Design modelling to minimise the risk for offshore platforms

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Design Modelling to Minimise the Risk for Offshore Platforms.

by

Kathryn Jane Foster

A DOCTORAL THESIS.

Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

September, 1999

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Abstract.

Safety cases must be produced by offshore operators to assess the risks posed to the personnel by potential accidents. On an offshore platform two of the major hazards are fires and explosions resulting from an accidental hydrocarbon release. The overpressures generated during an explosion can threaten the integrity of the platform structure. It is therefore important to be able to estimate the overpressures generated, should an explosion occur, and to predict the frequency of such an event.

A methodology has been developed to predict the frequency of explosions of different magnitudes occurring in a module on an offshore platform. This methodology combines established risk assessment techniques, such as event tree analysis and fault tree analysis, with fluid flow modelling. Assumptions have been made in the methodology to simplify the calculation procedure. These assumptions relate to the conditions under which the leak occurs, the build up of gas in air concentration and the probability calculations.

Frequency predictions are required to be as accurate as possible to enable the acceptability of the risk to be determined and reduced to a level which is as low as reasonably practicable. Hence each of the assumptions within the methodology has been addressed, to determine a more complete prediction tool.

Once an accurate frequency for the explosion occurring has been determined, the risk to personnel must be minimised to an acceptable yet practical level. On existing designs it is impractical to alter the layout of the platform. However the nature of the safety systems may be changed. These safety features include isolation, blowdown, mitigation and detection systems. An optimisation study presents three schemes to identify the optimum configuration of the safety systems, in terms of the overpressures generated, as a means of reducing the risk to the platform.
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# Contents

1 Introduction.  

2 Risk assessment and offshore safety regulations.  
   2.1 Introduction. ........................................ 5  
   2.2 Tolerability of risk. ................................ 6  
   2.3 Risk assessment in relation to offshore platforms. ........................................ 7  
      2.3.1 The Piper Alpha disaster. ............................ 7  
      2.3.2 Offshore Safety Division. ............................ 8  
   2.4 The future of risk assessment in the offshore process industries. .................. 10  
   2.5 Risk assessment methods. .................. 11  
      2.5.1 Qualitative methods. ............................. 12  
      2.5.2 Quantitative methods. ............................ 13  
   2.6 Risk assessment techniques used in the offshore process industries. ............. 15  
      2.6.1 Event tree analysis. ............................. 15  
      2.6.2 Fault tree analysis. ............................. 16  

3 Explosion modelling techniques.  
   3.1 Introduction. ........................................ 21  
   3.2 Consequences arising from an explosion. ........................................ 21  
      3.2.1 Overpressures. .................................... 22  
   3.3 Influencing factors. ..................................... 23  
      3.3.1 Flame speed. ..................................... 23  
      3.3.2 Geometry. ........................................ 23  
      3.3.3 Ignition sources and location. ...................... 24  
      3.3.4 Explosion relief. .................................. 25  
   3.4 Modelling and validation. ................................ 27
3.4.1 Experiments and scaling factors ........................................ 28
3.4.2 Types of models .......................................................... 30
3.4.3 Empirical based models .................................................. 30
3.4.4 Physical models .......................................................... 32
3.4.5 CFD based models ......................................................... 33
3.5 Discussion ........................................................................ 37

4 Dispersion modelling techniques. 38
4.1 Introduction .................................................................... 38
4.2 Influencing factors ......................................................... 38
  4.2.1 Source data .............................................................. 40
  4.2.2 Geometry and meteorology ......................................... 40
4.3 Cloud build-up ............................................................... 42
  4.3.1 Entrainment .............................................................. 42
4.4 Dispersion models ........................................................... 42
  4.4.1 Basic models ............................................................ 43
  4.4.2 Passive dispersion .................................................... 44
  4.4.3 Plume modelling ....................................................... 46
  4.4.4 Physical modelling .................................................... 47
  4.4.5 CFD modelling ........................................................ 49
4.5 Discussion ........................................................................ 50

5 Optimisation techniques. 52
5.1 Introduction .................................................................... 52
5.2 The optimisation process ................................................. 52
5.3 Mathematical programming .............................................. 54
  5.3.1 Simple search techniques ............................................ 55
  5.3.2 Linear programming .................................................. 56
  5.3.3 Non linear programming and multi-variable searches ...... 57
  5.3.4 Integer programming ................................................ 58
  5.3.5 Combinatorial programming ....................................... 60
  5.3.6 Heuristic programming ............................................. 61
5.4 Evolutionary procedures ................................................... 62
  5.4.1 Sequential SIMPLEX methods .................................... 62
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4.2 Genetic algorithms.</td>
<td>63</td>
</tr>
<tr>
<td>5.4.3 Simulated annealing.</td>
<td>64</td>
</tr>
<tr>
<td>5.5 Discussion.</td>
<td>65</td>
</tr>
<tr>
<td>6 A methodology for calculating the frequency of explosions.</td>
<td>67</td>
</tr>
<tr>
<td>6.1 Introduction.</td>
<td>67</td>
</tr>
<tr>
<td>6.2 The platform.</td>
<td>67</td>
</tr>
<tr>
<td>6.2.1 The safety systems.</td>
<td>70</td>
</tr>
<tr>
<td>6.2.2 The modules.</td>
<td>71</td>
</tr>
<tr>
<td>6.3 Input data.</td>
<td>74</td>
</tr>
<tr>
<td>6.4 Calculation methodology.</td>
<td>77</td>
</tr>
<tr>
<td>6.5 Operation of code.</td>
<td>80</td>
</tr>
<tr>
<td>6.6 Criticism of SAROS.</td>
<td>82</td>
</tr>
<tr>
<td>6.7 Discussion.</td>
<td>85</td>
</tr>
<tr>
<td>7 Modelling the release.</td>
<td>86</td>
</tr>
<tr>
<td>7.1 Introduction.</td>
<td>86</td>
</tr>
<tr>
<td>7.2 Calculation procedures.</td>
<td>86</td>
</tr>
<tr>
<td>7.3 Changing temperature - no heat input.</td>
<td>89</td>
</tr>
<tr>
<td>7.4 Constant temperature - total heat input.</td>
<td>91</td>
</tr>
<tr>
<td>7.4.1 Gas only leak.</td>
<td>92</td>
</tr>
<tr>
<td>7.4.2 Gas and condensate leak.</td>
<td>93</td>
</tr>
<tr>
<td>7.5 The leak flow inventory.</td>
<td>95</td>
</tr>
<tr>
<td>7.6 Leak inventory comparison with the changing temperature model.</td>
<td>96</td>
</tr>
<tr>
<td>7.6.1 The separation module.</td>
<td>96</td>
</tr>
<tr>
<td>7.6.2 The compression module.</td>
<td>104</td>
</tr>
<tr>
<td>7.6.3 The wellhead module.</td>
<td>112</td>
</tr>
<tr>
<td>7.6.4 Conclusion of the leak inventory comparison with the changing temperature models.</td>
<td>118</td>
</tr>
<tr>
<td>7.7 Leak inventory comparison with the constant temperature model.</td>
<td>118</td>
</tr>
<tr>
<td>7.7.1 The separation module.</td>
<td>119</td>
</tr>
<tr>
<td>7.7.2 The compression module.</td>
<td>125</td>
</tr>
<tr>
<td>7.7.3 The wellhead module.</td>
<td>133</td>
</tr>
</tbody>
</table>
10.4 The activation time for the deluge. ........................................... 200
10.5 The leak hole size distribution. ........................................... 209
10.6 The frequency of occurrence of the leak holes. ....................... 215
10.7 The distribution of ventilation rates. ..................................... 219
10.8 The failure frequency of the deluge once operational. ............ 226
10.9 Discussion. ........................................................................... 231

11 Approaches to optimise the configuration of the safety systems. 233

11.1 Introduction. ......................................................................... 233
11.2 The objective function. ....................................................... 233
11.3 The components and the design vector. ................................. 234
11.4 Applicable optimisation techniques. ...................................... 238
11.5 Limits and bounds. ............................................................... 239
11.6 The stepping process. .......................................................... 240
   11.6.1 A two variable example. .................................................. 241
   11.6.2 The stepping algorithm. .................................................. 243
   11.6.3 Results from the stepping process with a mid case initiator. ... 243
   11.6.4 The results from the stepping process with a worst case initiator. 248
   11.6.5 An evaluation of the stepping process. ............................... 253

11.7 The linearisation process. ..................................................... 256
   11.7.1 The linearisation algorithm. ............................................. 257
   11.7.2 Results from the linearisation process with a mid case initiator. ... 257
   11.7.3 The results of the linearisation process from a worst case initiator. 263
   11.7.4 An evaluation of the linearisation process. ......................... 266

11.8 A heuristic approach. ........................................................... 267
   11.8.1 The design vector. .......................................................... 268
   11.8.2 The strategy. ................................................................. 270
   11.8.3 The heuristic method in practice. ..................................... 272
   11.8.4 An evaluation of the heuristic method. .............................. 285

11.9 Discussion. ........................................................................... 286

12 Summary and conclusions. ..................................................... 288

12.1 Conclusions. ................................................................. 290
12.2 Extensions to this work. ....................................................... 291
Appendix

A  Schematic diagrams of the sections on the platform.
List of Figures

1.1 A risk analysis methodology. ........................................... 2
2.1 Tolerability of risk: ALARP. ........................................... 6
2.2 An example fault tree, showing the types of gates and construction. .... 18
6.1 An example of the layout of an offshore platform. ...................... 68
6.2 The typical contents of a module. ........................................ 69
6.4 An example connection of sections relating to the event tree. .......... 74
6.3 An example event tree. ..................................................... 75
6.5 Possible profiles for the gas concentration with time within the module. . 78
6.6 Variation of overpressure with concentration. ........................... 79
6.7 The flow chart showing the operation of the code. ....................... 81
6.8 The flow chart showing the suite of subroutines employed in EXPLODE as an alternative to BANG. ........................................... 84
7.1 Comparison of the overpressure exceedence for the separation module using models 1, 2 and 3. ........................................... 103
7.2 Comparison of the overpressure exceedence for the compression module with models 1, 2 and 3. ........................................... 111
7.3 Comparison of the overpressure exceedence for the wellhead module for models 1, 2 and 3. ........................................... 117
7.4 Comparison of the overpressure exceedence for the separation module with models 4 and 5. ........................................... 124
7.5 Comparison of the overpressure exceedence for the compression module with models 4 and 5. ........................................... 132
7.6 Comparison of the overpressure exceedence for the wellhead module with models 4 and 5. ........................................... 136
List of Figures

7.7 Comparison of the overpressure exceedence for the separation module using the two temperature state models. .......................... 142
7.8 Comparison of the overpressure exceedence for the compression module with models 2 and 4. ............................................ 149
7.9 Comparison of the overpressure exceedence for the wellhead module with models 2 and 4. .................................................. 154

8.1 Time-concentration history, concentration below explosive range. ...... 157
8.2 Time-concentration history, concentration reaching explosive range. ...... 158
8.3 Time-concentration history, concentration exceeding explosive range. .... 158
8.4 Time-concentration history, concentration rising and falling through a specific concentration band when the concentration exceeds the explosive range. 160
8.5 Time-concentration history, concentration rising and falling through a specific concentration band when the concentration is within the explosive range. 161

9.1 A conventional node in 3 dimensions. .................................. 179
9.2 An example of the expected growth and decay of the volume within a concentration band, using the lognormal function. ................. 184
9.3 Representation of the volume variation for each concentration band with time. 185

10.1 A comparison of the exceedence frequency of the overpressures produced, due to the ignition frequency variation. ....................... 193
10.2 A comparison of the exceedence frequency of the overpressures produced, due to variation of the unavailability of deluge. .................... 199
10.3 The concentration within the module with time, exceeding the flammable region. 204
10.4 The effects of mitigating the gas cloud. .................................. 205
10.5 The concentration within the module with time, remaining within the flammable region. ....................................................... 206
10.6 A comparison of the exceedence frequency of the overpressures produced, due to the variation of the deluge activation time. ................. 208
10.7 The possible variation of the concentration profile occurring with the variation of the hole sizes. ............................................. 212
10.8 A comparison of the overpressure distributions for each module, with each model when the hole sizes are varied. .............................. 214
10.9 A comparison of the exceedence frequency of the overpressures produced, due to the variation of the frequency of occurrence of the leak holes. .......... 218
10.10 A comparison of the exceedence frequency of the overpressures produced, due to the variation of the ventilation rates. .......................... 225
10.11 A comparison of the exceedence frequency of the overpressures produced, due to the variation of the failure rate of the deluge system. .......... 230

11.1 Geometric interpretation of the linear optimisation procedure .......... 242

A.1 Section 1 - the atmospheric separator. ....................................... 300
A.2 Section 3 - the inlet separator. ............................................... 301
A.3 Section 4 - the low pressure scrubbers and compressors. ................. 302
A.4 Section 5 - the medium pressure scrubbers and compressors (stage 1). ... 303
A.5 Section 6 - the medium pressure scrubbers and compressors (stage 2). ... 304
A.6 Section 8 - the injection compressors. ........................................ 305
A.7 Section 9 - the wellhead and production header lines. ...................... 306
A.8 Section 10 - the gas injection line. ........................................... 307
A.9 Section 11 - the gas lift line. ................................................... 308
List of Tables

6.1 The inventory data for the sections within the compression module. 72
6.2 The isolation valves and the sections they connect. 73
6.3 The blowdown valves and their locations. 74

7.1 Explosion frequency contributions from leaks on section 1 (per year) - comparison between models 1, 2 and 3. 97
7.2 Explosion frequency contributions from leaks on section 3 (per year) - comparison between models 1, 2 and 3. 98
7.3 The total explosion frequencies for the separation module (per year) - comparison between models 1, 2 and 3. 98
7.4 The importance of the isolation valves in the separation module (percentage) - comparison between models 1, 2 and 3. 99
7.5 The importance of the blowdown valves in the separation module (percentage) - comparison between models 1, 2 and 3. 100
7.6 The importance of the sections in the separation module when the isolation and blowdown works as designed (percentage) - comparison between models 1, 2 and 3. 101
7.7 Total importance measures for the categories of explosions in the separation module (percentage) - comparison of models 1, 2 and 3. 101
7.8 Explosion frequency contributions from leaks on section 4 (per year) - comparison between models 1, 2 and 3. 104
7.9 Explosion frequency contributions from leaks on section 5 (per year) - comparison between models 1, 2 and 3. 105
7.10 Explosion frequency contribution from leaks on section 6 (per year) - comparison between models 1, 2 and 3. 105
7.11 Explosion frequency contribution from leaks on section 8 (per year) - comparison between models 1, 2 and 3. 106
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.12</td>
<td>The total explosion frequencies for the compression module (per year) - comparison between models 1, 2 and 3.</td>
<td>107</td>
</tr>
<tr>
<td>7.13</td>
<td>The importance of the sections in the compression module when the isolation and blowdown works as designed (percentage)- comparison between models 1, 2 and 3.</td>
<td>107</td>
</tr>
<tr>
<td>7.14</td>
<td>The importance of the isolation valves in the compression module (percentage) - comparison between models 1, 2 and 3.</td>
<td>108</td>
</tr>
<tr>
<td>7.15</td>
<td>The importance of the blowdown valves in the compression module (percentage) - comparison between models 1, 2 and 3.</td>
<td>109</td>
</tr>
<tr>
<td>7.16</td>
<td>Total importance measures for the categories of explosions in the compression module (percentage) - comparison of models 1, 2 and 3.</td>
<td>110</td>
</tr>
<tr>
<td>7.17</td>
<td>Explosion frequency contribution from leaks in section 9 (per year) - comparison between models 1, 2 and 3.</td>
<td>112</td>
</tr>
<tr>
<td>7.18</td>
<td>Explosion frequency contribution from leaks in section 10 (per year) - comparison of models 1, 2 and 3.</td>
<td>113</td>
</tr>
<tr>
<td>7.19</td>
<td>Explosion frequency contribution from leaks in section 11 (per year) - comparison between models 1, 2 and 3.</td>
<td>113</td>
</tr>
<tr>
<td>7.20</td>
<td>The total explosion frequencies for the wellhead module (per year) - comparison between models 1, 2 and 3.</td>
<td>113</td>
</tr>
<tr>
<td>7.21</td>
<td>The importance of the isolation valves in the wellhead module (percentage) - comparison between models 1, 2 and 3.</td>
<td>114</td>
</tr>
<tr>
<td>7.22</td>
<td>The importance of the sections in the wellhead module when the isolation and blowdown works as designed (percentage)- comparison between models 1, 2 and 3.</td>
<td>115</td>
</tr>
<tr>
<td>7.23</td>
<td>The importance of the blowdown valves in the wellhead module (percentage) - comparison between models 1, 2 and 3.</td>
<td>115</td>
</tr>
<tr>
<td>7.24</td>
<td>Total importance measures for the categories of explosions in the wellhead module (percentage) - comparison of models 1, 2 and 3.</td>
<td>116</td>
</tr>
<tr>
<td>7.25</td>
<td>Explosion frequency contributions from leaks in section 1 (per year) - comparison between models 4 and 5.</td>
<td>119</td>
</tr>
<tr>
<td>7.26</td>
<td>Explosion frequency contributions from leaks in section 3 (per year) - comparison between models 4 and 5.</td>
<td>120</td>
</tr>
<tr>
<td>Table No.</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>----------</td>
<td>-------------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>7.27</td>
<td>The total explosion frequencies for the separation module (per year) - comparison between models 4 and 5</td>
<td>120</td>
</tr>
<tr>
<td>7.28</td>
<td>Total importance measures for the category of explosions in the separation module (percentages) - comparison between models 4 and 5</td>
<td>121</td>
</tr>
<tr>
<td>7.29</td>
<td>The importance of the sections in the separation module when the isolation and blowdown works as designed (percentage) - comparison between models 4 and 5</td>
<td>121</td>
</tr>
<tr>
<td>7.30</td>
<td>The importance of the isolation valves in the separation module (percentage) - comparison between models 4 and 5</td>
<td>122</td>
</tr>
<tr>
<td>7.31</td>
<td>The importance of the blowdown valves in the separation module (percentage) - comparison between models 4 and 5</td>
<td>123</td>
</tr>
<tr>
<td>7.32</td>
<td>Explosion frequency contributions from leaks in section 4 (per year) - comparison between models 4 and 5</td>
<td>125</td>
</tr>
<tr>
<td>7.33</td>
<td>Explosion frequency contributions from leaks on section 5 (per year) - comparison between models 4 and 5</td>
<td>126</td>
</tr>
<tr>
<td>7.34</td>
<td>Explosion frequency contributions from leaks on section 6 (per year) - comparison between models 4 and 5</td>
<td>126</td>
</tr>
<tr>
<td>7.35</td>
<td>Explosion frequency contributions from leaks on section 8 (per year) - comparison between models 4 and 5</td>
<td>127</td>
</tr>
<tr>
<td>7.36</td>
<td>The total explosion frequencies for the compression module (per year) - comparison between models 4 and 5</td>
<td>127</td>
</tr>
<tr>
<td>7.37</td>
<td>Total importance measures for the category of explosions in the compression module (percentages) - comparison between models 4 and 5</td>
<td>128</td>
</tr>
<tr>
<td>7.38</td>
<td>The importance of the sections in the compression module when the isolation and blowdown works as designed (percentage) - comparison between models 4 and 5</td>
<td>129</td>
</tr>
<tr>
<td>7.39</td>
<td>The importance of the isolation valves in the compression module (percentage) - comparison between models 4 and 5</td>
<td>130</td>
</tr>
<tr>
<td>7.40</td>
<td>The importance of the blowdown valves in the compression module (percentage) - comparison between models 4 and 5</td>
<td>131</td>
</tr>
<tr>
<td>7.41</td>
<td>Explosion frequency contributions from leaks on section 9 (per year) - comparison between models 4 and 5</td>
<td>133</td>
</tr>
</tbody>
</table>
List of Tables

