LNG Safety

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Education and experience

- BS & MS in Engineering - Univ. of Michigan
- Licensed Professional Engineer - California
- PhD in Applied Science - Univ. of California, Davis
- Worked for LLNL for 36 years, recently retired
- Helped create and manage Liquefied Gaseous Fuels Program
- Managed joint projects with
  - Oil company participants including AMOCO, Shell, Exxon, etc.
  - Gas Research Institute
  - US Coast Guard
  - Other companies and government agencies
- Expert witness at trials
- Congressional testimony on transport of hazardous materials
- California legislative testimony on safety of refineries
- Conducted vulnerability assessments at refineries after 9/11
- Member of team of independent consultants reviewing LNG import terminal proposed for Vallejo, CA
- Currently consulting on LNG safety analysis with BHP Billiton, Sandia National Laboratory and others

What is LNG?

- Liquefied natural gas (LNG) is a cryogenic liquid and is mostly liquid methane
  - Density: 26.5 lb/ft³ (424 kg/m³) lighter than water
  - Boiling point: -260 °F (-162 °C)
- Natural gas is lighter than air and rises
- Vaporized LNG/air mixtures from spills are heavier than air because they are cold
- Natural gas is flammable between 5% (LFL) and 15% (UFL) by volume in air
- Combustible mixtures will detonate in confined spaces

What can cause an LNG spill?

- Collision with another ship
- Ship grounding or striking
- Terrorist attack
- Sabotage by insider
- Operations or unloading accident
- Natural disaster – earthquake, tsunami
- Leak
- Airplane collision

What happens when LNG spills?

- Forms a pool
- Vaporizes rapidly, faster on water than on land
- Forms a vapor/air cloud that is heavier than air and moves downwind
- If vapor cloud encounters an ignition source, it will burn back to source and form a pool fire
- Vapor cloud can explode if confined
- On water, it can undergo rapid phase transition
- This explosive boiling produces a damaging shock wave but does not involve combustion
- It can cause brittle fracture of carbon steel ship structures

In 1977 DOE/DOT initiated an LNG safety research program with these objectives

- Perform research necessary to understand, predict, and mitigate the consequences of large releases of LNG and other hazardous gases
- Evaluate and develop as needed computer models capable of predicting these consequences
- Conduct field tests to obtain required data
- Work closely with industry and government to solve specific problems

Why was this research program needed?

- Prof. J. Haven's 1977 USCG report cited model LFL distances from 0.75 mi to 50 mi for a catastrophic 25,000 m^3 LNG spill
- The Oxnard/Port Hueneme 1977 Safety and Site Analysis used these model results to estimate that a catastrophic 100,000 m^3 LNG spill from an import terminal storage tank would yield LFL distances from 3 mi to 127 mi
- Something needed to be done to reduce this uncertainty

