Research report

Atmospheric pressure above-ground storage tank loss of containment incidents involving petroleum, petroleum products, or other fuels
RESEARCH REPORT: ATMOSPHERIC PRESSURE ABOVE-GROUND STORAGE TANK LOSS OF CONTAINMENT INCIDENTS INVOLVING PETROLEUM, PETROLEUM PRODUCTS, OR OTHER FUELS

April 2017

First edition
The Energy Institute (EI) is the chartered professional membership body for the energy industry, supporting over 23,000 individuals working in or studying energy and 250 energy companies worldwide. The EI provides learning and networking opportunities to support professional development, as well as professional recognition and technical and scientific knowledge resources on energy in all its forms and applications.

The EI's purpose is to develop and disseminate knowledge, skills and good practice towards a safe, secure and sustainable energy system. In fulfilling this mission, the EI addresses the depth and breadth of the energy sector, from fuels and fuels distribution to health and safety, sustainability and the environment. It also informs policy by providing a platform for debate and scientifically-sound information on energy issues.

The EI is licensed by:
- the Engineering Council to award Chartered, Incorporated and Engineering Technician status;
- the Science Council to award Chartered Scientist status, and
- the Society for the Environment to award Chartered Environmentalist status.

It also offers its own Chartered Energy Engineer, Chartered Petroleum Engineer and Chartered Energy Manager titles.

A registered charity, the EI serves society with independence, professionalism and a wealth of expertise in all energy matters.

This publication has been produced as a result of work carried out within the Technical Team of the EI, funded by the EI's Technical Partners. The EI's Technical Work Programme provides industry with cost-effective, value-adding knowledge on key current and future issues affecting those operating in the energy sector, both in the UK and internationally.

For further information, please visit http://www.energyinst.org

The EI gratefully acknowledges the financial contributions towards the scientific and technical programme from the following companies:

Apache North Sea  Repsol Sinopce
BP Exploration Operating Co Ltd  RWE npower
BP Oil UK Ltd  Saudi Aramco
Centrica  Scottish Power
Chevron North Sea Ltd  SGS
Chevron Products Company  Shell UK Oil Products Limited
CLH  Shell U.K. Exploration and Production Ltd
ConocoPhillips Ltd  SSE
DCC Energy  Statkraft
DONG Energy  Statoil
EDF Energy  Tesoro
ENGE
ENI  Total E&P UK Limited
E. ON UK  Total UK Limited
ExxonMobil International Ltd  Tullow Oil
Innogy  Uniper
Kuwait Petroleum International Ltd  Valero
Maersk Oil North Sea UK Limited  Vattenfall
Nexen CNOOC  Vitol Energy
Phillips 66  Woodside
Qatar Petroleum  World Fuel Services

However, it should be noted that the above organisations have not all been directly involved in the development of this publication, nor do they necessarily endorse its content.

Copyright © 2017 by the Energy Institute, London.
The Energy Institute is a professional membership body incorporated by Royal Charter 2003.
Registered charity number 1097899, England
All rights reserved

No part of this book may be reproduced by any means, or transmitted or translated into a machine language without the written permission of the publisher.

ISBN 978 0 85293 818 8

Published by the Energy Institute

The information contained in this publication is provided for general information purposes only. Whilst the Energy Institute and the contributors have applied reasonable care in developing this publication, no representations or warranties, express or implied, are made by the Energy Institute or any of the contributors concerning the applicability, suitability, accuracy or completeness of the information contained herein and the Energy Institute and the contributors accept no responsibility whatsoever for the use of this information. Neither the Energy Institute nor any of the contributors shall be liable in any way for any liability, loss, cost or damage incurred as a result of the receipt or use of the information contained herein.

Hard copy and electronic access to EI and IP publications is available via our website, https://publishing.energyinst.org.
Documents can be purchased online as downloadable pdfs or on an annual subscription for single users and companies.
For more information, contact the EI Publications Team.