7.42 Explosion frequency contributions from leaks on section 10 (per year) - comparison between models 4 and 5 .......................................................... 133
7.43 Explosion frequency contributions from leaks on section 11 (per year) - comparison between models 4 and 5 .......................................................... 134
7.44 Total importance measures for the category of explosions in the wellhead module (percentage) - comparison between models 4 and 5 .................................................. 134
7.45 The importance of the isolation valves in the wellhead module (percentage) - comparison between models 4 and 5 .......................................................... 134
7.46 The importance of the sections in the wellhead module when the isolation and blowdown works as designed (percentage) - comparison between models 4 and 5 135
7.47 The importance of the blowdown valves in the wellhead module (percentage) - comparison between models 4 and 5 .......................................................... 135
7.48 Explosion frequency contributions from leaks on section 1 (per year) - temperature state comparison .......................................................... 138
7.49 Explosion frequency contributions from leaks on section 3 (per year) - temperature state comparison .......................................................... 139
7.50 Total explosion frequencies for the separation module (per year) - temperature state comparison .......................................................... 139
7.51 The importance of the sections in the separation module when the isolation and blowdown works as designed (percentage) - temperature state comparison 140
7.52 The importance of the isolation valves in the separation module (percentage) - temperature state comparison .......................................................... 140
7.53 The importance of the blowdown valves in the separation module (percentage) - temperature state comparison .......................................................... 141
7.54 Importance measures for the categories of explosions in the separation module (percentage) - temperature state comparison ................................. 141
7.55 Explosion frequency contributions from leaks on section 4 (per year) - temperature state comparison .......................................................... 143
7.56 Explosion frequency contributions from leaks on section 5 (per year) - temperature state comparison .......................................................... 143
7.57 Explosion frequency contributions from leaks on section 6 (per year) - temperature state comparison .......................................................... 144
List of Tables

7.58 Explosion frequency contributions from leaks on section 8 (per year) - temperature state comparison. ............................................... 144
7.59 The total explosion frequencies for the compression module (per year) - temperature state comparison. ................................. 144
7.60 Total importance measures for the category of explosions in the compression module (percentages) - temperature state comparison. .......................................................... 145
7.61 The importance of the sections in the compression module when the isolation and blowdown works as designed (percentage)- temperature state comparison. 146
7.62 The importance of the isolation valves in the compression module (percentage) - temperature state comparison. ................................. 147
7.63 The importance of the blowdown valves in the compression module (percentage) - temperature state comparison. ................................. 148
7.64 Explosion frequency contributions from leaks on section 9 (per year) - temperature state comparison. ............................................... 150
7.65 Explosion frequency contributions from leaks on section 10 (per year) - temperature state comparison. ............................................... 150
7.66 Explosion frequency contributions from leaks on section 11 (per year) - temperature state comparison. ............................................... 151
7.67 The total explosion frequencies for the wellhead module (per year) - temperature state comparison. ............................................... 151
7.68 The importance of the isolation valves in the wellhead module (percentage) - temperature state comparison. ............................................... 151
7.69 The importance of the sections in the wellhead module when the isolation and blowdown works as designed (percentage) - temperature state comparison. ............................................... 152
7.70 The importance of the blowdown valves in the wellhead module (percentage) - temperature state comparison. ............................................... 152
7.71 Importance measure for the categories of explosions in the wellhead module (percentages) - temperature state comparison. ............................................... 152
8.1 Explosion frequency for the separation module (per year) with the changing temperature model - comparison of the two probability models. ............................................... 170
8.2 Explosion frequency for the separation module (per year) with the constant temperature model - comparison of the two probability models. ............................................... 170
List of Tables

8.3 Explosion frequency for the compression module (per year) with the changing temperature model - comparison of the two probability models. ........ 171
8.4 Explosion frequency for the compression module (per year) with the constant temperature model - comparison of the two probability models. ........ 171
8.5 Explosion frequency for the wellhead module (per year) with the changing temperature model - comparison of the two probability models. ........ 172
8.6 Explosion frequency for the wellhead module (per year) with the constant temperature model - comparison of the two probability models. ........ 172
9.1 The physical data for methane and air. ........................................ 182
10.1 The variation of ignition frequency per hour. ............................ 190
10.2 The changes in explosion frequencies (per year) due to ignition frequency variation using the changing temperature model. ............. 191
10.3 The changes in explosion frequencies (per year) due to ignition frequency variation using the constant temperature model. .......... 191
10.4 The variation of the unavailability of the deluge. ....................... 194
10.5 The changes in explosion frequencies (per year) due to the variation of the unavailability of the deluge system using the changing temperature model. ................. 195
10.6 The changes in explosion frequencies (per year) due to the variation of the unavailability of the deluge system using the constant temperature model. .......... 196
10.7 The variation of the time to activate the deluge system in seconds. .... 200
10.8 The changes in explosion frequencies due to the variation of the activation time of the deluge system using the changing temperature model. ........ 201
10.9 The changes in explosion frequencies due to the variation of the activation time of the deluge system using the constant temperature model. ........ 202
10.10 The frequency of explosions occurring prior to deluge due to section 10 in the wellhead module when the activation time of deluge is 30 seconds. .... 204
10.11 The frequency of explosions occurring prior to deluge due to section 11 in the wellhead module when the activation time of deluge is 30 seconds. .... 206
10.12 The variation of leak hole diameters. ........................................ 209
10.13 The changes in explosion frequencies due to the variation of the hole size distribution using the changing temperature model. ............. 210
List of Tables

10.14 The changes in explosion frequencies due to the variation of the hole size distribution using the constant temperature model. ........................................... 210

10.15 The variation of the frequency of occurrence of the leak holes for the separation module. ......................................................................................... 216

10.16 The changes in explosion frequencies due to the variation of the frequency of occurrence of the leak holes using the changing temperature model. ........... 217

10.17 The changes in explosion frequencies due to the variation of the frequency of occurrence of the leak holes using the constant temperature model. ........... 217

10.18 The variation of the air changes per hour. ............................................. 219

10.19 The changes in explosion frequencies due to the variation of the ventilation rates using the changing temperature model. ........................................... 221

10.20 The changes in explosion frequencies due to the variation of the ventilation rates using the constant temperature model. ........................................... 222

10.21 The variation of the deluge failure rate per hour. ................................... 226

10.22 The changes in explosion frequencies due to the variation of the failure rate of the deluge system using the changing temperature model. ....................... 228

10.23 The changes in explosion frequencies due to the variation of the failure rate of the deluge system using the constant temperature model. ....................... 229

11.1 Data for the isolation and blowdown valves. ............................................ 235

11.2 Data for the isolation and blowdown system inspection. ............................ 235

11.3 Data for the deluge system. ...................................................................... 236

11.4 Data for the deluge system inspection. .................................................... 236

11.5 Data for the detection system. ................................................................. 237

11.6 Data for the detection system inspection. ............................................... 237

11.7 The system components used in the first stepping procedure from a mid range initiator. ................................................................. 244

11.8 The steps that may be taken during the first stepping procedure from a mid range initiator. ................................................................. 244

11.9 The system components used in the second stepping procedure from a mid range initiator. ................................................................. 245

11.10 The steps that may be taken during the second stepping procedure from a mid range initiator. ........................................................... 246
List of Tables

11.11 The intermediate solutions generated with the stepping process with a mid range initiator ................................... 247
11.12 The system components used in the optimal configuration with the stepping process, initiated from a mid range case. ........................................ 247
11.13 The system components used in the first stepping procedure from a worst case initiator ................................................................. 248
11.14 The steps that may be taken during the first stepping procedure from a worst case initiator ................................................................. 249
11.15 The system components used in the second stepping procedure from a worst case initiator ................................................................. 250
11.16 The steps that may be taken during the second stepping procedure from a worst case initiator ................................................................. 250
11.17 The system components used in the third stepping procedure from a worst case initiator ................................................................. 251
11.18 The steps that may be taken during the third stepping procedure from a worst case initiator ................................................................. 252
11.19 The intermediate solutions generated with the stepping process with a worst case initiator ................................................................. 252
11.20 The system components used in the optimal configuration with the stepping process, initiated from a worst case. ........................................ 253
11.21 A comparison of the system components used in the optimal configuration with the stepping process ................................................................. 254
11.22 The system components used in the first linearisation procedure from a mid range initiator ................................................................. 258
11.23 The steps that may be taken during the first linearisation procedure from a mid range initiator ................................................................. 258
11.24 The system components used in the second linearisation procedure from a mid range initiator ................................................................. 259
11.25 The steps that may be taken during the second linearisation procedure from a mid range initiator ................................................................. 260
11.26 The system components used in the third linearisation procedure from a mid range initiator ................................................................. 261
<table>
<thead>
<tr>
<th>Table Number</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.27</td>
<td>The intermediate solutions generated with the linearisation process with a mid case initiator.</td>
<td>261</td>
</tr>
<tr>
<td>11.28</td>
<td>The system components used in the optimal configuration with the linearisation process, initiated from a mid range case.</td>
<td>262</td>
</tr>
<tr>
<td>11.29</td>
<td>The system components used in the first linearisation procedure from a worst case initiator.</td>
<td>263</td>
</tr>
<tr>
<td>11.30</td>
<td>The system components used in the second linearisation procedure from a worst case initiator.</td>
<td>264</td>
</tr>
<tr>
<td>11.31</td>
<td>The steps that may be taken during the second linearisation procedure from a worst range initiator.</td>
<td>264</td>
</tr>
<tr>
<td>11.32</td>
<td>The system components used in the third linearisation procedure from a worst case initiator.</td>
<td>265</td>
</tr>
<tr>
<td>11.33</td>
<td>The intermediate solutions generated with the linearisation process with a worst case initiator.</td>
<td>266</td>
</tr>
<tr>
<td>11.34</td>
<td>The isolation systems in terms of the type and inspection interval ordered according to the unavailability.</td>
<td>268</td>
</tr>
<tr>
<td>11.35</td>
<td>The blowdown systems in terms of the type and inspection interval ordered according to the unavailability.</td>
<td>269</td>
</tr>
<tr>
<td>11.36</td>
<td>The deluge systems in terms of the type and inspection interval ordered according to the unavailability.</td>
<td>269</td>
</tr>
<tr>
<td>11.37</td>
<td>The detection systems in terms of the type and inspection interval ordered according to the unavailability.</td>
<td>270</td>
</tr>
<tr>
<td>11.38</td>
<td>The combination of safety system types selected as the initiator.</td>
<td>272</td>
</tr>
<tr>
<td>11.39</td>
<td>The contributions to the frequency of exceeding 3 bar of the safety systems selected as the initiator.</td>
<td>272</td>
</tr>
<tr>
<td>11.40</td>
<td>Possible improvements to the deluge system from the initiating case.</td>
<td>273</td>
</tr>
<tr>
<td>11.41</td>
<td>Iteration 1: intermediate step to find a feasible combination.</td>
<td>274</td>
</tr>
<tr>
<td>11.42</td>
<td>The combination of safety system types selected from the first selection process.</td>
<td>274</td>
</tr>
<tr>
<td>11.43</td>
<td>The contributions to the frequency of exceeding 3 bar of the safety systems selected during the first iteration.</td>
<td>275</td>
</tr>
<tr>
<td>11.44</td>
<td>The combination of safety system types selected from the second selection process.</td>
<td>275</td>
</tr>
</tbody>
</table>
List of Tables

11.45 The contributions to the frequency of exceeding 3 bar of the safety systems selected during the second iteration ................................................. 276
11.46 Possible improvements to the deluge system from the second iteration ............................................. 276
11.47 Possible cost savings with the detection system from the second iteration ............................................. 277
11.48 Iteration 3: intermediate step to find a feasible solution ................................................................. 277
11.49 The combination of safety system types selected from the third selection process .......................... 278
11.50 The contributions to the frequency of exceeding 3 bar of the safety systems selected during the third iteration ................................................. 278
11.51 Iteration 4: intermediate step to find a feasible solution ................................................................. 279
11.52 Possible time savings with the detection system from the third iteration ............................................. 279
11.53 The combination of safety system types selected from the fourth selection process .......................... 280
11.54 Iteration 5: intermediate step to find a feasible solution ................................................................. 280
11.55 The combination of safety system types selected from the fifth selection process .......................... 281
11.56 The contributions to the frequency of exceeding 3 bar of the safety systems selected during the fifth iteration ................................................. 281
11.57 The combination of safety system types selected from the sixth selection process .......................... 282
11.58 The contributions to the frequency of exceeding 3 bar of the safety systems selected during the sixth iteration ................................................. 282
11.59 All cases evaluated at present ................................................................. 283
11.60 Iteration 7: intermediate step to find a feasible solution ................................................................. 283
11.61 The combination of safety system types selected from the seventh selection process .......................... 284
11.62 The contributions to the frequency of exceeding 3 bar of the safety systems selected during the seventh iteration ................................................. 284
11.63 The combination of safety system types selected for the optimum configuration .......................... 285
1. Introduction.

In 1988 a hydrocarbon release developed on the Piper Alpha platform in the North Sea with catastrophic consequences. 167 people lost their lives as fires and explosions engulfed the platform generating dense smoke clouds and causing the eventual collapse of the platform. An enquiry led by Lord Cullen\(^\text{[17]}\) suggested reforms to the regulations governing offshore installations. As a result the Health and Safety Executive introduced the Offshore Safety Division which has the responsibility of overseeing the submission and assessment of safety cases. These safety cases must be produced by offshore operators to assess the risks posed to the personnel by potential accidents by demonstrating that all hazards have been identified and measures have been taken to ensure the risk is as low as reasonably practicable.

On an offshore platform two of the major hazards are fires and explosions resulting from an accidental hydrocarbon release. The overpressures generated during an explosion can threaten the integrity of the platform structure. It is therefore important to be able to estimate the overpressures generated, should an explosion occur, and to predict the frequency of such an event in order to judge the design acceptability.

The aim of this thesis is to consider methods to minimise the risk on an offshore platform. This has been performed by considering the explosion hazard and the consequences posed to the platform from such an event. This chapter introduces the problem and provides an outline of the contents of the thesis and the work achieved.

The risk analysis methodology used in this study may be represented as shown in Figure 1.1. Hazard identification is first performed on the system, this is followed by determining the likelihood of possible scenarios developing through risk assessment techniques such as event tree analysis and fault tree analysis. Each possible scenario is considered to determine the consequences should a hazardous event occur. On determination of the consequences the model parameters are analysed to determine their sensitivity. The final stage is to optimise the system to ensure that the risks are as low as reasonably practicable.
Chapters 2 to 5 provide a review of the current literature. Chapter 2 considers risk assessment in relation to the offshore process industries. This chapter provides a brief overview of the history of risk assessment and considers some of the methods used in the offshore industries. More detail is given to event tree analysis and fault tree analysis as these two methods were
used in the methodology described in this thesis. Within this chapter a review is given of the Piper Alpha disaster and creation of the OSD and its functionality.

Chapter 3 considers explosions, a major hazard on offshore platforms. This chapter discusses the consequences arising from an explosion and the factors that contribute to this. Different consequence estimation techniques are employed by different organisations, from experimental explosion testing to comprehensive CFD based models. This chapter considers the range of techniques used and their effectiveness.

A factor in determining the consequences of an explosion is the dispersion of the gas prior to ignition. The influencing factors for this are covered in Chapter 4 along with a review of current modelling techniques employed.

Chapter 5 considers the optimisation techniques applicable to solving mathematical programmes which have the features of the explosion modelling design problem such as no objective function and integer design variables.

The design modelling work in this thesis begins at the consequence analysis stage of the risk analysis methodology. Chapter 6 describes a methodology which has been developed, by Andrews and Smith (1994)\(^3\), to predict the frequency of explosions of different magnitudes occurring in a module on an offshore platform. This methodology combines established risk assessment techniques, such as event tree analysis and fault tree analysis, with fluid flow modelling. Assumptions have been made in the methodology to simplify the calculation procedure. These assumptions relate to the conditions under which the leak occurs, the build up of gas in air concentration and the probability calculations. Frequency predictions are required to be as accurate as possible to enable the acceptability of the risk to be determined and reduced to a level which is as low as reasonably practicable. Hence each of the assumptions within the methodology has been addressed within this thesis, to determine a more complete prediction.

Chapter 7 addresses the assumptions made in calculating the release flow. A comparison is provided between assuming different leak flows in terms of their constituents. A new model is provided to calculate the release flow under constant temperature conditions as opposed to the changing temperature originally assumed.

Chapter 8 considers the way in which the methodology calculates the probabilities of events
occuring. This method eliminates the major assumption to assess the validity of the original modelling.

Chapter 9 considers the assumption made on the gas cloud build up and provides the information required to effectively employ CFD to determine the gas cloud concentration build up with time. This chapter also details a method for integrating such dispersion correlations into the frequency modelling.

Having determined the consequences of an explosion as accurately as possible, the key parameters are considered in the sensitivity analysis of chapter 10. The aim of this chapter is to determine the magnitude at which slight inaccuracies within the empirical data will influence the overall frequency of an explosion occurring.

Once an accurate frequency for the explosion occurring has been determined, the risk to personnel must be minimised to an acceptable yet practical level. On existing designs it is impractical to alter the layout of the platform. However the nature of the safety systems may be changed. These safety features include isolation, blowdown, mitigation and detection systems. An optimisation study, in Chapter 11, presents three schemes to identify the optimum configuration of the safety systems, in terms of the overpressures generated, as a means of reducing the risk to the platform.
2. Risk assessment and offshore safety regulations.

2.1 Introduction.

Risk assessment has been used in some form, within the engineering industry, since the 19th century\(^{[52]}\) but had no legal standing until 1974. The UK Health and Safety at Work Act of 1974 states:

> It shall be the general duty of each person who has to any extent control of the premises ... to take measures ... so far as it is reasonably practicable, to ensure that they are safe and without risks to health.

Risk assessment techniques were first applied to the hydrocarbon process industries in the late 1970s. The application to offshore process facilities dates from the early 1980s. In 1983 the Royal Society commissioned a study group to consider risk and the assessment of risk\(^{[56]}\). This was followed by an updated report in 1992\(^{[57]}\). Both reports stated that there should exist an upper and lower bound for the acceptance of risks. A risk exceeding the upper limit is not to be tolerated at all. A risk below the lower limit may still be a risk but warrants no resources to lower it further. Between the limits exists the tolerable region where activities are to be tolerated if the means justifies the risk and continuous monitoring of the situation is maintained. Risk and the associated words were fully defined. Risk was defined to be:

> the probability that a particular adverse event occurs during a stated period of time, or results from a particular challenge.

Where an adverse event is defined to be an occurrence that produces harm.

The aim of this chapter is to provide a general overview of risk assessment and its applications to the offshore industry. Section 2.3 provides an overview of the Piper Alpha disaster, which
was the instigator of the offshore safety regulations reform, and details the current safety requirements. Section 2.5 looks at the methods in use within the process industries whilst Section 2.6 concentrates on two well documented methods; fault tree analysis and event tree analysis, which are employed during the preliminary phase of this project.

2.2 Tolerability of risk.

Risks must be as low as reasonably practicable, ALARP. A three tier structure can be used to represent the concept of ALARP as shown in Figure 2.1.

The width of the pyramid represents the magnitude of the risk involved. The lower region corresponds to all acceptable risks where there is no need to demonstrate that the risks are ALARP, but it is necessary to maintain assurance that the risk remains at this level. The upper region is where the risks are classified as unacceptable and can not be justified except in extraordinary circumstances. The central section contains all risks classed as ALARP, the risk is acceptable as long as the benefit outweighs the risk. However a cost benefit approach is required to compare whether the cost of further risk reduction would reduce the risk involved significantly. The higher the risk more, proportionally, must be spent on its analysis and consequent reduction. In 1988 the HSE defined the maximum tolerable risk to employees to be 1 death in $10^3$ per year whilst the maximum tolerable risk to the public...
is 1 death in $10^4$. The broadly acceptable risks, below which it is not reasonable to insist on improvements, is 1 death in $10^6$ per year for the public exposed to the hazard.

2.3 Risk assessment in relation to offshore platforms.

General impressions among the public is that the North Sea offshore oil industry is subject to high risk. Factors influencing this perception, given by Tveit (1994)[62], include the remoteness of offshore facilities from the shore, the unpredictability of the weather conditions surrounding them, the high energy which may be released and the complexity and size of the facilities. Establishing risk offshore is difficult due to the uncertainty in extrapolating information from past to present risk especially as the offshore activities have a short history and have changed a great deal. Consistency in the reporting and calculation of risk was lacking until a major incident in 1988 changed the industry's approach and introduced a regulating body to oversee all offshore process facilities.