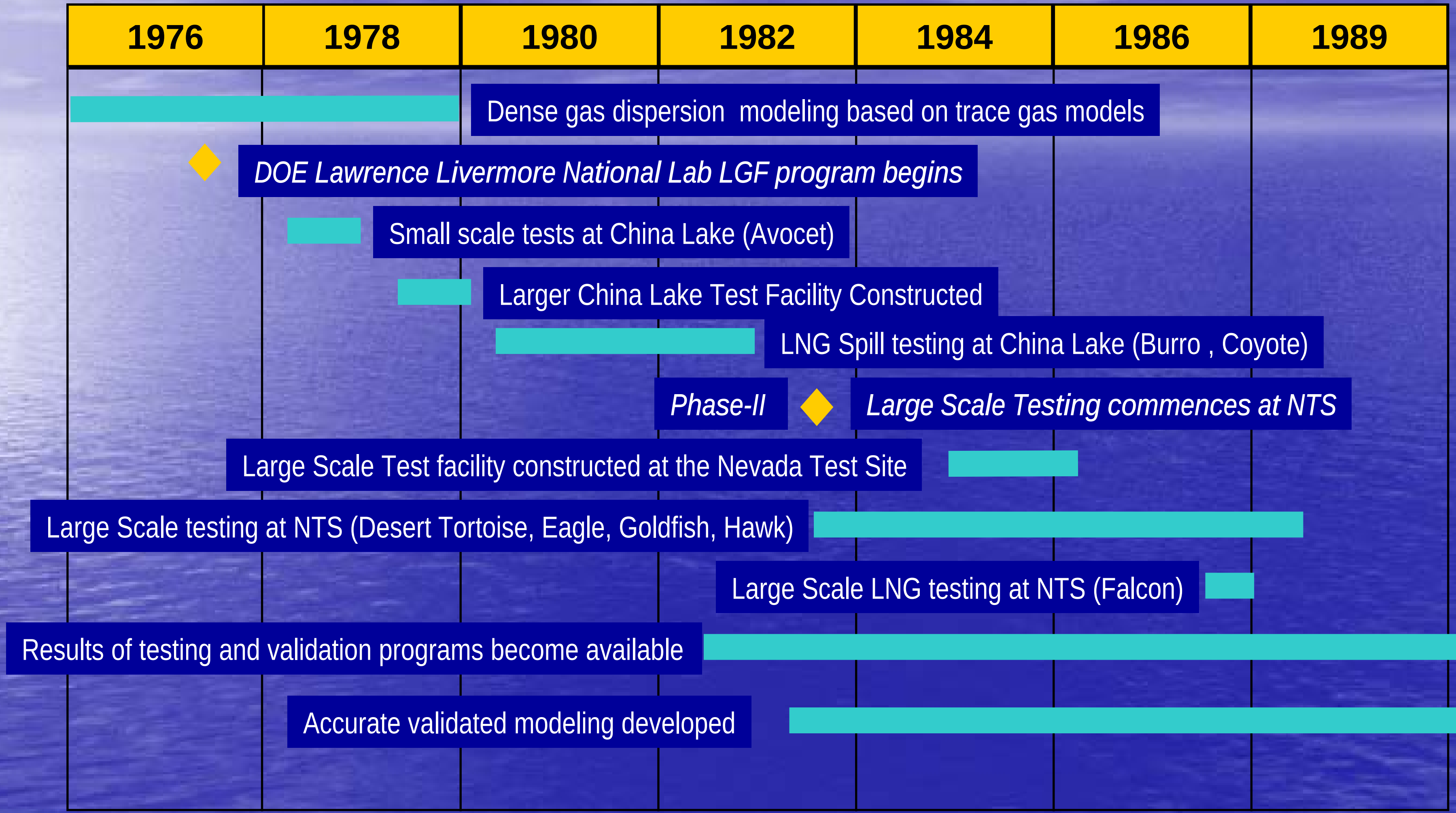
Large scale testing was the first priority

- Large scale testing commenced in the 1980’s
- Testing began simultaneously both in the US and the UK
- Models and predictions prior to that time varied greatly and accuracy was unknown
- Many scientific principles governing spills and dense gas dispersion in the atmosphere were not known or verified
- Scaling laws for large spills were not known

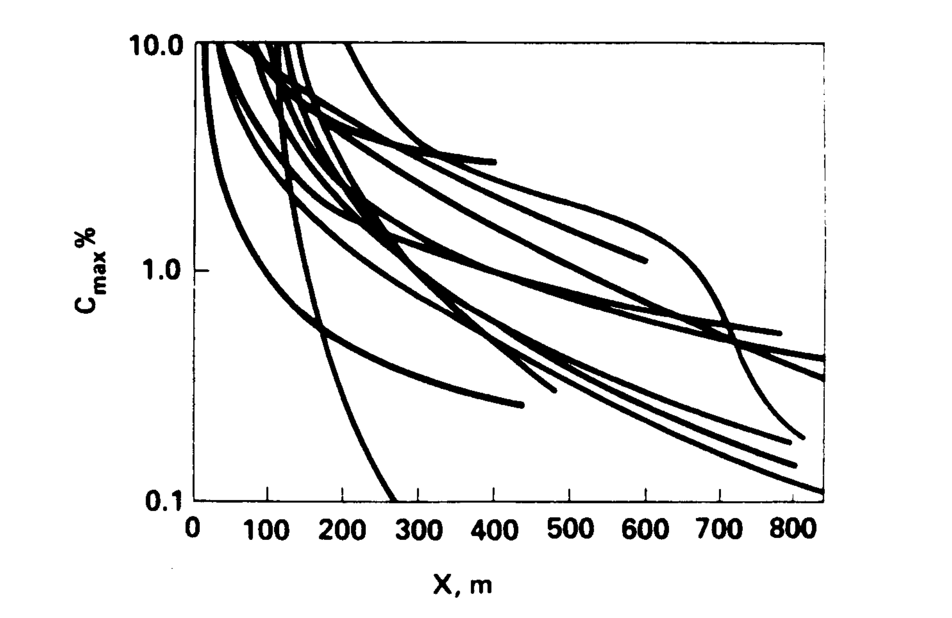
Large scale field experiments in the ’80s

