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ESTIMATING THE IMPACTS OF L.P.G. SPILLS DURING TRANSPORTATION ACCIDENTS

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SUMMARY

Transportation accidents involving releases of liquefied petroleum gases can cause substantial damage to the population and property adjacent to an accident scene. While some researchers have analyzed specific aspects of L.P.G. releases in detail, to date no single self-contained model could estimate all significant impacts of transporation-related releases at once. In response to this need, this paper describes a model which was designed to perform such an assessment. Both interactive and batch versions of the LPG-1 model have been implemented, which can be applied either in isolation or as modules within a larger risk assessment model.

The model's first module contains a representation of the spill mechanism following a transportation accident. It determines the amount of vapour flash-off and the size of any remaining pool based on the atmospheric conditions at the time of the accident, the amount of pre-heating of the container and the thermodynamic properties of the material shipped. Subsequently, simplified fireball, vapour cloud explosion and BLEVE models are used to compute the extent to which pre-specified levels of shockwave and heat radiation damage will be reached and the radius within which direct flame exposure will be experienced. During each phase of the analysis, the model considers relevant site-specific mitigating factors, such as the wind speed, air stability, combustion characteristics and the probability of encountering sparks.

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INTRODUCTION

Liquefied Petroleum Gas (LPG) is a term which applies to a group of combustible gases which are transported as compressed liquefied gases as their atmospheric pressure boiling points are below room temperature. The group is mainly made up of a variety of propane-butane mixtures, while ethane is a related material. Their primary hazard is their flammable and explosive nature, but at very high concentrations they may also cause asphyxiation. As the physical properties of LPG's vary only within a limited range, they are discussed below using propane as an example.

a. Properties of LPG's

At atmospheric pressure and normal temperatures, propane is a colorless, flammable gas which is approximately 50% heavier than air. It has a slight natural gas odour and usually has added odorants (ref. 1). Propane is not irritating to the eyes, nose and throat, but a concentration in air greater than 10% will cause dizziness in a few minutes, while a 1% concentration will cause the same symptoms after 10 minutes. High levels can cause asphyxiation due to the reduction of oxygen (ref. 1).

Propane is only flammable within a certain range of concentration within the air. The lower portion of the flammability range is dictated by the Lower Explosive Limit (L.E.L. or Lower Flammable Limit, L.F.L.), which is a concentration of about 2.3% in air (ref. 2). Below this value, the vapour is too lean to ignite. The upper portion of the flammability range is called the Upper Explosive Limit (the U.E.L. or Upper Flammable Limit, U.F.L.), which is a concentration of about 9.5% in air. At concentrations above this limit the gas-air mixture is too rich to burn. A given vapour cloud will typically have lean, flammable, and overrich zones at the same time, but in varying relative proportions (ref. 3).

b. Overview of the Paper

Subsequent sections of this paper will trace the events following a transportation accident involving an LPG release. Typical accident scenarios are presented and the material release, dispersion, and ignition properties are described. Models of cloud disperion and pool formation are described, and quantitative estimates of expected explosion, fire and fragmentation damage are presented. Finally, the complete LPG-1 model is presented and illustrated using an example.

1. ACCIDENT CHARACTERISTICS AND RELEASE SCENARIOS

There are four categories of accident stresses in the train accident environment that may fail an LPG container: fire, impact, crush and puncture. These are discussed below based on Rose (ref. 1), while details as to the probabilities of each of these events are provided in a complementary paper by Saccomanno, Stewart and Van Aerde (ref. 4).

a. Types of Failures

When a fire heats a container, it may weaken the container walls and increase the pressure of the contents. Both these factors increase the probability of a container failure. Since the Mississauga Show Cause Hearing (ref. 5) tank cars in Canada must be fitted with thermal insulation, which is intended to increase the time taken for a tank to fail due to heating. Experiments done in the United States have shown that an uninsulated tank car failed after 24 minutes in a fire, whereas an insulated car failed after 96 minutes according to Sandia (ref. 6).