2.3.1 The Piper Alpha disaster.

Piper Alpha was the main platform exploiting the oil reservoir in the Piper field. This oil field situated east of the Orkney Islands in the North Sea was licenced to Occidental. Piper Alpha was linked to three other platforms, Claymore, Tartan and MCP-01, by gas pipelines and to the oil terminal at Flotta with an oil pipeline. The platform had facilities to drill wells, extract, separate and process the well fluids. There were four main production modules on the platform; wells, separation, compression and utilities. Above these were various other facilities, accommodation blocks and a helideck.

Production on the platform began in 1976, initially the platform was designed for exporting oil to the shore, any gas extracted during processing was burnt at the flare. In 1978 the platform was altered to conform with the government regulations, whereby gas was compressed and sent ashore. Facilities were modified again in 1980, 1983 and 1984.

On July 6th 1988 an initial explosion occurred in the production modules. This was followed by more fires, explosions and dense smoke. The public inquiry[17] concludes that a leak of gas formed a flammable gas cloud, this found an ignition source causing an explosion and oil
leaking from the pipes formed a pool fire. Possible sources of ignition may have been sparks, hot surfaces or hot work (maintenance was being carried out in this area). The explosion caused other pipes to rupture therefore escalating the situation. Safety protection systems existed on the platform but failed to work. The gas was not detected prior to the initial explosion. The water spray mitigation system did not activate, had this have activated the gas may have been dispersed and the resulting overpressures reduced. The platform should have been isolated from its neighbours as soon as the explosion occurred, however it was not and more gas was allowed to fuel the explosion and fires.

Two hundred and twenty six people were on board the platform that night. Only sixty two people were working on the night shift, the remainder were in the accommodation blocks. One hundred and sixty seven people died. The main cause of death was smoke inhalation.

2.3.2 Offshore Safety Division.

After the Piper Alpha disaster\cite{17} the inquiry led by Lord Cullen suggested that reforms to the regulations governing offshore installations should be made. Lord Cullen’s report instigated the formation of the Health and Safety Executive’s Offshore Safety Division (OSD) to implement the 106 recommendations within the report.

Previous to this report the regulatory body was the Department of Energy (DoEn), they ensured compliance with regulations made under the Mineral Workings (offshore installations) Act (MWA) of 1971 which came about after the collapse of Sea Gem, an exploration rig, in 1965. Lord Cullen found that the DoEn lacked experience in safety management systems and formal safety assessment (FSA). As an example the Norwegian offshore regulatory body, the Norwegian Petroleum Directorate (NPD), was examined by Lord Cullen, he found that the NPD used FSA to ensure that risks were identified. Lord Cullen’s recommendations transferred the regulation of the offshore safety activities to the HSE, their main objective was to be a goal setter rather than a regulation enforcer. This goal setting included the requirement of safety cases from every company working offshore.

The safety case ensures that every company produces an FSA to assure itself that its operations are safe and secondary to this is the demonstration of this to the regulatory body. A safety case should demonstrate
that the safety management system of the company (SMS) and that of the installation are adequate to ensure that the design and operation of equipment are safe.

- that the potential major hazards of the installation and the risks to personnel have been identified and appropriate controls provided.

- that adequate provision is made for evacuation and temporary refuge should a major disaster occur.

The Offshore Installations (safety cases) Regulations in 1992 further defined quantitative risk assessment

quantitative risk assessment means the identification of hazards and evaluation of the extent of risk arising therefrom, incorporating calculations based upon the frequency and magnitude of hazardous events.

The OSD has the responsibility of overseeing the submission of the offshore safety cases, the initial safety cases were due in 1995, and then screening, assessing and discussing the reports and requesting modifications if necessary. The OSD currently employs approximately 150 inspectors to enforce the safety legislation. The inspectors must visit offshore installations regularly to inspect all aspects of health and safety, inspect and audit drilling and specialist operations, investigate accidents and complaints and assess the content of safety cases. The OSD also conducts its own research and development to provide insight and knowledge to perform assessment of the safety cases, investigate accidents and generally improve health and safety offshore. Their research programme, which is undertaken by over 100 different research contractors in the UK, has twenty specific areas of work, five of these have been assigned high priority. These topics are

- fire and blast.

- evacuation, escape and rescue.

- occupational health.

- diver physiology.

- collisions.
The OSD has identified strategic priorities within the category of fire and blast, these being explosion suppression and mitigation; fire protection; standardisation of fire tests; gas dispersion and smoke migration. In 1990 the OSD began an extensive research project into offshore explosions with an aim to understanding what they are, how they occur, the effects on the installation and how the damage can be mitigated. Phase I was essentially a literature review which was sponsored by 28 oil and gas companies. This work resulted in 26 reports summarising the current knowledge on explosion and fire engineering and interim guidance notes for the design and protection of offshore structures. Phase II involved constructing a full scale test rig for experiments to be performed in order to gain information regarding the characteristics of hydrocarbon explosions and fires. The results gained from this phase have been critical in the evaluation of computer models used in the preparation of safety cases. Phase III continues to utilise the test rig to develop strategies for reducing the effects of explosions, the main considerations are reducing confinement and applying water deluge. Modern offshore installations have been constructed on the basis of this and other research work. Designers of modern platforms must provide safe refuges to protect the personnel from fire and explosion. Older platforms are being upgraded, although due to the complicated nature of this task some operators have chosen to install new platforms adjacent to the existing ones. In some cases the accommodation section is now completely separated from the process platform on another platform.

2.4 The future of risk assessment in the offshore process industries.

According to Pitbaldo (1994) QRA studies have not been balanced. This was highlighted as a fault on safety cases presented to the HSE. At the Offshore Safety Case Conference in 1993 the HSE stated that safety management systems and the use of QRA were generally acceptable but major hazard identification was not complete. The majority of work was concentrated on performing consequence calculations, frequencies and risk results. More work was necessary in assessing the needs of the client; identifying possible failures; investigating alternatives; developing cost effective solutions and then communicating the results. Pitbaldo (1994) describes the procedures adopted by DNV Technica for reducing the uncertainty in their QRA results. This begins with the risk analysis study structure which
Risk assessment and offshore safety regulations.

is critical in determining the emphasis of the study. If the clients needs are misinterpreted inappropriate models may be selected. Risk assessment had been traditionally implemented using spreadsheets as a basis. Such methods involve errors as the spreadsheets become large as there is no way of identifying any changes made and the formulae are not readily available. The OHRA (Offshore Hazard and Risk Analysis) Toolkit was introduced to alleviate some of these problems. The basic objectives were that risk studies were constructed in diagrammatic form, transfer of data should be easy to identify and well documented, consequence models should be well defined and robust, new models should be easily incorporated, quality assurance should be straightforward and results should be meaningful and believable. The OHRA Toolkit was developed by DNV Technica in conjunction with 13 other sponsors; Amoco Norway Oil Company; Chevron UK Ltd; Conoco UK Ltd; Dovre SikteC; Elf Enterprise Caledonia; Mobil North Sea Ltd; Norsk Hydro AS; Phillips Petroleum Company Norway; Saga Petroleum; Scandpower AS; Shell SIPM; Statoil and VROM (Netherlands Government).

Miller (1994)[45] also agrees with this view and states that Shell UK aim to improve communication of the safety principles to design teams and future operators of the platform. A time based three-dimensional simulation of the hazards has been developed which veers from the traditional approach that assumed all safety systems had equal priority and could be considered independently. The new approach is to include more integration and human factors to avoid duplication or weak links and to demonstrate that the overall objectives are being achieved by improving the realism. Their method consists of generating scenarios that cause hazards, manually assessing the response of the outcomes (worst cases only, number too large) and then recomputing. Many risk assessment teams are developing similar approaches in the way they involve workers in the decisions and consider human factors important to their model.

2.5 Risk assessment methods.


*Risk assessment is a way of systemising our approach to hazard with a view to determining what is more or less risky. It helps to diminish our exposure whilst*
Risk assessment and offshore safety regulations.

Risk assessment is the general term used to describe the study of decisions subject to certain consequences. This study is subdivided into risk estimation, risk evaluation and risk management. Risk estimation involves identifying the outcomes, estimating the magnitude of the associated consequences and the probabilities of the outcomes. Risk evaluation is the complex procedure of determining the significance of the identified hazards and the estimated risks to those involved. Risk management involves making decisions about working practice where risks are concerned.

The estimation of risks is performed via two methods that should be used in conjunction with each other. The first is operability analysis (OA) which is a qualitative method for critical examination of hazards and their consequences. The second is quantitative risk assessment (QRA) which provides a numerical method for calculating the risk. Hazardous activities are often compared with historical data to give a comparative risk level with an everyday situation. Assumptions made in risk analysis lead to a simplification of the problem which may give lower casualty rates. This should always be a consideration when using comparative methods to determine a level of risk. Risks are calculated in terms of probabilities which removes any confusion regarding dimensions, hence comparisons are immediate.

2.5.1 Qualitative methods.

Qualitative risk assessment methods include hazard and operability studies (HAZOP), rapid ranking and preliminary hazard analysis (PHA).

HAZOP (hazard and operability studies) was introduced into industry by ICI Ltd to determine the potential hazards in a chemical plant. It is now widely accepted as the most complete qualitative method by the British Chemical Industry Safety Council and is used throughout the chemical and other potentially hazardous industries. The purpose of a HAZOP is to examine the operation of a system outside its normal design parameters to determine whether this may lead to safety problems. HAZOP is a formal structured method which uses clearly defined terms to systematically complete the required worksheets. These terms are; INTENTION which defines how the part is expected to function; DEVIATIONS are departures from the design intention; CAUSES are the reasons why the deviations may occur;
CONSEQUENCES are the results of the deviations; HAZARDS are the consequences which can cause damage, injury or loss. Guide words are used to clarify the deviations: NO/NOT; MORE; LESS; AS WELL AS; PART OF; REVERSE. To avoid failing to recognise potential hazards in the system, HAZOP studies are carried out by multi disciplinary teams with a wide range of knowledge including plant design and operating procedure. HAZOP studies can be adopted at any stage in an industrial plant’s life but it is most appropriate at the design stage.

A more cost effective method when dealing with an existing plant which is less time consuming than HAZOP is rapid ranking. This was also developed by ICI with the aim of identifying and ranking hazards. Plant areas are ordered in priority of study, such ordering is rational and has no subjective basis.

PHA (preliminary hazard analysis) is the method most widely adopted in the USA. It is similar to HAZOP in its disciplined analysis of the potential hazards. The method aims to identify the hazards as well as the causes and to assess the severity of the consequences. A common ranking scheme is used which are often referred to as criticality categorisations. These rank from class I to class IV where class I represents a hazard with negligible effects, class II has marginal effects, class III is critical and class IV is catastrophic. In general PHA is used as the first attempt to identify the events leading to hazards in a system, this is performed during the design stage.

2.5.2 Quantitative methods.

Quantitative risk assessment (QRA) methods include Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) as two of the most common and comprehensive methods. QRA involves four stages:

1. Identification of potential hazards.
2. Estimation of consequences.
3. Estimation of probability of occurrence of each hazard.
4. A comparison of results of the analysis against the acceptability criteria.
Although qualitative methods will have fulfilled the criteria of step 1, FMEA and FTA fulfil all the criteria.

FMEA (failure mode and effect analysis) is an upward, inductive procedure which begins from a detailed level and evaluates the failure effects of each component, on a component by component basis, meaning that the whole system is completely screened. The object is to identify the weak areas where modifications are necessary. The method utilises a classification system as a means to identify the severity of a failure. FMEA is the first stage of an FMECA (failure modes, effects and criticality analysis). FMECA is a procedure for identifying the potential failure modes of a system (FMEA) and classifying them according to severity (criticality analysis). Structured worksheets make this a systematic approach. The following steps are required to complete an FMEA/FMECA study.

- Define the system.
- Construct hierarchical block diagrams.
- Identify the failure modes at each level.
- Assign effects to each failure mode.
- Define severity of each effect.
- Incorporate other necessary data.
- Rank the failures.
- Analyse and maybe redesign the system.

The method is time consuming but can be applied at any level of detail.

Fault tree analysis presents a graphical model illustrating the combinations of faults which can lead to the failure of the system. It begins with the undesired event and works downwards to find the causes of such an event. Fault trees are initially qualitative models but may be evaluated quantitatively. The advantage of using a fault tree to represent the causes of failure of a system is that complex systems can be handled with ease.
2.6 Risk assessment techniques used in the offshore process industries.

Although each of the above qualitative and quantitative techniques are widely used in hazardous process industries, this section will concentrate on the two methods employed to create the data files for this project. Event tree analysis and fault tree analysis are respectively methods which pictorially illustrate the sequence and causes of events and both may be used as a qualitative or quantitative tool.

2.6.1 Event tree analysis.

The method was first applied between 1972 and 1975 to assess the risks associated with a light water nuclear power plant. It has since become the most frequently used tool to determine and characterise the possible hazardous scenarios.

Event trees (or consequence tree method) provide a pictorial representation of all events that may occur in a system. This method is described as a tree due to its nature of fanning out like branches of a tree as an increasing number of events are considered. The tree begins with an initiating event and is followed, from left to right across the page, by the sequence of events which consider the response of safety related systems. The events may be considered in any order as long as they do not operate sequentially with respect to each other. The paths can be followed to determine whether the consequences are considered acceptable or unacceptable. All paths in an event tree are mutually exclusive, if the events are independent, so the probability of a path occurring is the product of the probabilities of each event leading to the outcome.

There are usually two states a component may have, success and failure, therefore for an n component system there are $2^n$ paths of which $2^n - 1$ are potential accident scenarios. Should the component have the capability of residing in more than two states, for example limited performance, then the number of paths is even greater. In order to reduce the amount of work necessary, reduced event trees may be constructed. The reduced trees are constructed by considering the outcome of continuing down a path before the next event is considered. If it is known at that stage whether the sequence of events will lead to success.
or failure of the system irrespective of the following events then that branch is considered no further.

Event trees may be used as a qualitative or quantitative tool. Probabilities of the events occurring are assigned to the branches of the tree. The product of these event probabilities gives the probability of that sequence of responses being seen.

An example of the use of an event tree is given in Chapter 6.

### 2.6.2 Fault tree analysis.

Fault tree analysis or the cause tree method\(^6\) was developed as a tool for assessing the faults of systems with a view to improving the reliability between 1961 and 62 at the Bell Telephone Laboratories. The method proved to be successful in identifying the weak points. The method was improved into a formalised approach in 1965 by the Boeing company.

The objectives of the method are to identify the possible event combinations which lead to the undesired system outcome occurring, and to represent this graphically. The method is frequently used as a qualitative evaluation method to assist the designer and it can also be used for quantitative evaluation. A fault tree logic is essentially the reverse of event tree logic\(^6\) it uses a downwards deductive approach requiring the identification and the definition of an undesired system event. This undesired event is known as the top event. Typical top events are explosion, unavailability of safety system and toxic releases. The fault tree analysis works downwards to determine the relationship of lower level events causing the failure. The fault tree consists of successive levels of events which are connected such that each event ensues as a result of events at the level below, where each event is assumed independent from the others at the same level. The relationships between the events are represented using standard logic gates. The process is continued until the basic events are identified, i.e. where the events can not be resolved any further. Typical basic events are pump failure and control failure.

The formalised approach must be performed in strict order:

1. System definition.
2. Fault tree construction.
3. Qualitative evaluation (obtaining minimal cut sets).

4. Quantitative evaluation.

System definition.

The system must be defined in such a way that the top event and system boundaries do not lead to an analysis that is too broad or too narrow to produce useful results. Each fault tree considers only one failure mode therefore a system may require many fault trees for full analysis.

Fault tree construction.

A fault tree is built up using standard symbols to represent the logic gates and events. The top event heads the tree and is represented as a rectangle. The tree continues downwards to show the causes. The relationships between events are determined by logic gates as shown in Figure 2.2. Possible logic gates include AND, OR, VOTING, PRIORITY AND and EXCLUSIVE OR. An AND gate is only activated should all inputs to that gate have occurred. An OR gate must have at least one of the inputs occurring. For a VOTING gate to activate then $m$ inputs out of the $n$ possible inputs must have occurred. The EXCLUSIVE OR gate may only have one input occurring. The PRIORITY AND gate must have all inputs occurring in a set order. The events are resolved as far as possible with the underlying events being represented as basic events.
Henley and Kumamoto (1981)\cite{26} state some heuristic guidelines which are desirable for constructing fault trees:

1. Replace abstract events by less abstract events.
2. Classify events into more elementary events.
3. Identify the distinct causes for the event.
4. Couple the trigger event with 'no protective action'.
5. Find cooperative causes for an event.
6. Pinpoint a component failure event.

These guidelines should be coupled with the following rules given by Andrews and Moss (1993)\cite{2}:

1. Write the statements in event boxes as faults.
   - state precisely what the fault is and when it occurs.
2. Classify the event as a ‘state-of-component’ or ‘state-of-system’ fault.

   - ‘state-of-component’ faults should be developed into primary failure, secondary failure and command faults.
   - ‘state-of-system’ faults should be developed into immediate, necessary and sufficient causes.

3. If the normal state of the component causes a fault sequence then it is assumed that the component functions normally.

4. All inputs to a gate must be completely defined before further development is undertaken.

5. Gates should not be connected directly to another gate.

The three basic gates used, OR, AND and NOT combine in the same way as the Boolean operations of union, intersection and complementation and are used to aid qualitative and quantitative evaluation.

Qualitative evaluation.

A system must be analysed to eliminate the most likely cause of failure. To do this the system failure modes must be identified.

The cut set is a combination of events which result in the undesirable top event occurring. The minimal cut set is the smallest event combination resulting in the undesirable event such that removing an event causes the top event not to occur. There may be further classifications of minimal cut sets. A first order minimal cut set represents single failures causing the undesirable event. A second order minimal cut set represents double failures which when occurring together cause the top event. The minimal cut set of the lowest order must be identified as these are often the weakest links in the system. To determine a cut set the fault tree should be expressed in Boolean form. The Boolean algebra leads to an expression for the undesirable event.

\[
F = C_1 + C_2 + \ldots + C_m
\]
where $m$ is the number of cut sets and $C_1, \ldots, C_m$ are the cut sets. Boolean algebra is simple to perform for OR and AND gates and computer programs exist to process the minimal cut sets.

The identification of the minimal cut set allows quantification of the fault tree to be carried out.

**Quantitative evaluation.**

The probability of the system being unavailable is

$$P[F] = P[C_1 + C_2 + \ldots + C_m]$$  \hspace{1cm} (2.2)

This can be expressed as

$$P[F] = \sum_{i=1}^{m} P[C_i] - \sum_{j=2}^{m} \sum_{i=1}^{j-1} P[C_i \cdot C_j] + \sum_{j=3}^{m} \sum_{k=2}^{j-1} \sum_{i=1}^{k-1} P[C_i \cdot C_j \cdot C_k] - \ldots + (-1)^m P[C_1 \cdot C_2 \cdot \ldots \cdot C_m]$$  \hspace{1cm} (2.3)

When the elementary probabilities are low

$$P[F] \approx \sum_{i=1}^{m} P[\text{minimal cut set } i]$$  \hspace{1cm} (2.4)

The probability of the top event occurring has upper and lower bounds such that

$$\sum_{i=1}^{m} P[C_i] - \sum_{j=2}^{m} \sum_{i=1}^{j-1} P[C_i \cdot C_j] \leq P[F] \leq \sum_{i=1}^{m} P[C_i]$$  \hspace{1cm} (2.5)

**Advantages/disadvantages.**

This technique can be time consuming and requires the analyst to understand the system thoroughly, such limitations may be overcome by employing a team of experts. The final result is a diagrammatic view of the causes and the ultimate consequences of a failure constructed in a logical manner which can be used as a qualitative or quantitative tool. The major advantage is the ease with which complex systems can be handled.
3. Explosion modelling techniques.

