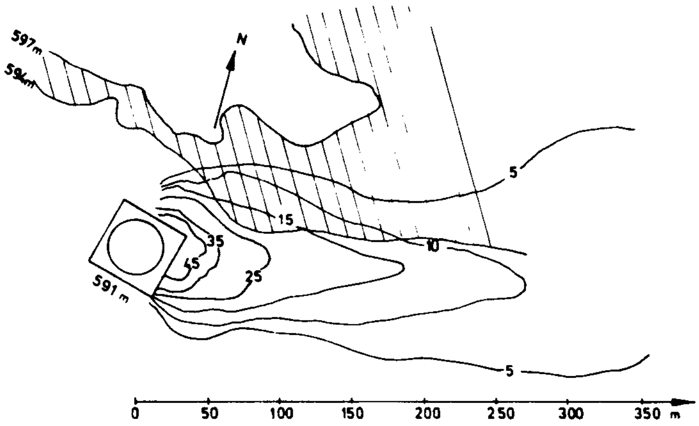

Figure 5: Ground Level Peak Concentration Contours (Run Number 6)

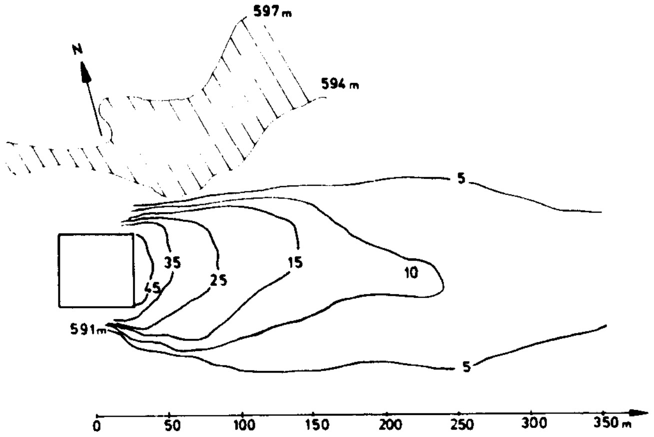

Figure 6: Ground Level Peak Concentration Contours (Run Number 7)

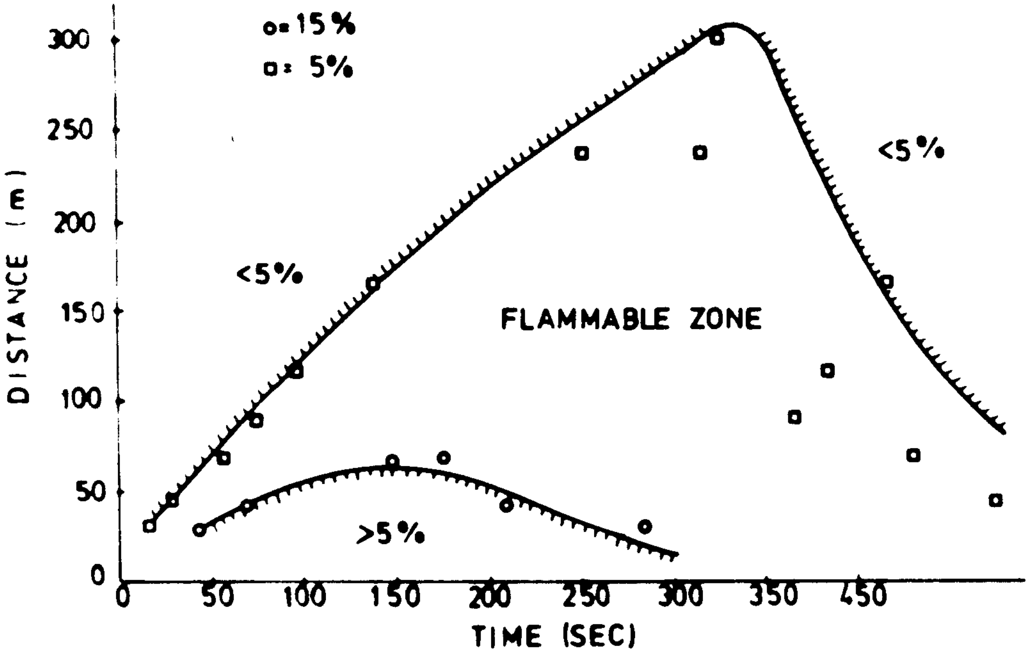

Figure 7: Maximum Limits of Flammable Zone as a Function of Distance and Time (Run Number 1)

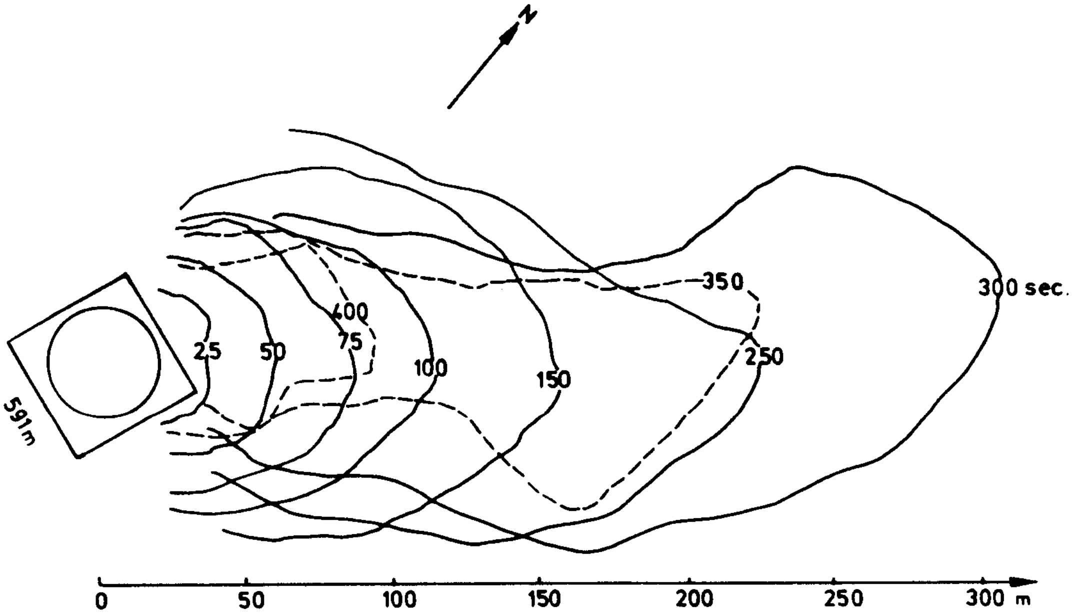

Figure 8: Time Origression of Ground Level LFL (Run Number 1)