Failure of rail tank cars may also be caused by accident impact forces, which are produced in approximately 15 % of all collision and derailment accidents (ref. 6). Impact is defined as a collision between the tank car and a rigid vertical surface, and it is expressed in terms of the accident velocity changes required to produce tank rupture. Failures due to crush loads primarily occur when the tank car rests between the ground and a derailed car. It is estimated that 25 % of derailed cars overturn, subjecting themselves to crush loads. The other 75%, which remain upright, may still be subject to other loads. It was also estimated that historically the rate of puncture was 18 % for tank walls and 82 % for rail tank car heads, but as tank cars must now be fitted with head shields, the frequency of head punctures has been reduced significantly according to data from the Railway Progress Institute (ref. 7).

The consequences of all of these failures are a direct function of material release conditions, such as the reaction of LPG upon exposure to atmospheric pressure, the material release rate, the initial cloud shape, the concentration of the cloud, and the time to ignition. These factors are discussed next.

b. General Evaporation Characteristics of L.P.G. Releases

For LPG's there are two significant components of vaporization to be considered, namely flash vaporization and pool evaporization. Flash vaporization takes place following a breach of containment when enough liquid is flashed off to restore the liquid's temperature to the boiling point at atmospheric pressure (ref. 3). Due to the violent character of this reaction, additional liquid becomes entrained in the air as small liquid droplets. This additional amount is usually equal to the original flashing fraction, such that for some LPG gases nearly all of the liquefied gas will become vapourized upon exposure to atmospheric pressure.

c. Continuous vs Sudden Releases

A continuous discharge results if there is a leak in the tank, or if the safety relief valves allow discharge to relieve excess pressure in the container. For continuous liquid releases both flash vaporization and pool evaporation must be considered. The amount of propane instantaneously vaporized is approximately 35% of the release rate, but as the surface vaporization from the growing liquid propane pool increases to equal the input rate to the pool, the total vaporization rate becomes equal to the total release rate.

A sudden or immediate release from a tank failure creates an initial flash vaporization cloud, containing about 35% of the tank's contents. However, Marshall(ref. 3) suggests that due to liquid entrainment in reality an additional 35% of the liquid is contributed to the initial vapour cloud. Any remaining unevaporated propane forms a liquid pool, which in turn forms a plume analogous to that from a continuous release (refs. 1 and 3). However, since the cloud developing from the pool evaporation would cover a smaller area than the cloud formed by the initial flash vaporization, pool evaporation is usually ignored in hazard evaluations of sudden releases.

The most dramatic containment failure occurs when the container is first engulfed with fire and either the tank's insulation has been damaged by the accident or the safety relief valve is defective. In this case the increased liquid temperature results in a much higher vapour pressure, such that when the container bursts, it violently vapourizes entire container contents, which ignites immediately.

2. EXPLOSION AND FIRE CHARACTERISTICS OF LPG

Based on the above discussion, 3 different general types of fire/explosion/ignition scenarios can result from a release of LPG during a transportation accident:

a. Continuous Releases Due to Mechanical Failure of Vessel
b. Sudden Releases Due to Mechanical Failure of Vessel
c. Sudden Releases Due to Heating of the Vessel

The exact sequence of probabilistic events, which results in each of these release scenarios, can be described using an event tree structure as indicated in a report by IRR (ref. 8). This section describes the events that take place within each of these scenarios, while the manner in which these events are modelled within LPG-1 is described in Section 3.

a. Continuous Releases Due to Mechanical Failure of Vessel

If the material from a continuous release meets with an ignition source immediately, a torch fire will likely develop at the release source location. The heat of this torch will evaporate virtually all liquid released such that no significant liquid pool forms. In addition, the torch heat may induce a sudden or immediate release of the remaining container contents. If the material does not ignite immediately, a vapour cloud and a liquid pool will form. This vapour cloud and any evaporation from the pool will form a joint cloud which may subsequently burn or explode, when a ignition source is encountered later. Similarly, any unevaporated liquid pool that remains may also catch fire and result in either a stationary or a running pool fire.

(i) Torch Fires When an ignition source is immediately available, and the fuel is released as a strongly directional jet, the result is a torch fire. Its flames are normally confined to a small local area with estimated torch temperatures for propane ranging from 1040 C to 1180 C (ref. 1). Torch fires can also lead to more significant hazards as the flame impinges on the propane tank (or any other nearby tanks). The additional heat may weaken the tank and allow it to rupture, releasing major amounts of propane and creating a fireball (BLEVE). In addition, a mechanism may develop from this sequence in which the whole rail car "rockets" several hundred feet (ref. 1).