3.1 Introduction.

Van Wingerden (1994)[64] quotes a review by Garrison concerning accidents, in the hydrocarbon process industry, between 1957 and 1986. This showed that 42% of these were due to explosions and 35% due to fires, illustrating the need to estimate explosion frequencies, their effects and consequences. Estimation of explosion frequencies involves determining: the likelihood of the release; the likelihood of the explosive mixture developing; the likelihood of the ignition. The likelihood of a release or occurrence of an ignition source is found either from publications such as the Hydrocarbon Leak and Ignition Data Base, Report Number 11.4/180[49] (a collation of historical and experimental data) or company data. This does not, however, provide the likelihood that the cloud of gas will ignite, factors such as the position and strength of the ignition source are important. The likelihood of having an explosive mixture depends on the rate and conditions of the release and how the gas is likely to disperse within the volume.

This chapter provides a summary of the literature regarding explosions on offshore platforms. It begins by looking at the consequences arising from an explosion and leads on to the factors that influence the severity should one occur. Within Section 3.4 existing modelling techniques are discussed.

3.2 Consequences arising from an explosion.

The two major consequences resulting from an explosion are the high overpressures and thermal load transfer onto the structure. Both of these lead to weaknesses being introduced to the platform structure. Thermal load is of most concern when considering fires from impacting jets. Phase I of the HSEs research into fire and blast provides a comprehensive review of the factors affecting thermal load and the modelling techniques available.[30, 31, 33]
3.2.1 Overpressures.

Following ignition in a flammable gas cloud a spherical flame front is formed, providing that there are no obstacles to deform it. The flame consumes the unburnt gas ahead of it leaving hotter gases behind. These hotter gases have a larger volume than the unburnt gases hence causing expansion. If the expansion is restricted then the pressure will rise. The rise in pressure above the ambient conditions is known as the overpressure. An alternative mechanism for generating overpressures is not related to confinement but to the speed of the flame as it propagates through the cloud. The flame effectively acts as a piston generating an overpressure wave due to the inertia of the unburnt gas ahead of the flame. This generation of overpressures is common in vapour cloud explosions.

Johnson et al. (1991)\cite{34} state that the magnitude of an overpressure is directly related to the speed of the flame propagating through the vapour cloud. Dobashi (1997)\cite{18} estimates the overpressure generated in an enclosed volume, if there are no disturbances on the flame front as

\[ p - p_0 = \frac{C p_0 S^3 t^3}{V} \]  

(3.1)

where \( S \) is the burning velocity (\( ms^{-1} \)), \( t \) is the time (s), \( C \) is a constant, \( V \) is the volume of the enclosure (\( m^3 \)), \( p_0 \) is the pressure at the time of ignition (\( Pa \)) and \( p \) is the pressure at the specified time, \( t \). However the pressure rises more rapidly when the flame front is disturbed, factors affecting this are turbulence, non uniform concentration within the enclosure and the flame front instability.

A high overpressure causes the structure to either fail or dramatically weaken, which will cause failure at a later date. This illustrates the seriousness of obtaining estimates of high overpressures and the need to determine exactly what does cause them and how it can be remedied. The extent of flame acceleration and overpressure potential is said to be a function of gas concentration, degree of congestion and the fuel type. Geometry and ignition location also influence the overpressures produced.

Catlin et al. (1993)\cite{9} produced a relationship between the overpressure produced and the concentration level at which ignition occurred. This relationship was related to the mitigation situation, experiments show that when the explosion is mitigated with water sprays the overpressures are significantly reduced.
3.3 Influencing factors.

Factors that influence the severity of an explosion include: confinement; turbulence; reactivity of the fuel; ignition source; cloud configuration and cloud mixing.

3.3.1 Flame speed.

Flames produce high temperature combustion products and therefore cause gas to be unable to expand completely, if in an enclosed volume, thus raising the pressure. Flame acceleration and speed depend on turbulence, fuel type and its volume concentration within the module. The maximum burning velocity is when the mixture is slightly above the stoichiometric concentration.

3.3.2 Geometry.

When discussing geometry we are considering a combination of congestion and confinement. Confinement relates to the walls of the structure and the consequent lack of capability for gas expansion. Congestion refers to the process vessels and pipe work within the enclosure, commonly referred to as obstacles. In general reducing confinement reduces overpressures, similarly increasing congestion increases overpressures. In particular positioning long pipes perpendicular to the direction of the flame flow increases the overpressures. If the combustion takes place in free space flames proceed at the laminar burning velocity and there is no significant change in pressure. On the other hand if there are obstructions turbulence is created increasing the flame speed and the pressures within the system. Confinement or obstacles allow recirculation to occur causing gas accumulation and higher pressures.\[^{14}\]

Offshore platforms have many regions of closely packed pipe work that promotes rapid flame acceleration and generation of high pressure levels. Mercx et al.\[^{44}\] define a loop which unless it is broken causes very high flame speeds and overpressures

Repeated obstacles cause expansion of combustion products behind the flame that generates flow over the obstacles ahead of the flame \(\rightarrow\) increases flame area \(\rightarrow\) increases rate of combustion \(\rightarrow\) increases flow speed and turbulence \(\rightarrow\) . . . .
At a distance from the obstacle the distortion of the flame diminishes and velocity starts to decay breaking the chain. Baker et al. (1996)\cite{4} state that the most important parameters in determining the effect of obstacles are the blockage ratio and the pitch. The higher the blockage ratio is, the higher the turbulence intensity is, therefore there are higher speeds and higher overpressures. It has been noted from experiments that there is usually an optimum value for the pitch which is not necessarily the maximum or the minimum distance. There appears to be an inability to quantify obstacle density but they can be categorised as either low, medium or high.

3.3.3 Ignition sources and location.

Eckhoff and Thomassen (1994)\cite{19} classify ignition sources into the following groups.

- a source of ignition that occurs continuously or frequently.

- a source of ignition that occurs only in rare situations.

- a source of ignition that can only occur in very rare situations.

Possible ignition sources include open flames, hot surfaces, mechanical sparks, electrical sparks, electrostatic discharges, jets of hot gaseous combustion products and shock waves. Ignition due to mechanical sparks, electric sparks or hot surfaces produce less severe effects than those generated by flame jet ignition.\cite{64}

Samuels (1993)\cite{58} and van Wingerden (1994)\cite{64} state that the highest overpressures are generated when the ignition source is at its furthest distance from all ventilation. When the ignition occurs close to the ventilation the burnt gases are dispersed therefore reducing the turbulence generation and hence keeping the pressure low. Mercx et al. (1993)\cite{43} concluded from their experiments that the ignition source location only has a minor effect on the maximum overpressures generated, the significant changes are in the pressure-time histories. Ignition at the rear wall has a peak of overpressures early in time compared to the central ignition, which in turn is earlier than the peak when ignition is at the vent opening.
3.3.4 Explosion relief.

There are two main ways of relieving an explosion. The classical method is by ventilation, drawbacks to this are the expenses incurred if experiments show that a change is required. The most recent method is by mitigation in the form of water sprays.

Ventilation.

Ventilation is important, without it the overpressures would continue to rise until the structures lose would have lost integrity. The size and location of vents are critical to the effectiveness of the ventilation system, but when the vent shape was varied in experimental tests, by Mercx et al. (1993)\cite{43}, the pressure-time histories did not change. When there is sufficient venting close to the ignition point burnt gases are vented, hence turbulence generated is limited. However when venting is further from the ignition point a strong turbulent flow field is generated, accelerating the flame and so causing high pressures. Therefore venting at an early stage is an effective means of reducing flame acceleration.\cite{64} Venting the flow ahead of the flame causes flame distortion that increases the flame area, increasing the volume production and so raising overpressures.

Ventilation may be natural or forced. Natural ventilation has two components, the external flow of the wind around the structure and the internal flow of the air through the structure. The external flow is governed by the shape of the structure and the properties of the on coming wind. The external flow creates a pressure field at the surface which together with the position and size of the vent openings determines the internal flow and hence ventilation rate.\cite{14} Many offshore platforms utilise natural ventilation by having semi enclosed modules. However in some cases natural ventilation may not be used effectively and so forced ventilation is incorporated. Due to the damage that high overpressures can cause to the structure certain strategic walls on offshore platforms are being replaced by failing panels. These panels are designed to withstand only a relatively small overpressure, once this is reached the panel will fail introducing further ventilation to the system. The failing panels should be designed to fail at pressures as low as possible taking into consideration the suction due to the wind.\cite{64}
Mitigation

Mitigation is a method of suppressing the flammability of the gas cloud, in the past this has been achieved with various substances. Halons (halogenated hydrocarbons) were used because they chemically interfere with the combustion process. Rather than lessen the hazard, halons presented more of a danger to personnel\cite{1} and to the ozone layer.\cite{32} Halons are not favoured on offshore platforms due to hazards posed by them, the major reasons being their habit of obscuring the monitoring equipment and the highly accurately timed response required in order for them to be effective.

Water is the main mitigation method used offshore. Water curtains can be effective in suppressing an explosion provided that they are positioned strategically, in terms of the likely direction of the flame front and the location of electrical equipment. The water curtain entrains air which is pumped into the flammable mixture, this acts as a dilution agent and renders the cloud non ignitable.\cite{35} The most prevalent method employed on offshore platforms utilises water sprays. Water deluge is ineffective for low flame speeds but at high flame speeds the water droplets break up giving a greater surface area that aids the rapid extraction of heat. In the early phases of flame propagation the pressure peak is reached earlier with mitigation than without due to the generation of turbulence caused by the water spray, however the mitigated pressure peak is of a lower magnitude than the unmitigated pressure peak. Catlin et al. (1993)\cite{9} state that the water must also be uniformly distributed to be effective, local deluge does not have a significant effect. The beneficial effect of the water is the effect of the vapour on the burning rate. In order to acquire vapour the water droplets must evaporate. For evaporation the droplets must be between 1 and 10\(\mu m\).\cite{64} Droplets from standard nozzles are greater than 100\(\mu m\) and do not readily evaporate, these must be broken up. Catlin et al. (1993)\cite{9} define the break up of the droplets to be connected to the Eotvos number, \(E_o\),

\[
E_o = \rho_w \frac{dU}{dt} \frac{d_d^2}{\sigma_w}
\]

where \(\rho_w\) is the density of the water (\(km^{-3}\)), \(\frac{dU}{dt}\) is the acceleration of the gas flow (\(ms^{-2}\)), \(d_d\) is the droplet diameter (\(m\)) and \(\sigma_w\) is the surface tension of the water (\(Nm^{-1}\)). Clift suggests that no break up occurs if \(E_o < 16\). The size of the droplets decreases as \(E_o\) increases, this will occur if the surface tension decreases, therefore adding foaming agents to the sprays to lower surface tension aids the mitigation effect. Van Wingerden et al. (1995)\cite{65} state that
droplet break up occurs when the critical Weber number, $W_c$, is reached.

$$W_c = \frac{\rho_g v^2 d_d}{\sigma_w}$$  \hspace{1cm} (3.3)

where $\rho_g$ is the density of gas ($kgm^{-3}$) and $v$ is the velocity of the gas ($ms^{-1}$). A relationship exists for the critical velocity at which break up occurs, based on experimental results:

$$v_c^2 d_d = 0.612m^3s^{-2}$$  \hspace{1cm} (3.4)

giving a critical Weber number of 10 if $\sigma_w = 73.10^{-3}$ and $\rho_g = 1.2$. These relationships show that flow velocities can decrease as the droplet size increases. Therefore for effective mitigation from water deluge the droplets must be very small, less than $10\mu m$, or large, greater than $200\mu m$.[65]

Blowdown.

Blowdown does not actually provide any relief for an explosion, however it is designed to reduce the gas inventory which feeds the gas cloud or leaking jet and reduce the pressure driving the release of gas. Blowdown is usually initiated when a leak of gas is discovered, valves open which send the gas to be burnt at the flare. To avoid overloading the flare there is a systematic ordering system depending on where the gas concentration is detected and which parts of the installation are most at risk. Blowdown can occur from vessels or pipes. If it occurs from a pipe then a significant pressure and temperature drop is observed. If, however, a vessel leaks the pressure drop is insignificant compared to the drop in temperature. These drops in temperature are hazardous because contraction of the vessel may occur.[24] Haque et al. (1992)[24, 25] have developed a model BLOWDOWN to predict the pressure of the vessel, temperatures and amounts of each phase and flow rates. This model is shown to have good agreement with experiments.

### 3.4 Modelling and validation.

With many different groups carrying out experiments using different methods and equipment for recording measurements various conclusions could be reached. Generally there appears to be a consensus on most variables and factors. However current work could have inaccuracies
due to the lack of full scale experimental data and the various approaches taken to validate
the explosion models. The MERGE project (Modelling and Experimental Research into Gas
Explosions) which involves the co-operation of eight research institutions in five countries
should eliminate future inaccuracies and provide an increased understanding of explosions.
This has been followed by the EMERGE project (Extended Modelling and Experimental
Research into Gas Explosions).

3.4.1 Experiments and scaling factors.

Knowledge of the factors and effects stems from observations made during experiments. The
models that follow have their variables based on these observations and have had their accu-
racy validated using the experimental data. Unfortunately due to cost and impracticalities
very little of the data originates from a full size offshore platform. Instead the data available
concerns experiments performed on scaled structures that raises doubts about the applica-

tibility to full size installations. For this data to be of use relationships between small scale
and full size geometries must exist, so that a scaled experiment can reproduce the effects
that could occur on a full size structure. Experiments have the following advantages over
models, scaled or full sized.\cite{58}

- the geometry can be more detailed than with any practicable computational dynamics
  model which use a one metre mesh.

- the fluids and combustion are modelled accurately compared to the simplification of
  numerical models.

- a quantitative pressure-time history at specific locations can be obtained rather than
  an overall maximum overpressure.

- a detailed insight into the development of the explosion allows critical features to be
  identified.

The severity of the explosion effects, especially overpressures, are reduced on scaled versions
due to the smaller distances and lower flame speeds. This has led to research on scaling

techniques with the objective to give results expected for realistic dimensions.\cite{42}
Scaling by oxygen enrichment.

Turbulence has a dominant effect on combustion and on scaled replicas the magnitude decreases resulting in lower flame speeds and overpressures\[^{34}\]. Controlling the turbulence allows the flame velocity to reach levels comparable to those expected on a full size structure. The main parameter determining turbulence is the Karlowitz number, therefore preserving this preserves flame speeds. This is the aim of oxygen enrichment, which is equivalent to preserving

$$\lambda u_l^4 = \text{constant}$$

where \(\lambda\) is the integral turbulence length scale and \(u_l\) is the laminar burning velocity. If the length scale is reduced then the burning velocity increases. Oxygen enrichment of the fuel/air mixture provides a controllable means of obtaining the required change in burning velocity. Experiments show that this type of scaling is successful.

**Fractal scaling.**

This involves consideration of the overall rate of fuel consumption that is given by the product of laminar burning velocity and the surface area of the flame. The hypothesis is that the flame area is similar to a fractal of the Mandelbrot set with dimension \(D\). Details of fractal scaling are given by Mercx et al. (1995).\[^{44}\] Fractal scaling is only appropriate if the flow is effectively incompressible, which is not usually the case with explosions offshore due to the obstacles creating turbulence. However using a less reactive fuel, such as ethane, on a small scale has been shown to behave like the more reactive fuels, such as methane and propane, on a large scale.

**Scaling with laminar flame speed.**

This utilises the fact that the increase in the flame surface area depends upon the velocity ahead of the flame.

$$U_{f_{n+1}} = U_{f_n} \left(1 + \frac{dA}{A}\right)$$

Where \(U_{f_n}\) is the flame speed before the obstacle is encountered, \(U_{f_{n+1}}\) is the flame speed after passing the obstacle, \(A\) is the flame surface area before the obstacle is encountered and \(dA\) is the increase in the flame surface area after passing the obstacle. It was observed,
by Mercx et al. (1995), that the flame speed at the first obstacle encountered by the flame was greater than the laminar flow speed, therefore an enhancement factor, $E_f$, was introduced.

$$U_{f1} = E_f U_l$$

$E_f$ depends on the fuel type and distance between ignition location and the first obstacle. This brings a dependence of the reactivity of gas into the model. This model is not in common use as very little data exists to quantify $E_f$.

### 3.4.2 Types of models.

There are three categories of models employed in explosion research, these are

- Empirical models. These use correlations of experimental data to attempt to extrapolate for real cases.

- Physical models. These describe the physical processes during an explosion with individual sub models, validated against a wide range of data.

- Computational Fluid Dynamic methods. These simulate the explosion at full scale solving numerically the Navier Stokes equations.

### 3.4.3 Empirical based models.

Baker et al. (1996) describe the weakness in the predictions of the pressures in vapour cloud explosions to be the subjectivity of the assumptions and judgements. Three of the main methods for modelling a vapour cloud explosion are TNT equivalence, multi-energy and Strehlow's spherical model which all require an estimate of the energy.

#### TNT equivalence model.

The original model to predict the explosion blast pressures was the TNT equivalence model. Vapour cloud explosions are modelled by using an amount of TNT charge that will produce an explosion with the equivalent energy. The TNT equivalence model has one parameter
which is the mass of TNT used, this basic model is described by the following equation

\[ W_{TNT} = \frac{a WH_c}{E_{TNT}} \] (3.5)

Where \( E_{TNT} \) is the energy generated from an explosion of TNT, \( W_{TNT} \) is the mass of TNT equivalent to the mass of hydrocarbon, \( W \) is the mass of hydrocarbon, \( H_c \) is the heat of combustion of the hydrocarbon and \( a \) is the yield factor. This model is flawed by the lack of clear definition for the yield factor, \( a \). The model can be made more flexible by introducing a second parameter, the height above ground level at which the explosion occurs.\[39\] This model has been widely used due to its simplicity, but has limitations and in many ways is not applicable to gas explosions on offshore structures.

- TNT explosions have short duration whereas a vapour cloud explosion has a much longer duration.\[39\]

- Overpressures were overstated.\[38\] The profile of the peak overpressures from a TNT explosion is higher in the near field and lower in the far field than that produced from a vapour cloud explosion.

- Factors such as confinement and turbulence are neglected in the predictions.

The multi-energy model.

This model was developed by TNO to replace the TNT equivalence model. The multi-energy model uses confinement and obstruction as its major factors in determining blast strength. The model assumes a hemispherical, steady flame speed, stoichiometric hydrocarbon-air explosion. The major drawback is its inability to model jet releases and dispersed gas clouds.\[38\] The method requires the user to make choices between blast curves to determine the energy term on the basis of the degree of confinement, therefore is subjective.\[4\]

Strehlow’s spherical model.

Strehlow’s spherical model is similar to the multi-energy model but requires the user to select the blast curve on the basis of the flame speed.
The Baker-Strehlow method.

The Baker-Strehlow method was developed as a combination of the multi-energy and the Strehlow models and incorporates correlations with experimental data as guidance for choice of parameter.\(^4\)

### 3.4.4 Physical models.

**CMBWAT.**

Madsen et al. (1994)\(^{40}\) detail a computer code based on physical principles to analyse explosive phenomena, called CMBWAT. They claim that it holds for comparison with data sets and is much more accurate than the TNT model. The model was developed specifically to analyse the explosive phenomena, both the detonation and the advance of the related shock wave with time and distance. The code calculates the initial stagnation temperature or the pressure increase and then attenuates the shock wave with distance. The shock wave is calculated from the conservation equations of mass, energy and momentum and the pressure is a function of the shock wave. The analysis solves for spherical or hemispherical blast waves for supersonic shock waves. The code has been validated with experimental results that are more appropriate to the nuclear industry than the chemical industry. It is more accurate at predicting the overpressures than the TNT model but has limitations. CMBWAT calculates the load imparted onto a structure in the reaction zone but does not model the distortion effects of obstacles or effects of ventilation. The model is heavily dependent on the database of 33 substances that it accesses.