e. pubs@energyinst.org
# Contents

<table>
<thead>
<tr>
<th>Acknowledgements</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive summary</td>
<td>7</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>10</td>
</tr>
<tr>
<td>2 Scope</td>
<td>11</td>
</tr>
<tr>
<td>3 Definitions</td>
<td>13</td>
</tr>
<tr>
<td>3.1 General</td>
<td>13</td>
</tr>
<tr>
<td>3.2 LOC – CTF and major LOC</td>
<td>13</td>
</tr>
<tr>
<td>3.2.1 CTF</td>
<td>13</td>
</tr>
<tr>
<td>3.2.2 Major LOC</td>
<td>14</td>
</tr>
<tr>
<td>3.2.3 Summary of LOC criteria</td>
<td>14</td>
</tr>
<tr>
<td>3.3 Breach of secondary containment</td>
<td>14</td>
</tr>
<tr>
<td>3.4 Overtop of secondary containment</td>
<td>15</td>
</tr>
<tr>
<td>3.5 Failure mode</td>
<td>15</td>
</tr>
<tr>
<td>3.6 Primary failure mode</td>
<td>15</td>
</tr>
<tr>
<td>3.7 Secondary failure mode</td>
<td>16</td>
</tr>
<tr>
<td>3.8 Failure cause</td>
<td>16</td>
</tr>
<tr>
<td>3.9 Primary containment</td>
<td>16</td>
</tr>
<tr>
<td>3.10 Secondary containment</td>
<td>17</td>
</tr>
<tr>
<td>3.11 Tertiary containment</td>
<td>17</td>
</tr>
<tr>
<td>4 Methodology for data source review, interrogation and analysis</td>
<td>18</td>
</tr>
<tr>
<td>4.1 Introduction</td>
<td>18</td>
</tr>
<tr>
<td>4.2 Data sources</td>
<td>18</td>
</tr>
<tr>
<td>4.2.1 LASTFIRE database</td>
<td>18</td>
</tr>
<tr>
<td>4.2.2 Thyer et al (2009)</td>
<td>19</td>
</tr>
<tr>
<td>4.2.3 Other data sources</td>
<td>19</td>
</tr>
<tr>
<td>4.3 Data analysis</td>
<td>21</td>
</tr>
<tr>
<td>5 Data source review and interrogation</td>
<td>22</td>
</tr>
<tr>
<td>5.1 Introduction</td>
<td>22</td>
</tr>
<tr>
<td>5.2 AST LOC incident data</td>
<td>22</td>
</tr>
<tr>
<td>5.3 Qualitative accounts of some AST LOC incidents</td>
<td>36</td>
</tr>
<tr>
<td>5.4 LASTFIRE database interrogation</td>
<td>39</td>
</tr>
</tbody>
</table>
6 LASTFIRE database AST LOC incident analysis ........................................ 42
   6.1 Allocation of LASTFIRE database AST LOC incidents to primary and secondary 
       failure modes, and failure causes and failure cause categories ............... 42
   6.2 Correlation of LASTFIRE database AST LOC incidents with AST type .......... 44

7 AST LOC incident analysis ........................................................................... 45
   7.1 Allocation of AST LOC incidents to primary and secondary failure modes ........ 45
   7.2 Distribution of AST LOC incident volumetric losses ................................ 45
   7.3 Correlation of AST LOC incidents with inventory ..................................... 46
   7.4 Correlation of AST LOC incidents with AST type ..................................... 47
   7.5 Common AST LOC failure causes ............................................................. 47
       7.5.1 Corrosion and design/structural failure causes ............................... 48
       7.5.2 Natural phenomena or other external factors ................................. 48

8 Quantitative analysis – incident frequencies .............................................. 50
   8.1 General .................................................................................................... 50
       8.1.1 Reference CTF incident frequency data ......................................... 50
   8.2 LASTFIRE database population data ....................................................... 51
   8.3 AST LOC incident frequency – Release into secondary containment .......... 52
   8.4 AST LOC incident frequency – Major LOC and CTF .............................. 52
   8.5 Sensitivity analysis – Worldwide vs. UK CTF incident frequency .............. 54
   8.6 Effect of maintenance on likelihood of CTF ......................................... 54
   8.7 Primary vs. secondary failure modes ....................................................... 55
   8.8 Breach of secondary containment frequency ......................................... 56
   8.9 Overtop of secondary containment frequency ......................................... 56

9 Qualitative analysis of AST LOC primary failure modes and primary and 
   secondary failure causes ............................................................................. 63
   9.1 AST LOC primary failure modes ............................................................. 63
   9.2 Main AST LOC failure cause categories ................................................. 67

10 Conclusions ................................................................................................. 69
    10.1 Introduction ............................................................................................ 69
    10.2 Incident frequencies .............................................................................. 69
    10.3 Dominant AST LOC failure modes, failure causes and other factors ........ 70

Annex A References ......................................................................................... 72
Annex B Glossary of acronyms and abbreviations ........................................... 74
LIST OF TABLES, FIGURES AND PHOTOGRAPHS

List of tables

Table 1: Summary of key LOC criteria ......................................................... 14
Table 2: AST LOC incidents involving single tanks ...................................... 23
Table 3: AST LOC incidents involving multiple tanks ................................. 33
Table 4: LASTFIRE database AST LOC incident failure causes for primary and secondary failure modes ......................................................... 40
Table 5: LASTFIRE database AST LOC incidents ...................................... 41
Table 6: HSE AST LOC failure data for COMAH sites ............................... 51
Table 7: AST operating experience by tank type ....................................... 51
Table 8: Statistical confidence intervals for major LOC and CTF incident frequencies ......................................................... 53