(ii) Stationary and Running Pool Fires Any spilled liquid fuel that is ignited forms a pool fire. If the spread of the release is restricted by natural barriers, the result is a stationary pool fire which may heat the the remaining tank content. Alternatively, if instead the runoff is not restricted, a running fire may result which could spread into nearby sewers or other areas.

(iii) Premixed Flash Fire (Vapour Fire) Propagating premixed fires occur when a cloud of gas inside the flammable range is ignited (ref. 9) and flames propagate outwards from the ignition source. Flash fires are more likely following the ignition of a cloud with a height less than its width, such as clouds formed by evaporation from liquid pools, or plumes from continuous releases. Usually, the low flame speeds (0.4 to 4.0 m/sec) which accompany a flash fire produce no overpressure effects. If there is some dispersion prior to ignition, the geometry of the cloud at the time of ignition is assumed to form the boundaries of the fire. This area is commonly approximated by an ellipse, with the major and minor axes of the volume being defined by the cloud's downwind and crosswind distances.

(iv) Unconfined Vapour Cloud Explosion (UVCE) A continuous release of vapour with dispersal and delayed ignition causes an unconfined vapour cloud explosion (UVCE). The usual sequence of events includes a massive release of combustible fuel, a reasonable delay in ignition (30 seconds to 30 minutes), and an ignition of the cloud to detonation. An UVCE is a significant flame hazard and many also result in a shock wave. Flame speeds can increase to about 170-200 m/s, which results in overpressures that are sufficient to cause extensive damage both within and outside the cloud. However, detonative combustion is required before a destructive blast wave can be formed.

Historical data have shown that for an explosion to occur the cloud must be large (at least 5 tonnes of hydrocarbon must be released), the rate of release of vapour must be large (1 tonne/min or more) and a significant delay before ignition is required (greater than 30 seconds) (ref. 9). The Canvey report (quoted in ref. 10) considers that the probabilities of explosion for spills less than 10 tonnes, for spills between 10-100 tonnes, and spills greater than 100 tonnes are 0, .1 and 1 respectively. In addition, for a continuous or massive spill the medium fraction of fuel, at any one time within the combustible range, is usually about 10% (ref. 10).

b. Sudden Releases due to Mechanical Failure of Vessel

In some situations the impact forces in an accident may fail the entire container, such that its entire contents are released virtually instantaneously. Subsequently, an immediate ignition results in a fireball; a slightly delayed ignition results in a diffusion flash fire, while an ignition delay of more than a minute may result in a pre-mixed flash fire. In both of the latter cases, an unconfined vapour cloud explosion or a pool fire are also possible.

(i) Fireballs Considine et al. (ref. 9) assume that the immediate ignition of an instantaneous container burst always creates a fireball, but that only a short delay is necessary before pre-mixed conditions occur. A fireball is a propagating diffusion flame with a flame geometry that may vary somewhere between a sphere and a hemisphere. As a hemispherical fireball will expose more ground area to direct flame, this configuration is used for a conservative damage estimate (ref. 1). According to Roberts (ref. 11) and Marshall (ref. 3), the maximum diameter of the fireball is relatively insensitive to fuel type and to the mechanism of cloud formation.

(ii) Diffusion Flash Fires A diffusion flash fire is an example of a propagating diffusion flame (ref. 9). Flash fires are more likely following the ignition of a cloud with a height less than its width, such as for example "slumped" hemispherical clouds. Ignition takes place at the edges of the cloud because the central core is above the U.F.L. Subsequent burning is controlled by entrainment of air and its mixing with fuel. This is a relatively slow process. For large clouds, diffusive burning may be complete before the flame is able to propagate around the whole cloud surface.