**CLICHE.**

CLICHE (Confined LInk CHamber Explosion model) was designed by British Gas\(^1\) to provide a practicable means of performing offshore explosion hazard assessments. The aim was for it to be as fundamentally based as possible so it could be applied to different situations. CLICHE simplifies the partial differential equations (PDEs) which describe the conservation of mass, energy and momentum of the flow to ordinary differential equations (ODEs) for ease of solution. This system of coupled ODEs are solved numerically using a general linear
multi step algorithm. A fundamentally based combustion sub model is used to determine the laminar and turbulent burning velocities. The model is unable to predict the flame distortion directly, the flame shape must be described empirically as a function of geometry and the volume of unburnt gas it encloses. These approximations are valid when applied to a volume with a single vent and when there are no significant spatial pressure gradients. This makes the model invalid in many offshore geometries where there are many obstacles and vents.

**CHAOS.**

CHAOS (Consequence and Hazard Assessment of Offshore Structures) has been developed by British Gas. It consists of a suite of interactive theoretical models which deal with gas build up, explosion loading and response and fire loading and response.[51]

The explosion model incorporated in this package assesses the turbulence generated ahead of the flame and takes into account the obstacles given in the geometry input file. This affects the combustion rate, the effects have been found via experiments. The overpressures are then calculated depending on the flame behaviour during the explosion and the fuel air mixture in the module. This model is not restricted to the worst case scenario of a stoichiometric fuel air mixture, it can also take into account any positioning of the ignition source and estimates the effects of the mitigation system. This model has been validated against $\frac{1}{5}$ and $\frac{1}{3}$ scale experiments and applies to cubical modules.

### 3.4.5 CFD based models

Freeman (1995)[21] discusses the validation of computational fluid dynamics (CFD) based explosion models. Although these models will be cheaper to run than experimental trials there are limitations.

The aim of explosion models is to predict the maximum overpressures generated by the explosion, CFD models are also able to predict other quantities of interest such as the flow speeds and temperature. Comparing the CFD models to experimental results shows up some inaccuracies but using the other quantities predicted, assessment of where the CFD models are failing is facilitated. CFD codes use the $k-\epsilon$ turbulence model to predict the turbulence
within the system. This model was originally developed to model shear layer flows without recirculation, however recirculation is likely to exist in confined regions, therefore the $k - \epsilon$ model is not appropriate. However, as no proven alternative has been found and due to its simplicity it is still widely used. Freeman summarises his assessment by saying that explosions could be modelled with CFD models if the $k - \epsilon$ model is improved or replaced, as the turbulence is not adequately addressed and therefore can not be entirely validated with experimental results. Due to the complexity of the offshore geometries using a fine mesh to resolve all of the details is impracticable. The large difference in scale between the region of influence of the explosion and the relatively much smaller structures within the flame and in the wake of obstacles has led to a need for sub grid models. Sub grid models give approximate mathematical descriptions of the finer details, these are then used to produce the overall picture on the computational grid.

**Hjertager's model.**

Most current models use burning velocity to predict the flame and pressure development this is successful if no obstructions lie in the path of the gas or flame. Hjertager (1991) claims that it is more useful to model propagation by calculating the rate of fuel combustion at different points in the flammable cloud. This is accomplished by utilising the Navier Stokes equations and the time-mean evolution of the time-mean values of the dependent variables to account for turbulence. The $k - \epsilon$ turbulence model is employed. The rate of combustion is modelled according to the eddy dissipation concept, involving a turbulent eddy mixing time scale. Due to the complexity of the geometry on offshore platforms, modelling every detail would require a fine resolution grid. Instead a Porosity Distributed Resistance (PDR) formulation of the governing equations was used which introduces volume fraction and resistance factors. A finite volume procedure was then used to solve the equations. This theory has been validated by comparison with experimental data but it is not easy to implement. Hjertager proposes to improve the combustion model and to develop the PDR formulation for high density obstacle fields.
FLACS.

FLACS (FLame ACceleration Simulator) was a code developed by the Christian Michelsen Institute as a three dimensional gas explosion and dispersion simulator.[5] FLACS is numerically intensive requiring a large computer to solve the three dimensional Navier Stokes equations. A 1m³ control volume is used to solve the equations on a fixed grid, using the hybrid scheme for the convection terms, and a staggered grid for the velocity incorporating a SIMPLE pressure algorithm.[5] The model accounts for interaction between the gas flow and complex geometries. Where geometrical details are too small to be resolved on a numerical grid empirical formulae are used to determine factors such as the flame acceleration. Users of the model must input initial data such as the gas cloud composition, size and location of the cloud, ignition location and specific output parameters required. The model calculates the explosion pressure as a function of time and space, velocity, temperature, density, turbulent parameters and combustion rate. The output data is tabulated and shown graphically (pressure-time curves). The results are first order accurate in time and space. Experimental data compares well, the code has been validated against more than 2000 experiments.[5] Although there may be under or over prediction in some instances the results are within 30-40% of the experimental data.

μ FLACS. This is a PC program based on FLACS. It is designed to assist the user in making correct decisions to limit the consequences of accidental gas explosions. It is easy to use and ideal for sensitivity studies for layouts of plants. It can not be used as a replacement for FLACS as it does not have the same level of detail, it works with a reduced spatial resolution and simplified definitions of the parameters.[5]

EXSIM, COBRA and REAGAS.

The MERGE project investigated the CFD explosion models that five of the involved research organisations had developed.[53] These included COBRA from British Gas, FLACS from Christian Michelsen Institute, EXSIM from Telemark Technological Research Development Centre (Tel-Tek), REAGAS from TNO Prins Maurits Laboratory and GEISHA from Imperial College. GEISHA is omitted from these discussions as it is a general CFD code with no specific intentions. COBRA, FLACS, EXSIM and REAGAS all solve for the Navier
Explosion modelling techniques.

Stokes equations; conservation of mass, momentum and energy. All use sub models to describe the physical processes which occur at scales below the computational grid, and all use the $k - \varepsilon$ turbulence model. However differences do exist in the solution procedure. EXSIM, FLACS and REAGAS solve the energy equation in terms of enthalpy whereas COBRA solves for total energy. COBRA uses the second order explicit Godunov method to solve for the convection terms on an adaptive grid, whilst the others use the hybrid scheme incorporating the SIMPLE pressure algorithm on a fixed grid. The varying mathematical bases lead to different accuracy levels in the numerical solution. EXSIM and REAGAS are first order, FLACS is second order for flame tracking and COBRA is fully second order.

The models vary most in their empirical sub models (sub models are necessary for modelling the flame), the turbulent combustion, the drag and the turbulence. The models have used varying techniques and in cases with the same method have used differing constants, in order to get consistent agreement with the experimental data available to them. The models were all compared on the same data and all successfully demonstrated a consensus. The aim of the work by the MERGE project\cite{53} was to develop a unified approach to explosion modelling, therefore the major differences in the sub models have been eliminated, however subtle differences do still exist retaining a level of empiricism.

Commercial Codes.

Many commercial CFD packages are on the market, such as FLUENT, PHOENICS and FLOW3D. These are all highly sophisticated three dimensional numerical codes which require a lot of computer processor time. The codes are multi purpose with an emphasis on the characteristics of flow. Generally the packages have the required data for the main gases and water, but the user must be aware of the chemical background of the fluid in question. It is possible to model an explosion using these packages but due to their general nature sub models do not exist, hence the geometry must be completely resolved on the grid, which requires an extremely fine mesh in most cases and extensive computer time.
3.5 Discussion.

The main consequence of an explosion on an offshore platform is the generation of high overpressures which may reduce the integrity of the platform structure. Overpressures are caused by high flame speeds propagating in confined and congested regions. For any model to represent effectively the overpressure generation it must include the following as factors; the ignition location, gas cloud concentration, ventilation, mitigation, congestion and confinement.

The most complete analysis would come from a set of experiments performed on a full scale replica of an offshore platform under varying environmental conditions. However this is impractical in terms of resources, therefore scaled versions have been employed incorporating various scaling techniques such as those described in Section 3.4.1.

Empirical based models provide a very general overview of the situation, but such models do not account for the complexity of the offshore geometry.

Physical models use sophisticated mathematical techniques coupled with experimental data to model the overpressure generation. In most models assumptions must be made to simplify the calculation procedure because it is difficult to account for all the contributory factors unless reliable data is known and extensive computer processor power available.

CFD based models are useful modelling techniques to take account of all factors. However these also require reliable data and large amounts of computer processor power. Specific CFD codes written for offshore geometries are necessary as commercial codes are unable to completely resolve the geometries in a reasonable amount of processor time.

If an estimate of the overpressure generation is the only variable under consideration during an explosion then physical models combining experimental data are adequate modelling techniques.
4. Dispersion modelling techniques.

4.1 Introduction.

Emission and vaporisation are followed by the dispersion of the gas to form a vapour cloud. When discussing the nature and effects of an explosion an important factor is the contact between the ignition source and the vapour cloud.

On an offshore platform there may be obstacles, confining walls and varying wind speeds and directions. Therefore the vapour cloud is unlikely to build up with uniform concentration throughout the module. The aim of this chapter is to consider the influencing factors and different modelling techniques available in order to determine a concentration profile for a module on an offshore platform.

4.2 Influencing factors.

Dispersion situations are varied. Lees (1996)[39] provides a comprehensive review of factors affecting the dispersion of a gas, these are

- Fluid buoyancy
- Momentum
- Source geometry
- Source duration
- Source elevation
- Meteorology
- Topography
Dispersion modelling techniques.

The buoyancy of the fluid depends on the density of the released gas and the initial mixing with the air. Gases are said to be neutrally buoyant when their density is close to that of air or when the concentration of the gas is low. The dispersion of gases which are neutrally buoyant is known as passive dispersion, where the external wind disperses the gas.

Lighter than air gases have positive buoyancy, these gases have low molecular weights and are usually hot gases. Such gases tend to rise rapidly. Denser than air gases have negative buoyancy, these gases tend to slump to the ground.

The momentum of the release is dependent on the release conditions, high pressure releases lead to greater momentum. If the release has low kinetic energy then it is likely that a plume will be formed which results in the slow mixing of the gas and air. Whereas a high kinetic energy release forms a momentum jet with defined shape. A high momentum release will increase the amount of air entrained into the gas cloud, which in turn affects the density of the cloud. The momentum force will be dominant for a while before the cloud is classed as a plume.

Breaks in pipes cause leaks, these are point sources when the subsequent gas cloud originates from the break. Alternatively liquid could drop to form a pool in which case the source is referred to as an area source.

The duration of the leak can be continuous, instantaneous or intermediate. A continuous source is usually associated with a constant release rate, as the gas disperses a plume is formed. An instantaneous release will only last for a matter of seconds forming a puff. Most accidental sources fall into the intermediate category, such releases last for a while but with a time variable release rate. From pressurised containers, this flow rate usually follows an exponential formula with time.\(^\text{[23]}\)

The elevation of a source is most important if dealing with atmospheric releases. An elevated source of buoyant gas is advantageous as it will disperse to atmosphere much quicker. A ground level source of dense gas is more hazardous as it will follow the contour of the land as it disperses.

Apart from the above factors, in order to model dispersion accurately the chemical composition of the gas must be known.
4.2.1 Source data.

Hanna and Drivas (1987) state that in order to model the dispersion of a gas the chemical composition must be known. This includes knowledge of the molecular weight, diffusivity, conductivity, boiling point, thermal conductivity, density and specific heat. In addition the release rate is required which is related to the geometry of the source.

The source of a release on an offshore platform is natural gas, the composition of this is approximately 95% methane with the remaining 5% consisting of denser products such as ethane and propane and lighter products such as nitrogen. Methane is a hydrocarbon with an explosive range of approximately 5% to 15% gas in air by volume. The density of methane is $0.667 \text{kg m}^{-3}$ which means that, with air having a density of $1.2 \text{kg m}^{-3}$ at its ambient temperature, natural gas will behave with positive buoyancy.

The majority of leaks on offshore platforms come from flange failures in pipes, these provide high pressure releases from small diameter orifices. Hence the most appropriate scenario is a high momentum jet from a point source which will have a decaying release rate and will form a plume further away from the source.

4.2.2 Geometry and meteorology.

The build up of gas depends on the release rate and the volume within which it is accumulating. A release into a fully enclosed region is the worst case scenario, there is no means of dispersing the gas cloud. On offshore platforms the leaks will occur into regions which are semi confined, include obstacles and are ventilated by the wind.

Confinement.

Experiments show that a horizontal jet will widen more rapidly in a confined region than in free air. The dilution rate of the released material has been observed to be less in confined jets than in free jets.
Obstacles.

Obstacles in the paths of jets leads to modifications in the flow and formation of the gas cloud. Important parameters in determining this behaviour are the width and angle of incidence of the jet impacting on the obstacle and the dimensions and shape of the obstacle. A small obstacle in the path of a large jet will exert little drag on the flow and will have negligible effect. However a bigger obstacle may divert the jet. In this case the pressure field exerted by the jet will cause the flow to follow the sides of the obstacle. This tendency to adhere to the obstacle is greater if the obstacle is smooth. As the flow is passing the rear of the obstacle the flow is likely to recirculate into the jet forming a slightly wider flow, this will have reduced momentum due to the drag exerted by the obstacle. An obstacle that is much larger than the diameter of the jet will cause the flow to form a radial fan or a wall jet.

Ventilation.

The dispersion of a gas cloud is heavily dependent on the ventilation. The main source of ventilation is the wind. The principal characteristics are direction, speed, persistence and turbulence. Wind direction and speed are summarised from measurements in a wind rose. A wind rose is a polar diagram where the lengths of the spokes depict the frequency of that speed occurring in that particular direction. The persistence of the wind is a measurement of the directional constancy. If the wind is strongly directional the area over which the gas cloud is formed may be reduced in the up wind direction but more complex in the down wind direction\(^{23}\). Generally the wind is classified in terms of stability, the simplest cases are stable, neutral and unstable. Dispersion is greatest in unstable conditions.

Cleaver et al. (1994)\(^{14}\) describe two limiting cases between which all release situations fall. These are small releases dispersed by the internal flows of the structure and large releases which produce flows which will dominate the internal flow. The existence of internal air movements ensures that minor leakages do not lead to a substantial build up of gas.
4.3 Cloud build-up.

The release of gas will not immediately form a vapour cloud. Initially the release may be described as a puff, plume or jet depending on the momentum of the release. As the release continues into an enclosed region a vapour cloud is formed.

4.3.1 Entrainment.

When confining surfaces are present entrainment of the external air is prohibited so that the gas cloud does not build up uniformly. When the velocity of the release jet is the same order as the velocity of the air flow then recirculation regions are set up. The width and height ratio of the module directly influence whether recirculation areas can occur and whether they will occupy the whole of the module or just a section. Offshore modules contain a lot of processors and pipe work as well as confining walls therefore many recirculation regions are expected. When recirculation occurs the release material is drawn back into the cloud therefore building up the concentration in this area. This is known as a primary cell. Depending on the buoyancy of the release further recirculation cells may appear.

4.4 Dispersion models.

Hanna and Drivas (1987)[23] state that it is generally assumed that accidental releases of gas on an offshore platform will initially form a jet due to the dominant momentum. The jet will lose momentum as it entrains air and behave as a plume. Length scales have been established to determine the point at which the release ceases to behave like a jet and buoyancy forces take over producing a plume. It is normally assumed that if the jet was travelling in a horizontal direction it would turn upwards at this point.

Briggs (1975)[11] calculates the maximum distance travelled by the jet before it turns by utilising the wind speed and the initial velocity of the release

\[ L = 4.8 \frac{u_0 r}{u} \]  

where \( u_0 \) is the initial velocity of the release (\( m s^{-1} \)), \( r \) is the initial radius of the jet (\( m \))(i.e. the radius of the release hole) and \( u \) is the wind speed (\( m s^{-1} \)).
Dispersion modelling techniques.

Cleaver and Edwards (1990)\textsuperscript{[13]} define the distance the jet will travel before it becomes a plume to be

\[ L = d \sqrt{\frac{\rho_g u_0^2}{\rho_a u^2}} \] (4.2)

where \( \rho_a \) and \( \rho_g \) are the densities of air and gas respectively. In a further paper by Cleaver et al. (1994)\textsuperscript{[15]} the length was defined in terms of the Richardson number, \( R_i \)

\[ L = \frac{3r_j}{\sqrt{R_i}} \] (4.3)

However this definition of the length scale uses the mean radius of the jet, \( r_j \), which is dependent on the wind speed and direction and is typically found experimentally.

The Richardson number is defined in terms of the densities of air and gas, \( \rho_a \) and \( \rho_g \), the gravity, \( g \), the radius of the leak hole, \( r \) and the initial velocity of the jet, \( u_0 \)

\[ R_i = \frac{rg(\rho_a - \rho_g)}{u_0^2 \rho_a} \] (4.4)

Considering the Richardson number also determines whether or not dense gas effects can be ignored. Richardson numbers less than 10 imply that the flow is buoyant, this is to be expected on offshore platforms.

Once the length scale for changing models has been determined care must be taken to ensure that the mass of gas is conserved and that the peak concentrations and the plume dimensions match. The plume model should only be used where initial jet effects have become unimportant. Hanna and Drivas\textsuperscript{[23]} do not recommend using a plume model less than 100m from the source as it can create additional uncertainty when dealing with gases that could have dense gas properties.

### 4.4.1 Basic models.

Initial methods for determining the dispersion of gases were based on the fundamental diffusion equation

\[
\frac{\partial c_g}{\partial t} + u \frac{\partial c_g}{\partial x} + v \frac{\partial c_g}{\partial y} + w \frac{\partial c_g}{\partial z} = K_x \frac{\partial^2 c_g}{\partial x^2} + K_y \frac{\partial^2 c_g}{\partial y^2} + K_z \frac{\partial^2 c_g}{\partial z^2} \] (4.5)

where \( K_x, K_y \) and \( K_z \) are diffusion coefficients, \( u, v \) and \( w \) are the mean wind speeds in co-ordinate directions \( x, y \) and \( z \) and \( c_g \) is the concentration of gas. The diffusion coefficients
are found for specific situations experimentally, empirical relations are used to extrapolate these to other situations. The following modelling techniques are based on this equation and prove to be very limited and basic. They have no means of dealing with obstacles, confinement or ventilation and neglect convection. However they were the building blocks upon which further advanced models were based.

Diffusion equation models.

Gradient transfer models are direct solutions of the diffusion equation. These usually require numerical solutions. Statistical models are obtained by representing the diffusion coefficients by a constant \( K \). Then an analytical solution may be found. The concentration profiles may be represented by a Gaussian distribution which is characterised by the standard deviations. These are known as dispersion coefficients, \( \sigma_x \), \( \sigma_y \) and \( \sigma_z \).

Dimensional models.

Similarity models consist of an equation derived from dimensional analysis of the rate of increase of some characteristic dimension of the cloud. In order to learn anything from this model regarding the concentration distribution additional relationships are necessary. These are gained empirically.

Top hat models represent the cloud in the shape of a 'top hat', therefore implying that the cloud has a defined height throughout the region. The box model treats the cloud as a vertical cylinder with uniform concentration at any given time. The slab model assumes that the concentration is a function of distance away from the source. The main application of these models is with dense gases.

4.4.2 Passive dispersion.

Passive dispersion is the dispersion of neutral and buoyant releases, sometimes referred to as atmospheric dispersion. Passive dispersion models include the Roberts model, the Sutton model, the Pasquill model and the Pasquill-Gifford model which are based on the basic diffusion models described above. These models lead to the Bi-Gaussian distribution for the
Dispersion modelling techniques.

description of plumes.

Roberts model.

This model uses the fundamental equation for diffusion as a basis, developed in 1923 by Roberts it was one of the earliest well used models for dispersion. The Roberts model, for a continuous point source when the dispersion is anisotropic when $W$ is the source term, gives the concentration of the gas cloud as

$$c_g(x, y, z) = \frac{W}{4\pi x (K_x K_y)} \exp \left[ -\frac{u}{4\pi} \left( \frac{y^2}{K_y} + \frac{z^2}{K_z} \right) \right]$$

(4.6)

There are limitations involved with the Roberts model. Firstly it relates to elevated sources, any ground level releases will give double the concentration. Secondly the equations for continuous sources are steady state and hence only apply to fully established plumes. Any time varying continuous sources are not catered for. Finally the model does not hold with experimental results. The Roberts model assumes that $c_g \propto x^{-1}$ whereas experiments give $c_g = x^{-1.75}$.