name	year	material	no.	size m^3	rate m^3/min	purpose	sponsor
Maplin	1980	LNG, LPG	34	5 -31	1 - Inst	Dispersion, Combustion	Shell
Burro	1980	LNG	8	24-39	12-18	Dispersion	DOE
Coyote	1981	LNG	18	3-28	6-19	Combustion, RPT	DOE
Thorney Island	1982 1983 1984	Freon	43	2000 (gas)	Inst - 300	Dispersion, Obstacles	UK HSE
Desert Tortoise	1983	Ammonia	4	15-60	7-10	Dispersion	USCG, TFI
Eagle	1983	N_2O_4	6	1-4	0.5-2	Dispersion, Source	USAF
Goldfish	1986	HF	6	4	0.1-2	Dispersion, Mitigation	Amoco
Falcon	1987	LNG	5	20-66	9-30	Model Validation	GRI, DOT
Hawk	1988	HF	88	0.2	0.02	Mitigation	Mobil

Time line for scientific experimentation and model validation conducted through DOE LLNL Liquid Gaseous Fuels Program



By 1983 model predictions of HSE dense gas trials still varied by more than a factor of 100



- Pretrial dispersion model predictions of instantaneous release of Freon (2x air density)
- Simple, small release.
- Isothermal, flat terrain, no chemical reactions, no thermodynamic effects

- Early model predictions were not based on adequate understanding of dense gas dispersion in the atmosphere
- The scientific basis was developed through experiments and models during the 1980's

Coyote LNG vapor cloud burn experiment, China Lake, 1981

Poolfires

Regression rates for poolfires on land or water

- Burn on insulating concrete
  - Reg rate = 3.3×10^{-4} m/s
    = 0.14 kg/m^{2}s
- Vaporization only on water
  - Reg rate = 4×10^{-4} m/s
    = 0.17 kg/m^{2}s
- Burn on water (sum above)
  - Reg rate = 7.3×10^{-4} m/s
    = 0.31 kg/m^{2}s

Rapid phase transition (RPT) explosions

- RPTs involve the explosive release of energy associated with boiling
- Rapid phase change not combustion
- They occur when a cold liquid is immersed in a hot liquid and heated to its superheat limit
- At the superheat limit, the cold liquid spontaneously and explosively vaporizes
- RPT accidents occur in metal foundries and the paper pulp industry also

RPTs can be dramatic and damaging

Burro 9 RPT data

83% methane

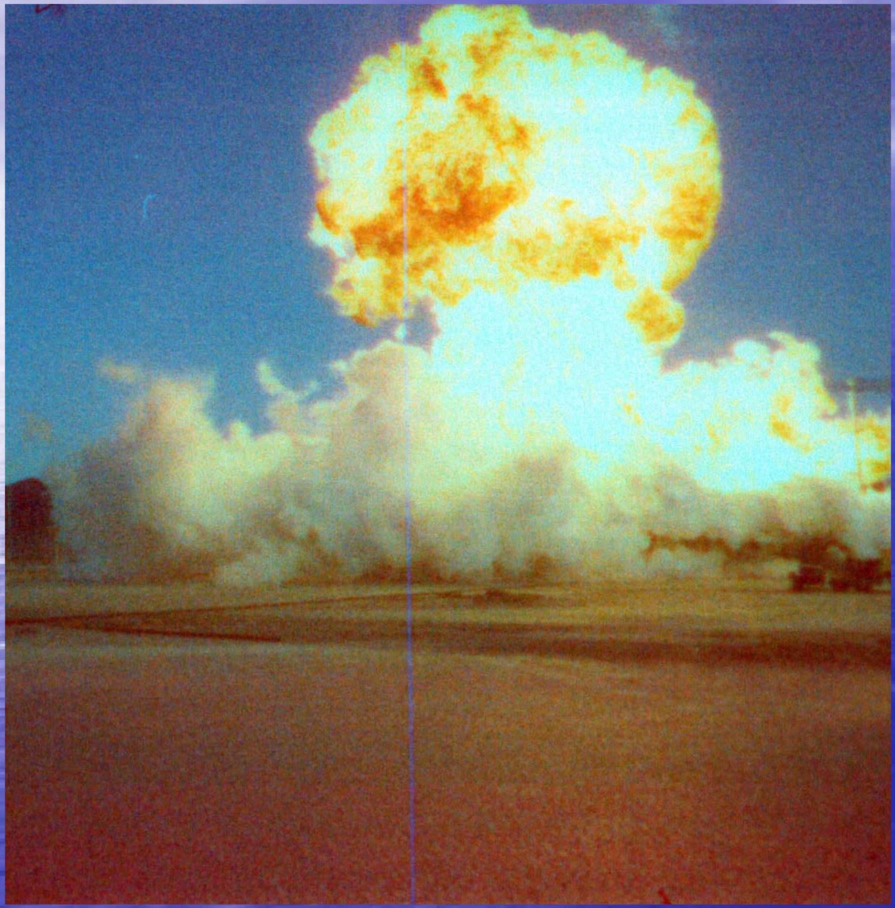
Time[a] (s)	Side-on Pressure[b] (psi)	TNT equivalent[c] (g)
6.5	0.12	36
7.1	0.15	64
9.2	0.27	295
21.4	0.57	1890
35.1	0.72	3500
43.2	0.10	23
46.0	0.12	36
54.1	0.12	36
54.9	0.13	45
66.9	0.19	120
72.7	0.12	36