(iii) Pre-Mixed and Diffusion Flames If there is delayed ignition, there may be a transition from diffusive to premixed burning. Considine et al. (ref. 9) indicate that a diffusion flame occurs if the cloud is mostly above the U.F.L., whereas a premixed flame occurs when the majority of the cloud is within the flammability limits. For a pre-mixed flame, there will not be a well defined "flame front" but the whole cloud will appear to be on fire. A method is proposed by Considine et al. (ref. 9) to determine the exact combustion mode.

c. Sudden Releases due to Heating of the Vessel

A BLEVE (Boiling Liquid/Evaporating Vapour Explosion) is initiated by a torch or pool fire which engulfs an LPG container. The heat of the fire will weaken the unwetted part of the container while raising the vapour pressure inside. Eventually the safety valve can no longer dissipate the excess pressure, resulting in a tank failure when the shell becomes too weak to even sustain normal working pressures. Rose (ref. 1) states that American tests have shown that tanks fail when they are about half full of liquid. If the safety valves are blocked, are not working, or cannot adequately handle the discharge, the above overpressurization of the tank will occur much more quickly. Because of the heating by a torch fire prior to the BLEVE, the percentage of flash vaporization will be near 100%.

A description of the phases of a fireball from a large (80 tonnes) BLEVE is given by Crawley (ref. 12). He indicates that phase one of the fire ball lasted about 2 seconds. During the first second the flame heat was about 1300 C and the fireball reached about half of its final diameter. During the next second, the fireball grew to its final diameter and flame temperatures dropped to 1100 to 1200 C. In the second fireball phase, which lasted about 10 seconds, the fireball size and the flame temperatures remained constant. Finally, the burn-out lasted about 5 seconds and during this time the cloud did not change in size.

d. Ignition

Critical to all LPG incidents is the time to ignition, as it determines the amount and concentration of the material being ignited. Historical data suggests that most ignitions take place at the accident site, but very little documentation exists to support this idea (ref. 1). Considine et al. (ref. 9) consider the probability of a delayed ignition at the source for large releases to be independent of wind direction. They also assign a larger ignition probability as time goes on, as more ignition sources would be encompassed by the travelling cloud. For small releases the probability of a delayed ignition at the source was reduced for those wind directions carrying the cloud away from the site.

If there is no ignition prior to the time the vapour disperses to a concentration below its Lower Explosive Limit, no blast or fire effects will be incurred. However, this may still not be a totally safe condition as there may be toxic effects below the L.F.L. (ref. 12).

3. LPG-1 DAMAGE MODELLING

This section of the paper describes the actual modules within the LPG-1 program which estimate the damages associated with the above release events/secenarios. The routines to model the actual spill, the fireball, the vapour cloud shockwave, and any pool fire are described separately below, while the inputs and results of a sample model run are provided in Section 4.

a. Spill Submodel

The purpose of the spill model is to determine which fractions of a shipment's cargo will contribute to forming a fireball, a vapour cloud explosion or a pool fire following an accident. It considers the size of the shipment, the prevailing environmental conditions and those factors which may influence the expected time to ignition.

The mass of the material shipped is determined as the product of the container volume, the percentage to which it is filled, and the density of the liquid that is being shipped. The mass of LPG that is actually spilled is specified as a spill-fraction, which may be a function of the type of accident. The amount of vapour contributing to either a fireball or vapour cloud explosion is derived from the mass spilled, multiplied by the flash fraction and the additional amount of liquid entrainment.

The amount of LPG remaining as a liquid pool is determined as the difference between the amount spilled and the amount of vapour formed. The relationships used to determine the amount of vapour and liquid released in the spill are listed in Figure 1. The example lists the properties of propane for any commodity-specific analysis variables, but for other LP-gases these variables should of course be changed.

Marshall's flashing fraction relationship is based on the liquid's temperature, which for non-fire situations will be close to the ambient air temperature. However, in a fire situation the liquid temperature may rise quickly to about 60 degrees Celcius, which is the temperature at which the safety relief valves open and relieve sufficent vapour to keep the liquid at 60 degrees. Therefore knowledge of a previous fire situation dictates that the temperature inputs for this case should be 60 degrees Celcius.

Figure 1: Relationships Employed in LPG Spill Submodel

1. Calculate weight in container:

$$W = (V * PF) * D_L$$

$$W_T = W / 1000$$

where: W = weight of LPG in container (kg)
V = container volume (m^3)
PF = percent full (input value)
D_L = density of liquid (kg/m^3)
W_T = weight of LPG in container (tonnes)

2. Calculate the tonnes spilled:

$$Q_T = SF * W_T$$

where: Q_T = tonnes spilled
SF = fraction of container spilled (input value)

3. Calculate the amount of flash vapourization:

$$ff = 0.05537 * T + 0.22907$$

where: ff = flashing fraction (ref. 3)
T = temperature (deg C)

4. Calculate the amount of vapour formed:

$$Q_V = Q_T * (ff + ff * e)$$

where: Q_V = amount of vapour formed instantaneously (tonnes)

e = liquid entrained (input as a fraction of ff)

b. Fireball Formation

The damage contours around a fireball are established within the model based on the size and duration of the fireball, and the heat radiation thresholds for various types of damage. The actual relationships used are listed in Figure 2.