Sutton model.

This model, based on Roberts model, was developed by Sutton in 1953. The model incorporates a diffusion index, $n$, and diffusion parameters, $C_x$, $C_y$ and $C_z$, which are meteorological parameters. The diffusion parameters are functions of the height above the ground and the stability conditions. Common values for these are between 0.21 and 0.09 for elevations of 0m to 50m with wind speeds of 5ms$^{-1}$. The diffusion index is a function of the stability conditions which ranges between zero and one (0 indicating high turbulence and 1 indicating negligible turbulence), on average this is taken to be 0.25.

Although this model is an improvement on Roberts model by accounting for ground level sources and incorporating turbulence as a factor, the other limitations still exist.
4.4.3 Plume modelling.

The models used to describe passive dispersion have led to solutions similar to the Bi-
Gaussian distribution. Most models for the dispersion of neutral density gases are based
on this distribution. The Bi-Gaussian distribution is a three dimensional, symmetrical bell-
shaped distribution and is specifically appropriate for releases of gas into unconfined regions.
The models may have to be abandoned for confined regions where the cloud grows to such a
size that entrainment is expected due to the impingement of the cloud on walls and obstacles.

The Bi-Gaussian distribution is recommended by the American Environmental Protection
Agency (EPA)[11] for application to positively buoyant releases of gas. For a continuous
source

\[ c_y = \frac{W}{2\pi \sigma_y \sigma_z} \exp \left[ -\frac{1}{2} \left( \frac{(y - y_0)^2}{\sigma_y^2} + \frac{2(h - z)^2}{\sigma_z^2} \right) \right] \]  

(4.7)

where \( h \) is the elevation of the plume centre line above the ground, \( y_0 \) is the lateral cross-
wind position of the centre line and \( \sigma_y \) and \( \sigma_z \) are dispersion coefficients. The dispersion
coefficients are defined as functions of the meteorological conditions, release height, surface
roughness, source distance and time. The dispersion coefficients are different to the diffusion
coefficients in that they account not only for the diffusion of the gas into the air but
also the convection. When wind is a factor in determining the dispersion it is important to
consider the convection, therefore models using dispersion coefficients are more appropriate
than those applying diffusion coefficients. Dispersion coefficients can crudely account for ob-
stacles due to their dependency on surface roughness, however variations in the coefficients
are made according to the results of experiments. The dispersion coefficients are sometimes
estimated directly from turbulence measurements which are made under strict experi-
mental conditions with a known release inventory. Vanderborght and Kretzschmar (1984)[63]
consider alternative methods utilising tracer experiments.

Pasquill and Gifford have modified the Bi-Gaussian dispersion model for instantaneous and
continuous sources, these models have the origin of the co-ordinate system fixed at the source.
For continuous sources this model gives

\[ c_y = \frac{W}{\pi \sigma_y \sigma_z} \exp \left[ -\frac{1}{2} \left( \frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2} \right) \right] \]  

(4.8)

Pasquill (1961) determined \( \sigma_y \) and \( \sigma_z \) from tracer experiments and wind direction fluctu-
ations, for specific distances, emission heights and terrain roughness. These results are
Dispersion modelling techniques.

Tabulated, dispersion coefficients for further situations can be found by extrapolation. The inclusion of emission height and distance in the calculation of dispersion coefficients accounts for the differences between the Pasquill-Gifford model and the Bi-Gaussian model.

Högstram (1964) has demonstrated experimentally that $\sigma_z$ is a function of the vertical temperature gradient and the square of the wind speed and that $\sigma_y$ is dependent on the stability of the wind direction and the thermal stability. Bultynck (1972) obtained similar values for $\sigma_y$ and $\sigma_z$ to Pasquill’s. However there were slight differences in the values which was emphasised by the concentration profiles obtained. Briggs (1973) suggested formulae for $\sigma_y$ and $\sigma_z$ which are dependent on the weather stability, these are of the form

$$\sigma = ax(1 + bx)^p$$

These values, gained experimentally, are tabulated according to the terrain and stability class. Pasquill’s stability classes relating to the meteorological situation are used. Here class A corresponds to extremely unstable conditions, class D refers to neutral conditions and class F has moderately stable conditions. Typical values of $\sigma$ for class D are:

$$\sigma_y = 0.08x(1 + 0.0001x)^{-\frac{1}{2}} \quad \sigma_z = 0.06x(1 + 0.0015x)^{-\frac{1}{2}}$$

4.4.4 Physical modelling.

The majority of jet modelling has been conducted via physical models. These attempt to solve the conservation mass, momentum, energy and species equations by using correlations and simplifications.

Cleaver and Edwards (1990)[13] detail an integral model, designed by British Gas, for predicting dispersion and provide experimental data as a comparison. The model predicts the dispersion of a turbulent jet which is emerging into a cross flow wind with no obstructions. Nine equations concerning nine unknowns require solution in order to determine the concentration on the centre line of the jet. Various profiles can be used to relate the centre line values to the bulk values. The developers of this model have chosen a cosine profile which brings in another four equations. The model is only applicable to jets and is therefore appropriate in the ‘near field’ before atmospheric turbulence dominates, it makes no allowance for obstructions and has been designed as a means to model vertical releases. Comparisons with experimental results show that the trajectory and concentration decay are in agreement.
Dispersion modelling techniques.

The model is appropriate for determining the dispersion of gases when they are released from vertical stacks.

Caulfield et al. (1993)[10] build on the previous integral model by introducing the $k - \epsilon$ turbulence model (this model is discussed in Chapter 9). This is necessary if concentration fluctuations are to be predicted, rather than the mean concentrations. The model consists of 6 ordinary differential equations which are solved using a Runge-Kutta technique. These equations are the conservation of mass, conservation of momentum in the horizontal and vertical directions and the $k - \epsilon$ transport equations. Predictions of the model agree well with experimental data.

In a totally confined enclosure or one with nominal ventilation not only must the behaviour of the jet be considered but also the impact and interaction with the walls. Cleaver et al. (1994)[15] state that the behaviour of the jet and the build up of the concentration can be calculated from nine parameters; density of gas, $\rho_g$; density of air, $\rho_a$; radius of leak hole, $r$; volume flux, $Q_0$; specific momentum flux, $\omega$; buoyancy flux, $B$; volume of enclosure, $V_m$; cross-sectional area of the enclosure, $A_m$ and the distance from the leak to the wall, $x_w$. This model assumes that the gas will disperse to produce an upper well mixed layer of depth $h_1$ which remains at a constant height from the ceiling downwards. Beneath this the gas will begin to concentrate forming a layer of depth $h_2$, which increases to a maximum of the enclosure’s height minus $h_1$. Equations for the conservation of gas are established and require solving to gain knowledge of the concentration build up. This model is appropriate for enclosures with nominal ventilation provided that they are cubical in shape. It provides an accurate representation of the maximum concentrations in the upper layer and a 95% accuracy for the depth of the layer. However the model does not account for stratification which exists in the lower layer. A more sophisticated approach is required.

Consequence and Hazard Assessment of Offshore Structures (CHAOS).

CHAOS is a suite of software developed by British Gas[51]. This is designed to assess the consequences of the hazards on offshore structures. The package models fires, thermal loading, dispersion, explosions and blast loading and looks at the response to such events.

The dispersion model accounts for jet releases driven at steady or decaying pressure through
Dispersion modelling techniques.

a circular orifice. The dispersion of the gas with the air is then determined. This model uses the technique of Cleaver and Edwards[13] to assess the trajectory of the jet and its interaction with obstacles. The build up of gas is considered to occur differently within four zones. The module is split into zones and the amount of blockage from obstacles and subsequent levels of ventilation are determined for each zone. Therefore this model does not estimate the literal concentration build up, however the zone method provides good estimates of the bulk concentration build up within a module.

The model is applicable to releases from hole sizes between 10mm and 50mm diameter into modules with aspect ratios of 4 : 2 : 1 or 2 : 2 : 1 (length:width:height), the developers do not recommend extrapolation for other situations. The model has been tested against experimental and observational results, these showed that the release rates were accurate however the ventilation rates were not for strong directional high wind speeds.

PHAST Professional.

PHAST Professional is a software product designed to give a collection of consequence models for hazard analysis. This model may be used at any time in the operation of a process plant, however it will have more value in the design and planning stages. Discharge, dispersion, fire and explosion effects are modelled mathematically to calculate the consequences of hazardous releases. The main emphasis is the dispersion to the atmosphere. Confined releases are assumed to uniformly fill the confined region which in turn provides a new source to leak to the atmosphere. Hence this package is not appropriate for modelling the dispersion of the gas in air within the confined region as required for this scenario.

4.4.5 CFD modelling.

Computational fluid dynamics involves solving the conservation equations and the transport equations explicitly.
McBrien (1993)\cite{411} used PHOENICS to model the dispersion of a high pressure natural gas release into crosswinds. The release came from a 13.2\textit{mm} diameter hole at pressures several times greater than the ambient pressure, therefore the scenario initially led to a jet. The release was modelled as vertical into crosswinds of speeds ranging between \(1.35m/s\) and \(3.34m/s\). PHOENICS is a commercial code which was used to numerically simulate the dispersion with the continuity, momentum, energy and species equations. These standard flow equations provide a simplified version of the model equations required to simulate the under expanded sonic jet immediately downstream. The standard PHOENICS flow model solves the incompressible form of the equations, hence ignoring turbulence. Incorporating any enhancements terms to account for the random variation of turbulence led to less stable solutions when compared to experimental data. Assuming that the effects of turbulence, viscosity, thermal conductivities and specific heats are negligible limits the applicability of the model to situations where the source to atmospheric pressure ratio \(\frac{P}{P_a} = 2.4\).

The transport equations were solved over relatively large control volumes on a Cartesian grid. The model predicts non dimensional concentration values to within ±25\% of experimental values in the regions of the jet where momentum still dominates the flow.

### 4.5 Discussion.

In order to model effectively the concentration build up of gas on an offshore platform it is necessary to either have experimental data for the specific situation or to use a computational fluid dynamic approach. In order to use the integral models and CFD we must know the dimensions of the module that the gas is leaking into, the meteorological conditions, the position of obstacles, the degree of confinement and the potential positions of the accidental release in relation to the location of obstacles.

If there is no effect from the wind and the momentum of the release is low (i.e. a plume is expected) then the diffusion equations can be used to model the diffusion of the gas in the air. However the wind is of a strength that can not be ignored so convection of the gas is expected leading to models which use dispersion coefficients rather than diffusion coefficients. The
wind is also of variable direction and invariably creates turbulent effects within the module therefore leading to integral/physical models.

The gas released offshore is predominantly methane, this is a buoyant gas which will tend to rise into the atmosphere. A release into an unconfined, obstacle free region could effectively be modelled using atmospheric dispersion techniques. This would lead to Bi-Gaussian distributions skewed according to the strength and direction of the wind. If the gas contains components which imply that the release may have dense gas effects then dense gas models would apply. However it is unlikely that the dense gas effects would be strong enough to cause the release to slump to ground level. It is expected that the dense gas effects would be outweighed by the buoyant effects leading to a predominantly buoyant state or a neutral/passive state.

Due to the momentum of the release from high pressure vessels, the leak will begin as a jet. The jet models discussed either do not account for obstacles or have in built coefficients based on experimental data for a particular scenario. Recirculation and entrainment occur when obstacles are in the near field of the jet. To model this effectively the distance from the origin of the leak to the first impact must be known along with the density of the obstacles in the region, even if this is known current models do not appear to be able to cope with any situation apart from those it was designed to model.

Once the jet is modelled sufficiently there will be a point when the momentum effects are dominated by buoyancy. A such distances a plume modelled must be incorporated, however care must be taken to ensure that there is continuity between the two models.
5. Optimisation techniques.

5.1 Introduction.

The design of any engineering system is an iterative process beginning with preliminary design followed by analysis, appraisal and redesign. These steps are carried out using engineering judgement, operational experience and must adhere to relevant system safety requirements. Once an adequate design is selected optimisation processes may be adopted to produce the best design possible. Optimisation is not restricted to the design process, it may be carried out at any stage of the life of the system.

Once an offshore structure is operational it is impractical to consider redesign of the layout as a means of minimising the risk it poses. It is reasonable to consider the types of components used in the safety systems and determine whether any improvement in their unavailability will reduce the risk. The risk to be considered is the exceedence of an overpressure of 3 bar, the frequency of which is obtained through the prediction tool SAROS (see Chapter 6). Due to the complexity of SAROS, it will be regarded as a 'black box' model. The types of components used are identified by integer variables. There will be no algebraic constraint function for the problem, although there will be a limit placed on the cost of altering the nature of the components.

This chapter looks at the optimisation process and the various techniques available to optimise a system. The techniques appearing appropriate to the requirements of the problem discussed are summarised and evaluated in terms of applicability.

5.2 The optimisation process.

Optimisation is accomplished by defining an objective function to approximate the system behaviour and minimising this subject to constraints. The solution generated will only be optimum within the framework of the assumptions made, design variables selected and the
Optimisation techniques.

constraints specified. The classical optimisation problem is defined as

\[
\min Q(x) \quad (5.1)
\]

subject to \( g_i(x) \geq 0 \quad i = 1, \ldots, m \) \quad (5.2)

\( h_j(x) = 0 \quad j = 1, \ldots, p \) \quad (5.3)

The objective function, \( Q(x) \), must be minimised subject to the \( m \) inequality constraint functions, \( g(x) \), and the \( n \) equality constraint functions, \( h(x) \), using the design vector, \( x \), to provide a solution vector \( x^* \). Optimisation problems may be ones of maximisation, these can be converted to minimisation problems, as seen in Equation (5.4) and treated in the same way as the classical problem.

\[
\max Q(x) = -\min -Q(x) \quad (5.4)
\]

Optimisation problems are typically approached assuming that \( x^* \) exists and is unique, however this does not hold in all situations. It is only practical with most methods to assume that the solution located is a local minima \( \hat{x} \) and not necessarily the global minima \( x^* \). The local solution to the optimisation problem satisfies the condition (5.5)

\[
Q(x) \geq Q(\hat{x}) \quad \forall x \quad \text{sufficiently close to } \hat{x} \quad (5.5)
\]

If it is known that the solution found may be local and the global solution is required then global optimisation schemes are available.

The classical theory of unconstrained optimisation finds a minimum of \( Q(x) \) where all first partial derivatives,

\[
\frac{\partial Q}{\partial x_i} \quad \text{exist} \quad \forall i
\]

with a necessary condition

\[
\frac{\partial Q}{\partial x_1} = \frac{\partial Q}{\partial x_2} = \ldots = \frac{\partial Q}{\partial x_n} = 0
\]

and a sufficient condition that

\[
\frac{\partial^2 Q}{\partial x_j \partial x_k}
\]

exists at this point, \((j, k = 1, \ldots, n)\), and the Hessian matrix is positive definite.

Solving a constrained optimisation problem with equality constraints requires use of the Lagrange multipliers. The Lagrangian is defined for problem (5.1) with constraints of the form of (5.3) as

\[
L = Q(x) - \sum_{\forall j} \lambda_j h_j(x) \quad (5.6)
\]
The solution must satisfy
\[ \frac{\partial L}{\partial x_1} = \ldots = \frac{\partial L}{\partial x_n} = 0 \quad h_j(x) = 0 \quad (5.7) \]

The Lagrangian is used to convert a constrained problem to an unconstrained one.

Should the constraints include inequalities slack and surplus variables may be introduced to convert the problem to one involving equality constraints. The Kuhn-Tucker conditions are then used to obtain a Lagrangian.

This classical approach may only be used if an objective function is known. The type of objective function and constraints determines the optimisation algorithm employed to obtain a solution.

There are two main areas of optimisation theory; mathematical programming and variational methods. Pike (1986)\(^{50}\) describes the differences in these techniques and provides an introduction to the two areas. The differences in these categorisations is the manner in which the objective is defined. The objective of mathematical programming is to locate the best point that optimises the model of the process. In general these methods are used to optimise steady state problems. The objective of variational methods is to locate the optimal function that optimises the model, this is typically required of dynamic problems and the most common solution method is that of calculus of variations. Extensions to mathematical programming are evolutionary procedures which consider the natural evolution of selection and optimisation over time as a basis.

The optimisation problem under consideration requires a point solution rather than an optimal function therefore requires a mathematical programming method or an evolutionary procedure.

### 5.3 Mathematical programming.

There exists a variety of mathematical programming methods which can be classified as direct or indirect methods. Direct methods include multi-variable searches and linear programming, these move from a starting point to an optimum solution. Indirect methods such as analytical methods and geometric programming rely on solving a set of algebraic equations to generate a solution which may be the optimum of the model.
Optimisation techniques.

Analytical methods use the classical theory of maxima and minima to identify the extreme points of a function. Geometric programming is an extension of this. Both methods require a well defined objective function, hence indirect methods must be neglected when no specific algebraic objective function exists.

The basic optimisation methods are direct searches, these are simple techniques which prove valuable when solving unconstrained problems. When dealing with constraints one of the most common direct mathematical programming methods is linear programming. This method requires having a linear objective function optimised with linear constraints and is most effectively solved using the SIMPLEX method. If the objective function is quadratic but the constraints remain linear then quadratic programming techniques are available. These involve converting the problem to a linear programming problem for solution with the SIMPLEX method. Dynamic programming is a technique which uses a series of partial optimisations to solve the problem. When the problem involves a non linear objective function or an undetermined function, such as a computer program which uses specified inputs to produce an output, non linear programming or multi-variable search methods may be used. These are based on simple search methods which begin at a feasible starting point and move to the optimum following a search plan. Integer programming is an extension of linear programming where the variables take on discrete values, these problems are commonly adapted to linear programming problems by techniques such as the branch and bound method. Combinatorial programming is often seen as a technique which encompasses the other methods, it includes linear, integer and dynamic programming techniques. This method is used when the solution involves choosing from subsets of the variables. The final mathematical programming method discussed is heuristic programming which uses rules of thumb to approximate an optimisation technique.

5.3.1 Simple search techniques.

Search methods of optimisation are simple to implement and may be used for complex problems where the model and constraints are in the form of a computer program rather than a specific equation, commonly referred to as ‘black box’ models.

Search problems are classified by the number of independent variables and by the presence of random error. Deterministic problems have no experimental error or random factors present.
as they usually are mathematical models of processes where the outputs are calculated by computer program from specified inputs. Stochastic problems have random error present usually in the form of experimental errors.

Single variable deterministic problems have powerful solution techniques based on the minimax principle however there are no comparable multi-variable techniques.

The efficiency of search techniques is reliant on the search plan. This is the set of instructions for performing n sets of experiments, these may be simultaneous or sequential. An experiment consists of specifying one set of values of the independent variables and determining the values of the output. Sequential searches involve the outcome of one experiment to determine which experiment to do next. Generally when implementing a simple search to optimise a problem the initial interval of the independent variable is known, this is known as the initial interval of uncertainty. The search plan involves a procedure to reduce this interval of uncertainty, this may be accomplished by placing experiments in a manner that will eliminate parts of the initial interval that do not contain the optimum. The best search plan is desirable to avoid unnecessary experiment evaluations. A measure of the effectiveness of the search plans is necessary, this must be independent of the function being optimised to avoid any functional dependencies arising.

These search plans are extremely effective for problems of one variable, which are unimodal and when the approximate location of the optimum is known.

### 5.3.2 Linear programming.

A typical linear programming problem has the standard form of

\[
\min \sum_{i=1}^{n} c_i x_i \quad (5.8)
\]

subject to

\[
\sum_{i=1}^{n} a_{ij} x_i = b_j \quad j = 1, \ldots, m \quad (5.9)
\]

and

\[
x_i \geq 0 \quad i = 1, \ldots, n \quad (5.10)
\]

The standard form has m linear equality constraints and is subject to non negativity conditions. Should the constraints be inequalities slack and surplus variables may be introduced
to convert the problem to the standard form.

\[
\text{slack } \sum_{i=1}^{n} a_{ij}x_i \leq b_j \quad \text{gives} \quad \sum_{i=1}^{n} a_{ij}x_i + y_j = b_j
\]

\[
\text{surplus } \sum_{i=1}^{n} a_{ij}x_i \geq b_j \quad \text{gives} \quad \sum_{i=1}^{n} a_{ij}x_i - y_j = b_j
\]

where \( y_j \geq 0 \). Variables which are not required to be non-negative can be transformed via

\[
x_k = u_k - v_k \quad k = 1, \ldots, p
\]

where \( u_k \geq 0 \) and \( v_k \geq 0 \). Substituting this form retains the linear form of the problem and requires all variables to be non-negative. This problem now has \( n + p \) variables and a degree of redundancy since the representation of \( x_k \) is not unique. To rectify this an alternative would be to eliminate \( x_k \) by using a constraint equation and writing \( x_k \) in terms of the other non-negative variables giving the standard linear form with \( n - p \) variables and \( m - p \) constraints.