[a] t = 0 is start of spill-valve opening.
[b] Measured at distance of 30 m.
[c] Equivalent free-air point-source explosion of TNT.


Spill Test Facility,
Nevada Test Site


Falcon LNG Vapor Barrier Experiments
Nevada Test Site, 1987
87 6 12

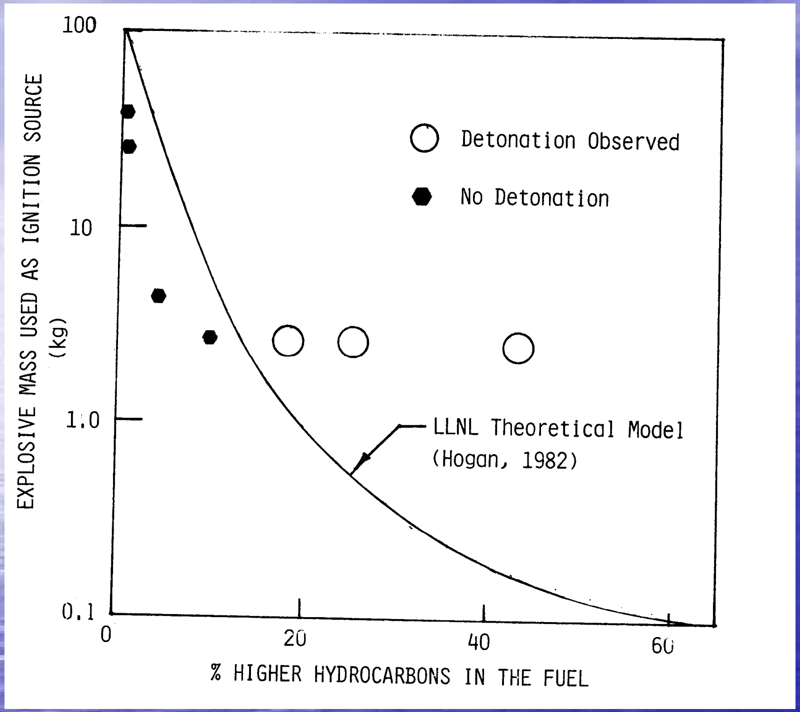
Fireballs



Fireball from accidental ignition of Falcon5 LNG test in 1987

- Fireballs form when a rich compact vapor cloud is ignited. The hot spot rises, creating a vortex that rapidly incorporates the rest of the fuel
- They burn in seconds releasing a large amount of radiant energy
- They are common for propane and butane but not LNG

Vapor cloud explosions and detonations



Detonation threshold NWC data with LLNL model for stoichometric fuel-air mixtures

- Unconfined ordinary LNG vapor clouds burn but do not detonate
- At higher hydrocarbon levels of 40% or more detonations can occur in unconfined clouds
- Detonations can always occur when vapor clouds are confined by walls, buildings, equipment racks or terrain

What did the LGF program produce?

- Extensive scientific data on LNG spill and dense gas behavior for model development and validation
- Models to accurately predict the consequences and behavior of LNG and other dense gases
- A facility for large scale experiments

The ultimate product was confidence that the modeling programs and techniques were based upon good science, observation, measurement, and understanding of actual behavior.