The size and duration of a fireball are primarily a function of the amount of material involved. From these measures a basic threshold distance can be derived using one of two approaches. The first approach, as discussed in Rose (ref. 1), considers the gas emmissivity, the Stephan-Boltzman constant, the flame temperature, and the fireball's surface area. The second approach, as discussed in Roberts (ref. 11), considers the fraction of heat release, the combustion heat and the fireball's duration. Despite their obvious differences, they can be reduced to very similar functions of the amount of material spilled. In each case the desired damage contours that are derived for different heat radiation threshold values are also similar. Each type of damage has a corresponding radiation threshold and the distance to this threshold is derived using an application of the inverse square law. In addition, each threshold value is a function of exposure duration time, and the model considers this exposure time to be equal to the fireball's duration.

c. Vapour Cloud Shock Wave

Damage contours from a vapour cloud explosion are established using a TNT equivalent weight for the vapour cloud and a unique coefficient for each damage level. To calculate the actual distance to a particular type of damage, relationships presented by Clancey (ref. 13) are used, which are listed in Figure 3. The TNT equivalent weight is a function of the heat content of propane, the amount of vapour in the explosive range, and the heat content of TNT, while the efficiency factor E accounts for partial combustion and for physical differences between TNT and gaseous explosions.

The entire amount of vapour that is formed instantaneously is considered to contribute to the shock wave. This produces a rather conservative damage estimate, as some studies have shown that only 10% of the vapour released may be in the flammable range at one time. This conservative bias of the model is somewhat compensated for by the fact that pool evaporation is not added to the total amount of vapour in the cloud.

Figure 2: Relationships for LPG Fireballs

1. Calculate dimensions:

$$R = C_R * (Q_T)^{1/3}$$

$$A_S = 2 * 3.1416 * R^2$$

$$t_{fb} = C_t * (Q_T)^{1/3}$$

where: R = fireball radius (m)

C_R = coefficient for fireball radius equation
Q_T = quantity spilled (tonnes)
A_s = surface area of fireball (m^2)
t_{fb} = duration of fireball (seconds)
C_t = coefficient for fireball duration equation

2. Calculate threshold distances:

$$D_{ros} = (E * S * T_{fb} * A_s) / (3.1416 * 1000)$$

$$D_{rob} = (F * H * Q_T * 1000) / (4 * 3.1416 * t_{fb})$$

where: E = gas emissivity
S = Stephan-Boltzman constant ($5.67 * 10^{-8}$ J/sm^2K^4)
T_{fb} = fireball flame temperature (deg K)
F = fraction of heat radiated from fireball
H = heat of combustion (kJ/kg)

3.Calculate heat flux for a given damage level:

$$H_f = 10 \exp[C_A * \log(t_{fb})/\log 10 + C_B]$$

where: H_f = heat flux (kW/m^2)
C_A and C_B = coefficients for a given damage

4. Calculate distance to damage:

$$D_L = (D_{ros} / H_f)^{1/2}$$

where: D_L = Rose's distance to a given damage level (m)

Figure 3: Relationships for LPG Vapour Cloud Explosions

1. Calculate TNT equivalent weight:

$$W = (E * H_{cp} * Q_V * 1000) / H_{cTNT}$$

where: W = TNT equivalent weight (kg)
E = constant
H_{cp} = propane heat of combustion (cal/kg)
Q_V = quantity of propane vapour (tonnes)
H_{cTNT} = TNT heat of combustion (cal/kg)

2. Calculate distance to damage:

$$L = C * W^{1/3}$$

where: L = distance to damage (m)
C = coefficient for specific damage level

d. Pool Fire

When a pool of liquid propane is exposed to the atmosphere, it will evaporate producing flammable vapours. An ignition source will ignite the vapours above the pool, causing what is known as a "pool" fire. The major damage from this event is the heat radiation which can then ignite secondary fires or heat other containers to cause a BLEVE. The damage contours around a pool fire are established based on the surface area of the pool and the heat radiation thresholds for various types of damage. Relationships used to estimate these quantities are listed in Figure 4.