The most widely accepted method for solving linear programming problems is the SIMPLEX method. This is a well documented technique with specific texts on the method (Murty (1976)[47], Lau (1988)[37] & Sultan (1993)[61]) and most general texts on basic optimisation have chapters dedicated to it (Pike (1986)[50] & Fletcher (1987)[20]).

5.3.3 Non linear programming and multi-variable searches.

Multi-variable search methods encompass the theory and algorithms of non-linear programming which use algorithms based on geometric or logical concepts to move rapidly from a starting point to the optimum. The most basic yet time consuming method is that of a random search which divides the feasible domain into discrete regions and then places the experiments randomly.

There are essentially six types of procedures to solve constrained non-linear optimisation problems. Four of which convert the constrained problem to unconstrained ones these are penalty or barrier function methods, augmented Lagrangian functions, generalised reduced gradients and feasible directions. The other two methods are successive or sequential linear and quadratic programming.
When dealing with an unconstrained problem simple gradient searches may be used. Quasi Newton methods and conjugate gradient methods require the objective function to be a differentiable function so that the search can progress in the direction of the lowest gradient. Logical methods begin with local exploration and attempt to accelerate in the direction of success.

Successive linear programming begins by selecting a starting point and linearising the model and constraints about this point. This is then solved as a linear programming problem to obtain an intermediate solution. The model is then relinearised about this point and the method repeated until convergence is obtained. Successive quadratic programming works in the same manner with the model being transposed into a quadratic model and the constraints being linearised allowing quadratic programming methods to be applied.

5.3.4 Integer programming.

Integer programming is an extension of linear programming where the variables must take discrete values. These variables impose additional constraints on the design problem. Problems may be pure integer where all variables must be integer but they are generally mixed integer problems in that some of the variables are integer with the remainder being continuous. All integer programming problems have an associated linear programming problem which is identical except for allowing all the variables to take non integer values, these are known as the continuous problems. The problems can be represented as

\[
\begin{align*}
\min & \quad Q(x) \\
\text{subject to} & \quad x \in R, \quad x_i \in Z^+ \forall i \in I
\end{align*}
\]  

(5.11)

where \( I \) is the set of integer variables and \( R \) is the feasible region of the continuous problem. One method for finding the optimum solution is to solve the continuous problem then assign the nearest discrete integer values and check the design for feasibility. This trial and error procedure can be adapted to a potentially more accurate method known as an adaptive numerical optimisation procedure. First the optimal solution must be obtained with continuous variables then only the variables close to discrete integer values are assigned as integers. The problem is optimised again and this is repeated until all the variables are properly assigned. These methods are very simple however they lack efficiency. The computer time necessary to solve an integer problem is many times greater than that needed for solving the continuous
Optimisation techniques.

problem. A reasonably successful method for solving the integer problem in terms of the continuous problem is the cutting plane method. This method involves the addition of extra constraints to reduce the feasible region each time the continuous problem is solved. Due to the increasing size of the problem, it has been generally rejected in favour of the branch and bound method.

Commonly investigated integer problems are the travelling salesman problem and the resource allocation problem, which are both covered in many texts on integer programming. The multiple choice problem is an integer problem which involves the selection of the correct combination. This was defined by Dantzig in 1967 as

\[
\begin{align*}
\min \ & cx \\
\text{subject to } & Ax - b \geq 0 \\
& \sum_{j=1}^{n_i} x_{ij} = 1 \quad i = 1, \ldots, m \\
& x_{ij} \in \{0, 1\} \\
\end{align*}
\]

(MCIP) \hspace{1cm} (5.12)

This formulation relies on having a linear objective function subject to linear constraints and the multiple choice constraint (MCIP). To solve this problem explicitly may require investigating \(\prod_{i=1}^{m} n_i\) combinations, which grows exponentially. The most successful ways of solving such a problem were using branch and bound techniques combined with linear programming. Incorporating Lagrangian relaxation introduces a weighted linear penalty function whilst dropping some constraints, however this may fail to give reasonable solutions when multiple optima exist. Hadj-Alouane and Bean (1997)\[22\] successfully applied genetic algorithms to the problem providing a speedier solution method which generates very reasonable solutions. However the objective function must be in a linearised form.

The branch and bound method.

A reasonably efficient method with wide applicability was introduced by Land and Doig in 1960, this was named the branch and bound method. The name describes the main features of this method used to solve mixed integer linear problems. Problems of the form of Equation (5.11) are solved assuming continuous variables. If the minimiser \(x'\) exists for the problem in the continuous case and it is a feasible solution for the original problem, i.e. the solution variables are integer, then it is the solution. If it is not feasible because there exists an \(i \in I\)
for which $x_i$ is not an integer then two problems are defined by branching on variable $x_i$. These are described as

\[
\begin{align*}
\text{branch - } & \min Q(x) : x \in \mathbb{R} \quad x_i \leq \lfloor x_i \rfloor \quad x_i \in \mathbb{Z} \quad \forall i \in I \\
\text{branch + } & \min Q(x) : x \in \mathbb{R} \quad x_i \geq \lceil x_i \rceil + 1 \quad x_i \in \mathbb{Z} \quad \forall i \in I
\end{align*}
\] (5.13) (5.14)

An optimal solution from problem (5.13) or (5.14) will be a feasible solution for the original problem. This branching process may be repeated until an integer solution is found. The tree structure generated is not unique as the solution to the continuous problem may violate more than one of the constraints giving a choice of variable to branch with. Nemhauser and Wolsey (1988)[48] provide a clear algorithm and worked examples of the method.

This method has wide applicability however a disadvantage is that the number of nodes on the tree grows exponentially with the number of variables and may not be finite. Therefore it is expensive to examine the whole tree and is usually impossible. For an effective strategy two important decisions must be made whilst generating the tree: which problem or node should be solved next and which variable should the branch be made on. In most cases a partial tree may be considered, concentrating on the most sensitive variables.

### 5.3.5 Combinatorial programming.

Combinatorial programming is a mixture of linear, integer and dynamic programming. Frequently the variables in a combinatorial problem are binary integers, \{0,1\}, therefore the problems may be represented as integer programming problems. Müller-Merbach (1975)[46] states that the essence of combinatorial problems is that there are distinct elements of one or more sets which have to be ordered or divided into subsets (of selected and not selected elements). Generally these are problems whereby any particular kind of combination between distinct elements of one or more sets are seeked. The number of different types of combinatorial problems is very large and each type requires a tailor made method. However a general solution approach may be followed.

1. State the problem.

2. Build an integer programming model - solve this using IP methods otherwise proceed.

3. Estimate the number of solutions feasible.
4. Check whether explicit enumeration is an adequate method - enumerate otherwise proceed.

5. Apply tree searches (implicit enumeration) - if too time consuming proceed.

6. Develop and apply heuristic methods (incomplete enumeration).

Building an IP is suggested (2) even though such algorithms are highly inefficient because they provide an insight into the structure and size of the problem. In building the IP a relationship to standard problems, for which solution methods exist, may emerge. However only in a few cases are IP methods more efficient than tree searches.

5.3.6 Heuristic programming.

Heuristic methods are not subject to precise mathematical criteria therefore there are no restrictions regarding the structure. However there are some guidelines as to the aims of a good heuristic method[46].

- Solutions should be yielded within a reasonable amount of computer time.
- Solutions should be close to the optimum, most of the time.
- The probability of single solutions being far below the optimum should be small.

Solutions gained from heuristic methods are not necessarily optimal solutions, however good solutions can be generated based on intuition. A test of the quality of a particular heuristic solution is to try and find a good lower bound which can be used as a guide to assess the optimality of the solutions generated by the method. Along side this stopping criteria may be introduced which will determine whether the solution generated is close enough to the lower bound for the iterative procedure to cease. A common test of an heuristic procedure is to try to solve the problem using alternative methods, even if crude, as a comparison.
5.4 Evolutionary procedures.

Evolutionary operation (EVOP) was introduced by Box (1955)\cite{8, 71} as an analogy to the survival of adolescent lobsters whose survival depends on the combination of their characteristics. The evolutionary process demonstrates survival of the fittest. This natural selection causes the lobster population to evolve towards the optimum. The term EVOP was adopted to describe a process where the systems evolve to their optimum contours of constant response. The main ideas behind EVOP are

1. Evolution concepts are applicable to experimental response.
2. Replace the random natural variation with orderly, statistically based variation.
3. Determine the direction to move from the results obtained.
4. Kill off all experimental conditions except the ones that produced the most desirable result.
5. Create a new generation of experiments in the desirable direction.

Improvements have been made in EVOP processes leading to the introduction of genetic algorithms. In the 1970s Holland\cite{28} invented the genetic algorithm to mimic the processes observed in natural evolution. This technique is more sophisticated than the EVOP methods used previously and research into its applications is ongoing.

5.4.1 Sequential SIMPLEX methods.

Box chose classical factorial designs to represent the variation in the process, primarily because they allow estimates of the interactions among factors. In order to make EVOPs an automatic procedure with formalised decisions, Spendley et. al. (1962)\cite{60} proposed using a SIMPLEX pattern in an evolutionary scheme. SIMPLEX EVOP (or sequential SIMPLEX) has two noticeable advantages over classical EVOP. The number of experiments in the initial SIMPLEX design is \( k + 1 \) instead of \( 2^k \) in the factorial design. The SIMPLEX requires only one new experiment to move to an adjacent region whereas the factorial design requires at least half of the number of initial experiments.
Optimisation techniques.

The sequential SIMPLEX uses a geometric figure which has a number of vertices equal to one more than the dimensions of the space. The response for each vertex is calculated, the vertex with the worst response is rejected. The simplex is reflected through the mid point of the hyperface between the next to worst and the best response. The reflected vertex is evaluated and the procedure is repeated by rejecting the next to worst response of the previous simplex. This method is formalised using standard worksheets, examples of which are provided by Walters et. al. (1991)[67]. The sequential simplex algorithm may be improved by using a variable step size. The variability of the step size is determined by comparing the response of the best value of the previous simplex with the response of the reflected vertex. Variable sized simplexes are ideal for dealing with a situation where the locality of the optimum is unknown. A large simplex covering the whole domain may be used initially as this can then collapse onto the optimum.

Constrained optimisation limits the range in which the simplex can move. This leads to boundary violation for the factors. Should the simplex attempt to cross the boundary then in the case of a variable simplex the out of bounds vertex must be assigned an infinitely bad response therefore forcing a contraction into the feasible region. For a fixed size simplex the responses should be set so that the simplex is forced to spin back into the feasible range, however this will involve creating a few phantom experiments.

To find the optimum the simplex must converge. For a multi factor simplex the optimum has been found when the simplex spins on the best vertex. Convergence with the variable sized simplex may never occur within the time allowed for the optimisation, although the region of the optimum will be reached relatively quickly.

Sequential simplex algorithms may not be used in all situations. Discrete and integer variables are incompatible with the simplex method. The method involves evaluating many responses within the feasible region. A narrow feasible region will involve many evaluations which are outside the boundaries wasting valuable time and resources.

5.4.2 Genetic algorithms.

Holland created the genetic algorithm based on the observation that natural evolution operates on chromosomes rather than the living beings they describe. Natural selection causes
the chromosomes that encode successful structures to reproduce more often than those that do not. Along with natural selection, mutations occur which cause the chromosomes of the children to be different from those of the biological parents.

A genetic algorithm is a technique for solving difficult problems in a similar way to nature by working on the variables rather than the responses in a blind manner. This means that the algorithm has no memory, the information about the previous responses is not used for producing a new set of variables. A genetic algorithm works on strings of binary digits which represent the variables, emulating a chromosome. The genetic algorithm is initiated by randomly choosing a population of strings, unlike most optimisation methods which initiate their search from a point. The strings are manipulated using processes of reproduction, crossover and mutation to produce a new string. Each string is assigned a fitness value based on the constraints and the system evaluation, a common utility for the fitness value assignment is the biased roulette wheel. Strings with a suitable fitness value are reproduced and placed in the mating pool ready for crossover and mutation. The strings in the mating pool are paired ready for parenting, crossover mates the parents at a random point, swapping the substring after this point producing two new children. Reproduction and crossover effectively combine previous good strings however they may neglect potentially useful material and hence mutation is employed to avoid this. Mutation is the occasional random change in the value of a string position. The fitness values of the members of this population are evaluated. This process is repeated until convergence of the string is obtained.

Genetic algorithms are naturally unconstrained, however constraints are easily incorporated by attaching penalties to any infeasible solutions. Genetic algorithms have the advantage of being very robust, covering a wide diversity of optimisation fields and maintain a good level of efficiency. A downfall to genetic algorithms is the random quality they possess in determining the string, this can lead to many system evaluations being necessary in order to optimise the system.

5.4.3 Simulated annealing.

Simulated annealing is also known as Monte Carlo annealing, probabilistic hill climbing, statistical cooling and stochastic relaxation and may be regarded as a variant of the heuristic local neighbourhood search. This method is analogous to physical annealing which involves
increasing the temperature of a solid to the maximum value causing the solid to melt and then decreasing the temperature carefully until the particles solidify. The analogy is that the solutions in combinatorial optimisation problems are equivalent to the states of physical systems with the cost being equivalent to the energy of a state. A transition is a combined action resulting in the transformation of a current solution to a subsequent solution. This transition is applied in two steps; application of a generation mechanism and application of acceptance criteria. The transition matrix which consists of the probabilities of moving from one state to another is a homogenous Markov chain.

Unlike local neighbourhood searches this method is not restricted to finding only local optima. Difficulties in using the method lie in finding a suitable acceptance criteria to decide the probabilities of moving from one solution to another and determining the local neighbourhood in which to initiate the search. The method involves long running times to converge to an approximate solution, with fine tuning being necessary for a more accurate solution. Advantages in using the technique are the ease at which it may be implemented and the applicability to most combinatorial problems. An introduction to the method and its applications is given in Reeves (1993)[54].

5.5 Discussion.

The methods of optimisation described in this chapter were chosen due to their possible applicability to the problem.

The classical theory of optimisation provides the basis for further optimisation schemes. As it stands the classical theory is inappropriate as the problem under consideration does not have a known algebraic objective function. The problem posed requires a point solution therefore mathematical programming methods have been looked at rather than variational methods. The problem relies on the evaluation of a ‘black box’ deterministic model as an objective function therefore search techniques appear more appropriate than function reliant programming methods. However a search technique requires a search plan. Existing search plans are robust for one variable models, when the problem is unimodal and the approximate location of the optimum is known. Optimising the safety systems on an offshore structure involves many variables therefore a multi-variable search is needed. For this purpose sim-
Optimisation techniques.

Simple gradient searches are common but generally require a well defined algebraic objective function.

Much work has been done on linear programming techniques which require the objective function and the constraints to have linear forms. Non linear programming techniques are not as common and invariably rely on approaches to linearise the model. A promising approach is successive linear programming for which the model should be linearised about a point then existing linear schemes are employed to find another point when linearisation is again used until convergence is obtained. Linear programming schemes are efficient when using continuous variables. The variables in our problem are integer which would require the use of integer programming schemes. Integer programming methods allow the integer variables to be used within linear programming schemes but such methods can be long winded and the computer processor time involved is significantly higher than that used in a linear programme. Hence a successive linear programming scheme with integer variables will use a vast amount of processor time.

The main drawback to evolutionary procedures is the randomness of selecting initiating points and the many system evaluations required to obtain an optimum.

There are no methods immediately appropriate to optimising the system described. It appears that heuristic techniques may be the best option.
6. A methodology for calculating the frequency of explosions.

6.1 Introduction.

SAROS (Safety and Reliability of Offshore Structures) is a computer program developed at Loughborough University by Andrews and Smith\(^3\), to predict the frequency of explosions of different magnitudes, arising from an accidental release of gas, occurring in a module on an offshore platform. This methodology combines established risk assessment techniques, such as event tree analysis and fault tree analysis, with fluid flow modelling. Fault tree and event tree methods are used to determine the frequencies of occurrence of all possible scenarios resulting from a leak of gas. Each scenario evolves from the initial gas leak from a process section which can be isolated. The event tree branch points determine whether the gas detection system functions, the relevant isolation and blowdown valves function and the deluge system activates. A distribution of leak hole sizes is considered. Using fluid flow modelling the gas release rate is computed allowing the variation of the module gas concentration with time to be calculated. The frequency of an explosion is calculated by combining the time that the concentration is between the flammable limits with the predicted ignition rate. The severity of the overpressures generated from the explosion are calculated based on an empirical relationship derived by British Gas.

This chapter provides the background on the platform being considered and the data required to use the SAROS program. A general overview of the workings of SAROS is given in Sections 6.4 and 6.5. The limitations of SAROS are presented in Section 6.6.

6.2 The platform.

An example platform is illustrated in Figure 6.1. Divisions of the platform are known as modules. Some platforms, as in the example, have a large proportion dedicated to accom-
accommodation

wellheads

separation

compression

Figure 6.1: An example of the layout of an offshore platform.

A methodology for calculating the frequency of explosions.

accommodation, facilities and service modules which are not of concern. The modules of interest are those in which a release of gas could occur. The three most susceptible modules are the wellhead, separation and compression modules. The wellhead module is where the well bay fluids are pumped from the sea, this mixture consists of gas, condensate, oil and water. Within the separation module the water is returned to the sea, the oil is separated off and stored for transportation ashore and the gas and condensate mixture carries on to the next stage. In the compression module the gas mixture is pressurised ready to be pumped ashore.

A module contains pipe work, process vessels, storage containers, blowdown and isolation valves. Figure 6.2 shows a hypothetical layout associated with a module which exemplifies the features. The modules are typically semi enclosed, therefore susceptible to the effects of the wind. A module is subdivided into sections. A section is defined, in our study, to be the pipe work and process vessels which may be isolated. For example in Figure 6.2 the first section is between isolation valve ISOL1 to isolation valve ISOL2, this contains the pipe work and compressor1 and has blowdown valve BDI connected to it. If a leak originates from a particular section, the adjacent isolation valves are assessed to determine the potential inventory of the leak. The isolation valves are designed to activate on detection of a leak, closing to prevent the inventory of the other sections from contributing to the leak. Blowdown valves activate on detection of a leak, opening to provide an escape route for the gas. They reduce the available inventory of the leak and the pressure within the section. If a leak has occurred on section 1 between ISOL1 and ISOL2, in Figure 6.2, the gas within
Figure 6.2: The typical contents of a module.
A methodology for calculating the frequency of explosions.

the pipes and compressor1 will influence the leak, with the flow rate being determined by the pressure and temperature of the mixture within the section. If ISOL2 has failed then the inventory of gas within the pipes up to ISOL3 and that in scrubber1 must also be taken into consideration.

Leaks are expected to develop at flange failures on pipe work or process vessels yielding holes with diameters of the order of millimetres. The flange failures fall into a range of hole sizes, for this methodology the hole sizes have been grouped and the mean of each group taken as the hole size for all members of that group. This provides discretised values to work with. In these modules three hole sizes are considered.