List of figures

Figure 1: AST LOC incident failure causes for primary failure modes .......... 43
Figure 2: AST LOC incident failure cause categories for primary failure modes .......... 44
Figure 3: Correlation of incidence of AST LOC with tank type (LASTFIRE database data only) ........ 44
Figure 4: Allocation of AST LOC incidents to primary and secondary failure modes ......................................................... 45
Figure 5: Distribution of AST LOC incident volumetric losses ................. 46
Figure 6: Correlation of AST LOC incidents with inventory ................. 47
Figure 7: Proportions of AST LOC incidents involving overtop of secondary containment ........ 57
Figure 8: Conceptual model of a bulk fuels storage facility showing source, pathways and environmental receptors ......................................................... 58
Figure 9: Event tree for CTF and overtop of secondary and tertiary containment with environmental impact consequences – Example template .......... 59
Figure 10: Event tree for CTF and overtop of secondary and tertiary containment with environmental impact consequences using base CTF incident frequency for worldwide CTFs ......................................................... 61
Figure 11: Event tree for CTF and overtop of secondary and tertiary containment with environmental impact consequences using ‘modified’ CTF incident frequency for UK facilities ......................................................... 62
Figure 12: Rocketing shell ....................................................................... 63
Figure 13: Shell/bottom failure ................................................................. 64
Figure 14: Bottom failure ....................................................................... 65
Figure 15: Rapid shell failure/unzipping ................................................... 66
Figure 16: Medium shell failure ................................................................. 66

List of photographs

Photo 1: Shell/bottom failure ................................................................. 64
Photo 2: Bottom failure ...................................................................... 65
Photo 3: Rapid shell failure/unzipping ................................................... 66
ACKNOWLEDGEMENTS

The research project described in this Research Report was contracted to Falck Fire Consulting Limited: Paul Watkins (Falck Fire Consulting Limited) was the main researcher, and Dr Niall Ramsden (ENERG Consultants) supported the research project. The research project was directed latterly by The Energy Institute’s (EI’s) Containment Systems Working Group (CSWG), which is a Process Safety Committee working group, and whose members comprised:

Dr Colin Cartwright
Dave Wright
David Athersmith
Dr Mark Scanlon
Kerry Sinclair (Secretary)
David Tarttelin
Mark Palmer
Paul Watkins
Tony Brown
Tammy Brantley
Alistair Kean
Liz Copland
Steve Flynn
Dr Irene Anders
Brian Blagden
Felix Nelson
Barrie Salmon
John Wormald
Jamie Walker
Ian Goldsworthy (Chair)

Atkins
BP
Consultant
Energy Institute
Energy Institute
Environment Agency
Esso Petroleum Company Ltd
Falck Fire Consulting Limited
Federation of Petroleum Suppliers
GB Oils
IKM Consulting Ltd
IKM Consulting Ltd
Rawell Environmental Ltd
Scottish Environment Protection Agency
Scottish Environment Protection Agency
Shell
Tank Storage Association
Total Lindsey Oil Refinery
UK Petroleum Industry Association
Valero Ltd

The EI acknowledges their direction and technical contributions to the research project. The listing refers to representatives’ last affiliation whilst participating.

The EI acknowledges the following who provided significant comments during the technical reviews:

Neil Macnaughton
Steve Clarke
Ken Palmer
Dr Mark Scanlon
David Tarttelin
Dr Mike Nicholas
Dr Aubrey Thyer
Peter Harper
Deborah Keeley
Jeremy Fox
Felix Nelson
Carol Pickard
BP
BP
Consultant
Energy Institute
Environment Agency
Environment Agency
Health and Safety Executive
Health and Safety Executive
Health and Safety Laboratory
IKM Consulting Ltd
Shell

The EI also acknowledges the LASTFIRE project members for providing access to the LASTFIRE database, which is the key data source interrogated in the research project.

Dr Mark Scanlon coordinated the research and technically edited this Research Report.
1 INTRODUCTION

Several major accidents resulting in atmospheric pressure AST LOC have occurred at bulk petroleum, petroleum products, or other fuels storage facilities worldwide. Often, incidents have occurred following a sequence of operational deviations, and some have resulted in catastrophic destruction of ASTs and LOCs, loss of the liquid inventory, including petroleum, petroleum products, or other fuels, or other hazardous liquids. Major accidents have detrimentally affected operating companies’ reputation and market value, as well as resulting in fatalities and severe environmental impact.