The amount of LPG in the pool is calculated by subtracting the vapour initially flashed-off, from the total amount spilled. Then the pool area is determined by considering this weight, the density of liquid LPG, and an externally specified pool thickness. The subsequent radiation equations are based on the estimate of this area and estimates of the burning rate and the heat release rate of the LPG that is used. The actual damage contours are derived for different heat radiation threshold values, which indicate particular types of damage.

Figure 4: Relationships for LPG Pool Fires

1. Calculate amount of LPG in the pool:

$W = Q_T - Q_V$

where: W = quantity LPG in pool (tonnes)
Q_T = total quantity spilled (tonnes)
Q_V = quantity of vapour formed (tonnes)

2. Calculate pool volume and area:

$V = (W * 1000) / D_L$

$A = V / (d * 0.01)$

where: V = volume (m^3)
D_L = liquid density (kg/m^3)
A = area (m^2)
d = pool depth (cm)

3. Calculate energy radiation to surroundings:

$Q = R_B * R_{HR}$

where: Q = rate of radiation per unit area (kJ/m^2s)
R_B = burning rate (kg/m^2s)
R_{HR} = heat release rate (kJ/kg)

4. Calculate the distance to damage:

$X = (Q / (4 * 3.14 * H_f))^{1/2} * A^{1/2}$

where: X = distance to a specific damage (m)
H_f = heat flux to produce the damage (kW/m^2)

5. APPLICATION OF THE LPG-1 PROGRAM

The LPG-1 model was implemented on a microcomputer using a series of subroutines in Basic. The most important input parameters to the model and some sample values are provided in Figure 5, while a copy of a sample listing of the results is illustrated in Figure 6.

Figure 5: Input Parameters to LPG-1 and Some Typical Values.

Spill Submodel Input Data:

13.5	Nominal container volume (m^3)
0.85	Fraction of container filled
493.5	Density of liquid in container (kg/m^3)
1.0	Fraction of container spilled
0.1	Delay of ignition (minutes)
20	Temperature (degrees celcius)
1	Entrained liquid as a percent of flashing fraction

Fireball Input Data:

27.5, 3.76	Fireball radius and duration coefficients
0.1, 5.67E-08, 2200	Gas emmissivity, Stephan-Boltzmann const, flame temperature (deg K)
0.3, 50340	Fraction of heat release—Roberts, Heat of combustion--CRC Handbook (kJ/kg)

-.7481, 1.751	Coefficients a and b for blistering bare skin — Roberts
-.4121, 2.068	Coefficients a and b for ignition of cellulose material
-.7418, 2.266	Coefficients a and b for 1 % mortality rate
-.7498, 2.52	Coefficients a and b for 50 % mortality rate
0.1	Efficiency factor
1.196E07	Heat content propane (cal/kg) — Rose (1984)
1.106E06	Heat content TNT (cal/kg) — Rose

Input Data for Vapour Cloud Shock Wave:

150	C coefficient for no damage (range 50-150) -- Clancey (1982)
10	C coefficient for injury to people, glass windows broken
7	C coefficient for damage to wooden doors
4.5	C coefficient for destruction of light partitions
3.5	C coefficient for collapse of brick walls in small buildings
1.5	C coefficient for destruction of stone and brick buildings

Input Data for Pool Fire:

2	Pool thickness (cm)
0.13	Propane burning rate (kg/m^2 s) -- Mizner and Eyre (1982)
50359	Propane heat release rate (kJ/kg) -- CRC Handbook
6	Blistering of bare skin in 20 seconds (kw/m^2) -- Roberts
34	Ignition of cellulose materials (kw/m^2)
20	1 % mortality rate (kw/m^2)
35	50 % mortality rate (kw/m^2)

Figure 6a: Sample Listing of LPG-1 Results (First Part).

```
 ------ lpg  explosion/fireball/pool fire  --------

  program by M. Van Aerde, A. D'Astous, A. Stewart and F. Saccomanno
  Institute for Risk Research, University of Waterloo
              June 16, 1986

  model components adapted from various sources in the literature
 -----------------------------------------------------------------
   SPILL CHARACTERISTICS

CONTAIN:  volume:   13.50 m^3          filled 0.85
liquid :  density: 493.50 kg/m^3      weight:  5.66 tonnes
SPILL  :  fraction:  1.00             weight:  5.66 tonnes

AIR CON:  temp deg Cel. : 20 C                      stability:  D
VAPOUR :  flash-off %   : 33.98    liq. entrain % of flash-off: 100

----------------------------------------------------------------------
    FIREBALL FORMATION
COEFFICI:  radius:    27.5         duration:  3.76
FIREBALL:  radius:    49.0 m    surface:  15096.4  m^2
DURATION:  time:       6.7 secs
DISTANCE:   638257 m
---------------------------------------------------------
HAZARD:  Blistering of Bare Skin
HEAT FLUX: 13.58 kw/m^2   COEFFICIENTS: a:  -0.748    b:  1.75
DISTANCE:  216.8 m                   AREA:     0.15 km^2

HAZARD:  Ignition of Cellulose Material
HEAT FLUX: 53.40 kw/m^2   COEFFICIENTS: a:  -0.412    b:  2.07
DISTANCE:  109.3 m                   AREA:     0.04 km^2

HAZARD:  1% Mortality
HEAT FLUX: 44.99 kw/m^2   COEFFICIENTS: a:  -0.742    b:  2.27
DISTANCE:  119.1 m                   AREA:     0.04 km^2

HAZARD:  50% Mortality
HEAT FLUX: 79.53 kw/m^2   COEFFICIENTS: a:  -0.750    b:  2.52
DISTANCE:   89.6 m                   AREA:     0.03 km^2
```

Figure 6b: Sample Listing of LPG-1 Results (Second Part).

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-----------------------------------------------------------------

 VAPOUR CLOUD SHOCK WAVE
HEAT CONTENT PROPANE: 1.196E+07  (CAL/KG)    HEAT CONTENT TNT:      1.106E+06
 EFFICIENCY FACTOR E: 0.10               TNT EQUIVALENT WEIGHT:     4.16 tonnes
--------------------------------------------------------------------
HAZARD:  None
DAMAGE:  type:  1      COEFFICI:       150   DISTANCE:  2412.8 m    AREA:  18.280

HAZARD:  Injury to People; Window Breakage
DAMAGE:  type:  2      COEFFICI:        10   DISTANCE:   160.9 m    AREA:   0.081

HAZARD:  Wooden Doors Damaged
DAMAGE:  type:  3      COEFFICI:         7   DISTANCE:   112.6 m    AREA:   0.040

HAZARD:  Damage to Light Partitions
DAMAGE:  type:  4      COEFFICI:         5   DISTANCE:    72.4 m    AREA:   0.016

HAZARD:  Collapse of Brick Walls
DAMAGE:  type:  5      COEFFICI:         4   DISTANCE:    56.3 m    AREA:   0.010

HAZARD:  Destruction of Masonary Buildings
DAMAGE:  type:  6      COEFFICI:         2   DISTANCE:    24.1 m    AREA:   0.002

-----------------------------------------------------------------


   POOL FIRE
POOL:        thickness :   2.0 cm                      area:  183.82 m^2
PROPANE:  burning rate: 0.13 kg/m^2 s        heat release rate: 50359 kJ/kg
--------------------------------------------------------------------
HAZARD:  Blistering of Bare Skin
DAMAGE:  type:  1        thermal intensity:  6.0 kw/m^2
DISTANCE:   126 m        HAZARD AREA:      0.050 km^2

HAZARD:  Ignition of Cellulose Material
DAMAGE:  type:  2        thermal intensity: 34.0 kw/m^2
DISTANCE:     53 m       HAZARD AREA:      0.009 km^2

HAZARD:  1% Mortality
DAMAGE:  type:  3        thermal intensity: 20.0 kw/m^2
DISTANCE:     69 m       HAZARD AREA:      0.015 km^2

HAZARD:  50% Mortality
DAMAGE:  type:  4        thermal intensity: 35.0 kw/m^2
DISTANCE:     52 m       HAZARD AREA:      0.009 km^2
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