Operators of petroleum, petroleum products, or other fuels bulk storage facilities, such as petroleum refineries, distribution terminals, crude oil import/export terminals and crude oil and gas separation plants, should identify and risk assess credible worst case scenarios in their safety reports required by NA COMAH regulations as part of their demonstration that all measures necessary (AMN) are being taken for prevention and mitigation of major accident hazards (MAH). Operating companies should use those risk assessments to identify risk reduction measures to control their operations.

In the UK and elsewhere, CAs and/or AHJs have suggested that CTF from ASTs, e.g. arising from a LOC such as sudden emptying of an AST via tank or pipework fracture, could cause secondary containment bunds to breach or overtop. Indeed, such CTFs have occurred in industry worldwide, and these incidents have the potential to result in significant environmental impact, asset loss and threats to life safety.

Thus there is a need to identify the likelihood of AST LOC, especially CTFs, and the likelihood that an incident will breach or overtop secondary containment, as well as the factors that influence their occurrence. These data may assist operating companies in determining whether there is an evidence-based need to better protect ASTs and to understand the potential demands on secondary and tertiary containment systems.

Moreover, it would be beneficial to understand through sensitivity analysis whether the determined frequencies of CTFs are likely to apply to ASTs in UK petroleum, petroleum products, or other fuels bulk storage facilities given the design methods, standards, metallurgies and ambient conditions typically in use.

This Research Report aims, therefore, to provide an evidence base to inform operators of petroleum, petroleum products, or other fuels bulk storage facilities about the risk of AST LOC, especially CTF.

The aims of the research project documented in this Research Report were to:

1. Critically review, interrogate and analyse existing data sources (e.g. literature and databases) on reported cases of AST LOCs, including those that are considered CTFs. Note that new data collection by operating company surveys was not in the scope of this research project.

2. Assess as far as possible from the available evidence, what proportion of reported AST LOCs are CTFs, and whether there is breach or overtop of secondary containment.

3. Identify as far as possible from the available evidence, what failure modes and failure causes have led to the AST LOCs, especially those primary failure modes relating directly to the AST and its appurtenances. In addition, assess as far as possible from the available evidence, the extent to which these failure modes and failure causes are likely to apply to UK facilities given the design methods, standards, metallurgies and ambient conditions in use in the UK rather than worldwide.
2 SCOPE

2.1 IN-SCOPE TANKS – TYPE

This Research Report applies to ASTs with the following characteristics and/or construction:
- operating at atmospheric pressure;
- vertical construction, and
- diameter $\geq 10$ m.

These ASTs would typically comprise the following types:
- external floating roof tanks (EFRTs) (sometimes referred to as open-top floating roof tanks (OTFRTs));
- fixed roof tanks (FIXRTs) (often called ‘cone roof’ tanks);
- internal floating roof tanks (IFRTs) (including those with internal floating roofs of lightweight ‘pan deck’ construction, and those with internal roofs of a type normally associated with EFRTs), and
- those with geodesic domes (often EFRTs converted by the addition of domed roofs), but here are considered IFRTs.

This Research Report does not apply to the following AST types:
- horizontal construction (these tanks are excluded due to having insufficient liquid head to generate a significant LOC);
- pressurised storage tanks (for example, pressurised liquefied petroleum gas (PLPG) tanks), and
- refrigerated or cryogenic storage tanks (such as refrigerated liquefied petroleum gas (RLPG) and liquefied natural gas (LNG) storage tanks).

These tanks are characterised by special storage conditions which may or may not result in different failure modes and causes to ASTs; this together with the limited data available on these types of tank means they are not further considered in this Research Report.

2.2 LIQUID INVENTORY

This Research Report focuses primarily on petroleum, petroleum products, or other fuels stored in ASTs; most incident data reviewed involved these liquids due to the prevalence of such data. However, incident data involving other liquids stored in in-scope ASTs also were reviewed but with caution, since causative or mitigating factors might be the same or differ from those pertinent to petroleum, petroleum products, or other fuels. Consequently, the findings outlined in this Research Report apply mainly to petroleum, petroleum products, or other fuels; where known, AST failure modes and causes have been identified for other liquids.
2.3 INCIDENT CONSEQUENCES

This Research Report does not necessarily consider whether an AST LOC incident also resulted in a fire or explosion consequence due to ignition of the released liquid. Whilst many data sources do identify whether or not there was ignition (e.g. resulting in pool fires), the main objective of this study was to identify instances, failure modes and failure causes of AST LOCs that were CTFs, and whether they breached or overtopped secondary containment.

This Research Report recognises cases where the presence of an external fire was a factor in initiating an AST LOC.