6.2.1 The safety systems.

The isolation and blowdown valves make up an integral part of the safety systems on the platform. However these will only operate automatically should the leak be detected, otherwise manual operation of the valves is required. The detection system installed on the platform is very important, it is designed to detect the presence of gas at a level of 20% of the lower flammable limit of the gas. The detection system dictates the response of the other safety systems. The isolation and blowdown valves work together to reduce the inventory of gas released into the module. Once the gas is within the module it may come into contact with an ignition source which may produce a fire or explosion. Explosions occur when the ignition source comes into contact with a gas cloud, hence an effective ventilation system is required to disperse the gas from the module before this happens. The platform considered has semi enclosed modules, with the module open to the natural effects of the wind speed and direction. For the purpose of the methodology the natural effects are described by a distribution of air changes per hour. Excessive overpressures, generated during an explosion, will damage the integrity of the structure. To suppress the overpressures generated mitigating systems are employed. Water deluge is used on the platform for this purpose. This is initiated on detection of the gas presence, however there will be a delay until the water reaches the gas cloud.
6.2.2 The modules.

The hypothetical platform being analysed in this thesis contains three modules which are divided into sections. Schematic diagrams of the modules may be found in Appendix A.

The wellhead module contains three sections, labelled 9 to 11, which may leak into this module. The actual volume of this module is $3630m^3$ but the effective volume is $907.5m^3$. This effective volume is $\frac{1}{3}$ of the module volume, it represents the volume in which the gas and air are assumed to mix taking into account the volume occupied by the process equipment. Section 9 is the wellhead and production header line which is connected to 19 production wells. This section is at a relatively low pressure of $19.67 \text{ bar } g$, temperature of $71^\circ C$ and has a volume of $1.73m^3$. Section 10 is the gas injection line which is connected to 2 gas injected wells. This section is at a pressure of $380 \text{ bar } g$, temperature of $107^\circ C$ and has a volume of $3m^3$. Section 11 is the gas lift line with 5 gas lift wells. This is at a pressure of $178 \text{ bar } g$, temperature of $51^\circ C$ and has a volume of $10.9m^3$. The mixture within each of the three sections is gas. Leaks in the wellhead module may contain gas, oil or condensate due to the connections to other sections in other modules. Section 9 is connected to section 3, within the separation module, via isolation valve 33XV001 and to section 14 by wellhead valve 19. Section 10 is connected to sections 8, in the compression module, and 15 via isolation valve 35XV383 and wellhead valve 2. Section 11 is connected to sections 8 and 16 via a non return valve and wellhead valve 5. The blowdown valves providing relief to the module are 34XV031, 35XV422 and 35XV382.

The separation module contains two sections, labelled 1 and 3, which may leak into this module. The actual volume of this module is $8000m^3$ with the effective volume being $2000m^3$. Section 1 is the atmospheric separator which is at a pressure of $1.6 \text{ bar } g$ and a temperature of $61^\circ C$. The section contains both gas and oil, gas occupies $51.49m^3$ and oil occupies $57.03m^3$. Section 3 is the inlet separator which is at a pressure of $19.69 \text{ bar } g$ and a temperature of $71^\circ C$. This section also contains gas and oil, gas represents a volume of $78.02m^3$ and oil $88.27m^3$. Section 1 connects to section 4, in the compression module, with two isolation valves 34XV001 and 35XV090, section 5 via 35XV186, section 6 with 35XV092 and section 12 with 41XV201. Section 1 also connects to section 3 by isolation valve 34XV033. Section 3 connects to section 5 with two valves 35XV125 and 35XV149 and to section 9 with 33XV001. There are eight blowdown valves which may provide relief. Should the leak...
be on section 3 blowdown valve 34XV031 is designed to activate. The other seven valves 35XV044, 35XV103, 35XV157, 35XV171, 35XV277, 35XV279 and 41XV002 will only provide an escape route for the gas if one of the isolation valves has failed.

The compression module has four sections, labelled 4, 5, 6 and 8, which may leak into this module. The actual volume of the module is $8000m^3$ with the effective volume into which a leak may occur being $2000m^3$. The sections within the compression module are further divided into subsections. Section 4 contains low pressure compressors and scrubbers. Section 5 contains medium pressure compressors, section 6 has medium pressure scrubbers and section 8 has the injection compressors. The volume, temperature and pressures of the subsections in the compression module are shown in Table 6.1.

<table>
<thead>
<tr>
<th>Section</th>
<th>Pressure (bar g)</th>
<th>Temperature (°C)</th>
<th>Volume $m^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1.2</td>
<td>61</td>
<td>14.44 (gas)</td>
</tr>
<tr>
<td></td>
<td>5.6</td>
<td>145</td>
<td>1.54 (gas)</td>
</tr>
<tr>
<td></td>
<td>4.65</td>
<td>30</td>
<td>6.94 (gas)</td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>147</td>
<td>0.28 (gas)</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>61</td>
<td>0.28 (gas)</td>
</tr>
<tr>
<td>5</td>
<td>19.4</td>
<td>76</td>
<td>1.75 (gas)</td>
</tr>
<tr>
<td></td>
<td>18.3</td>
<td>30</td>
<td>26.15 (gas)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11.34 (cond.)</td>
</tr>
<tr>
<td>6</td>
<td>46.1</td>
<td>105</td>
<td>2.75 (gas)</td>
</tr>
<tr>
<td></td>
<td>45.3</td>
<td>30</td>
<td>13.88 (gas)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.46 (cond.)</td>
</tr>
<tr>
<td></td>
<td>44.8</td>
<td>30</td>
<td>10.76 (gas)</td>
</tr>
<tr>
<td></td>
<td>169.5</td>
<td>150</td>
<td>2.63 (gas)</td>
</tr>
<tr>
<td>8</td>
<td>173.5</td>
<td>146</td>
<td>3.11 (gas)</td>
</tr>
<tr>
<td></td>
<td>169.2</td>
<td>38</td>
<td>5.81 (gas)</td>
</tr>
<tr>
<td></td>
<td>380</td>
<td>111</td>
<td>1.52 (gas)</td>
</tr>
</tbody>
</table>

Table 6.1: The inventory data for the sections within the compression module.

Section 4 contains gas and condensate, but leaks may occur which contain oil due to a
A methodology for calculating the frequency of explosions.

connection to section 1 via isolation valves 35XV090 and 34XV001. Section 4 also connects to section 5 via 35XV104. The isolation valves and the sections they connect to are tabulated in Table 6.2 and the blowdown valves are tabulated in Table 6.3.

<table>
<thead>
<tr>
<th>Connecting sections</th>
<th>Isolation valve</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 3</td>
<td>34XV033</td>
</tr>
<tr>
<td>1 4</td>
<td>35XV090 &amp; 34XV001</td>
</tr>
<tr>
<td>1 5</td>
<td>35XV186</td>
</tr>
<tr>
<td>1 6</td>
<td>35XV092</td>
</tr>
<tr>
<td>1 12</td>
<td>41XV201</td>
</tr>
<tr>
<td>3 5</td>
<td>35XV125 &amp; 35XV149</td>
</tr>
<tr>
<td>3 9</td>
<td>33XV001</td>
</tr>
<tr>
<td>4 5</td>
<td>35XV104</td>
</tr>
<tr>
<td>5 6</td>
<td>35XV172</td>
</tr>
<tr>
<td>6 7</td>
<td>XVX3</td>
</tr>
<tr>
<td>6 8</td>
<td>35XV306</td>
</tr>
<tr>
<td>6 12</td>
<td>41XV053</td>
</tr>
<tr>
<td>8 10</td>
<td>35XV383</td>
</tr>
<tr>
<td>8 11</td>
<td>N1</td>
</tr>
<tr>
<td>8 13</td>
<td>90XV6/7</td>
</tr>
<tr>
<td>9 14</td>
<td>WELL19</td>
</tr>
<tr>
<td>10 15</td>
<td>WELL2</td>
</tr>
<tr>
<td>11 16</td>
<td>WELL5</td>
</tr>
</tbody>
</table>

Table 6.2: The isolation valves and the sections they connect.
A methodology for calculating the frequency of explosions.

<table>
<thead>
<tr>
<th>Section</th>
<th>Blowdown valve</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>34XV031</td>
</tr>
<tr>
<td>4</td>
<td>35XV044 &amp; 35XV103</td>
</tr>
<tr>
<td>5</td>
<td>35XV157 &amp; 35XV171</td>
</tr>
<tr>
<td>6</td>
<td>35XV277 &amp; 35XV279</td>
</tr>
<tr>
<td>7</td>
<td>35XV419</td>
</tr>
<tr>
<td>8</td>
<td>35XV382 &amp; 35XV422</td>
</tr>
<tr>
<td>12</td>
<td>41XV002</td>
</tr>
<tr>
<td>13</td>
<td>90XV011</td>
</tr>
</tbody>
</table>

Table 6.3: The blowdown valves and their locations.

6.3 Input data.

The safety systems may fail, this leads to different scenarios occurring. Each isolation valve, blowdown valve, detection system and deluge system has a probability of failure. Event trees are used to determine the possible scenarios and the frequency of occurrence. Figure 6.3 shows an event tree relating to a leak on a section which is connected to two other sections as shown in Figure 6.4.

![Event Tree Diagram](image)

Figure 6.4: An example connection of sections relating to the event tree.

If the leak is initiated on section B the event tree demonstrates 55 scenarios that may occur. The first consideration is whether the gas leak is detected, if it is not none of the other safety systems will be initiated giving scenario number 55 with no blowdown valves and an infinite inventory of gas. If the leak is detected, we consider whether isolation valve ISOL1 closes, if it does section A does not contribute to the leak so the blowdown on
A methodology for calculating the frequency of explosions.

<table>
<thead>
<tr>
<th>Gas Leak Detection System</th>
<th>ISOL 1 Close Valve on Section A</th>
<th>Blowdown Valve on Section C</th>
<th>Water Spray Activated (Section B)</th>
<th>Water Spray Maintained</th>
<th>Blowdown Total Inventory Section Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Leak</td>
<td>ISOL 1 Close Valve on Section A</td>
<td>Blowdown Valve on Section C</td>
<td>Water Spray Activated (Section B)</td>
<td>Water Spray Maintained</td>
<td>Blowdown Total Inventory Section Numbers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.3: An example event tree.
A methodology for calculating the frequency of explosions.

section A is not considered. The next consideration is whether the isolation valve ISOL2 closes, if it does section C does not contribute to the leak and the blowdown on section C is not considered. As the leak occurs on section B the blowdown of section B must be considered, following this the mitigation system is considered. The mitigation state of the explosion affects the severity of the overpressures produced, therefore if the water spray is not activated unmitigated explosions occur. Unmitigated explosions may also occur if the water spray activates but is not maintained, hence this is the final consideration.

As an example path 26 in the event tree in Figure 6.3 is obtained by the following events occurring. The gas leak occurs and is detected. Isolation valve ISOL1 fails to close meaning that the inventory of the leak includes that from section B and section A. The blowdown valve on section A works as designed opening to provide pressure relief for the section. Isolation valve ISOL2 also fails to close adding the inventory of section C to the leak. The blowdown valve on section C opens to provide further relief. The blowdown valve on section B also operates as designed. The water spray mitigation system is activated however this is not maintained for the duration of the leak. This leads to the possibility of having a mitigated or an unmitigated explosion depending on when the failure takes place compared to the when the ignition takes place. This situation involves the leak having the inventory of sections A, B and C, but having relief from blowdown valves on all three sections.

From the initiating event of the gas leak occurring there are eight different events which are considered as a success or a failure leading to a possible 55 branches. The events are either a total success or a total failure. No partial failures are considered due to the large event trees generated for the modules with only the two states, this is justified by the fact that the total failure will give the worst case scenario.

Each of the events has an associated probability of occurrence. Each outcome has a frequency of occurrence which can be calculated by taking the product of the probabilities of each branch leading to that outcome. The probabilities of the failure of each valve or safety system is determined prior to the construction of the event tree by conducting a fault tree study. Such a study takes an event such as an isolation failure and considers all possible causes, breaking them down until basic events are reached.

The information provided by the event tree is the topology data file used by SAROS.

Along with the topology file, SAROS requires data relating to the inventory of the module.
A methodology for calculating the frequency of explosions.

This inventory file contains the details of each section on the platform, this includes the volume of gas, condensate and oil, the densities of these, the pressure and the temperature of the section. The inventory file also identifies the module being analysed and provides its ambient conditions, the hole sizes expected, their frequency of occurrence and the overpressure distribution data.

The creation of the topology file and the inventory file is done using a program named DAVROS (Detailed Analysis and Verification of Realistic Offshore Structures) created by Natural Solutions. DAVROS is a windows based program which allows the user to represent the platform layout and section connectivity graphically. Pull down menus facilitate the input of equipment data. DAVROS checks that it has been given the required data and checks that there are no connectivity errors in the platform construction before generating the topology and inventory files. This removes the need for constructing large event trees by hand which is a process prone to error.

6.4 Calculation methodology.

Working with each potential scenario, i.e. ventilation rate, section within the module, combinations of isolation failure and blowdown failure, the inventory of the leaking section is determined. From this a flow rate into the module may be calculated. For an explosion to occur the gas must form a cloud.

The concentration of the gas cloud is assumed to be uniform and fill the effective module volume. This concentration is calculated from the flow rate of the gas into the module and the ventilation rate, mimicking the natural effects of the wind speed and direction. For an explosion to occur the concentration of the gas must be within the flammable region which is bounded by the lower flammable limit (LFL) and the upper flammable limit (UFL). Below the lower flammable limit the concentration of gas is such that there is not enough fuel for ignition to occur. Above the upper flammable limit the concentration of gas is so high that there is not enough oxygen for ignition to occur. For natural gas the LFL is 5% and the UFL is 15%. The concentration profile may take one of three forms, Figure 6.5. The first profile demonstrates the concentration of gas rising to a peak below the flammable region. As the concentration never reaches the flammable region an explosion is not possible. The
A methodology for calculating the frequency of explosions.

Figure 6.5: Possible profiles for the gas concentration with time within the module.
second profile enters the flammable region and peaks blow the upper flammable limit. An explosion may occur when the concentration is between the flammable limits therefore an explosion is possible between t1 and t4. The final profile shows the concentration rising above the UFL before peaking then falling back through the flammable region. In this case there are two time periods in which an explosion may take place. An explosion is possible as the concentration rises, between t1 and t2, and again as it falls, between t3 and t4.

The concentration level at which an ignition occurs is important when determining the overpressure distribution. Figure 6.6, taken from Catlin et al. (1993)\(^9\), shows the correlation between the magnitude of the overpressure and the concentration level. Hence if the frequency of an explosion at a specific concentration level is known the magnitude of the expected overpressure can be determined.

![Figure 6.6: Variation of overpressure with concentration.](image)

The flammable region is typically divided into ten equal bands within this range, therefore giving 5%-6%, 6%-7% ... 14%-15%. For the frequency of an explosion to be calculated the times at which these concentration bands is reached is necessary. The overpressures generated are dependent on the state of the mitigation system, as can be seen from Figure 6.6 the greater the amount of mitigation the lower the generated overpressures are. The frequencies of explosions occurring are categorised dependent on whether the explosions are
mitigated or unmitigated.

6.5 Operation of code.

SAROS operation follows the flow chart in Figure 6.7. The code begins by processing the data from the input files in the subroutines INITIALISE and SETUP. For each ventilation rate, all the sections within the module are considered. For each section the ways that the sections combine due to isolation failure are considered in turn, for each combination all possible blowdown situations are looked at with each of the discretised hole sizes. This determines the situation and the inventory of gas available.

The subroutine BANG is called to calculate the flow rates of gas into the module and hence the concentration of gas within the module. This routine assumes a changing temperature scenario which may only be solved using a time stepping process. BANG returns the times at which each concentration range is reached.

For each concentration range the entering and exit times are considered. Depending on whether the concentration exceeds the UFL either SITU2 or SITU3 is called. Both subroutines use the times from BANG to calculate the probability of ignition occurring in the different mitigation situations. SITU2 calculates the frequency of the ignition if the gas cloud enters the concentration range but does not exceed it. SITU3 is based on the concentration range being exceeded.

The frequencies are tabulated according to the section number, concentration range and type of explosion. The results for each section are printed to a file within subroutine PRES1 and for the module in PRES2. The importance measures are printed by PRES3 and PRES4. These importance measures give the percentages of the explosion frequency due to different sections and scenarios.

Using the frequencies of explosions at different concentration levels the subroutine OVERPRES calculates the overpressure exceedence distribution.
A methodology for calculating the frequency of explosions.

Figure 6.7: The flow chart showing the operation of the code.
6.6 Criticism of SAROS.

The SAROS methodology makes assumptions on the flow rates, concentration build up and makes simplifications in the frequency calculations.

This methodology makes the assumption that should an isolation valve failure occur the contents of the connecting section influences the leak. The pressures and temperatures of the sections are averaged. This is an assumption that may not be correct, however this has not been addressed within this thesis.

The leaking section may connect to more than one other section, each of these isolation valves may fail therefore the situation may involve the contents of a few sections. However SAROS does not account for these connecting sections also having isolation valve failure leading to further sections. Contributions to the leak may only come from adjacent sections. For example in Figure 6.4 a leak initiating on section A may involve the contents from section B if ISOL1 fails, yet the failure of ISOL2 is never considered so the contents of section C have no influence. A study has been conducted into expanding the event tree to cover such situations by Chew (1995)[12] however the event trees generated were themselves very large leading to large data files which greatly increased in the computer processor time without a significant degree of accuracy obtained.

The frequency of an explosion is calculated by assuming a leak hole develops on a section. SAROS does not have the capability to calculate the frequency of an explosion should two leaks develop simultaneously. A crude approximation to this frequency would be to multiply the frequencies of the events together, but this would only be accurate if the events were independent. This is clearly not the case as the leaks may share the same inventory, effectively increasing the hole size. In any case more than one leak will result in a different concentration profile emerging within the module.

SAROS originally assumed that the leak flow consisted of all the components of the mixture within the leaking section, i.e., if $\frac{1}{2}$ of the mixture was gas, $\frac{1}{3}$ condensate and $\frac{1}{6}$ oil then the flow rate would be in the same proportions. Due to the relative densities of the oil, gas and condensate, oil is likely to be at the base of the vessel and therefore would not contribute to the leak if the hole appeared at the top. BANG has been modified to allow for leaks which neglect oil and leaks which neglect both oil and condensate. Since gas is the main factor
within the sections and oil and condensate do not appear in some scenarios, leaks consisting solely of oil or condensate have not been considered. Results of this study are presented in Chapter 7.6.

When the leak occurs it is assumed that the pressure and temperature of the leaking section drop. There is assumed to be negligible heat input to the system therefore giving constant entropy. In reality it is likely that there is an exchange of heat between the section and the module. To test this assumption a model has been developed that assumes that there is sufficient heat transfer to keep the section at constant temperature whilst condensate remains in the section hence retaining the driving pressure during this time. The theory of this model is presented in Chapter 7.4. The true scenario should lie between the two models, hence an upper and lower bound for the results should be found. The magnitude of the bound will determine how appropriate it was to make this assumption. The calculation procedure provides an alternative to BANG with EXPLODE. Unlike BANG, EXPLODE is a suite of subroutines as shown in Figure 6.8. The flow rates depend upon whether the flow is choked or unchoked and constant temperature depends on there being condensate within the section. In some cases analytical formulae may be used rather than the time stepping process employed in BANG, hence the reasoning for splitting EXPLODE into subroutines.

The concentration of gas is assumed to be uniform, immediately throughout the effective module volume and therefore an ignition source in any location has the same chance of igniting the gas. The concentration does in fact have to build up within the module with the area around the leak hole being more likely to have a higher concentration than the extremities of the module. The speed at which the gas is released and the effects of the strong wind speeds may mean that this assumption proves to be correct. However an alternative strategy using computational fluid dynamics correlations is presented in Chapter 9.

The simplification of the frequency calculations means that an explosion at a specific concentration level may occur within the time period that the concentration is at that level with no consideration of whether any ignition has occurred previously. New calculations take into account this possibility and are presented in Chapter 8. Within the code two new subroutines, PROBS1 and PROBS2, are provided as alternatives to SITU2 and SITU3.

Some of the data used to generate the inventory and topology files comes from observational and empirical sources. Historical data is common place however offshore installations
A methodology for calculating the frequency of explosions.

Figure 6.8: The flow chart showing the suite of subroutines employed in EXPLODE as an alternative to BANG.
originate from around 1960. Over the past four decades there have been many changes in operational procedure and the safety systems installed therefore this data may be unreliable. Chapter 10 is a sensitivity analysis on such data, done to show the effects of having errors within the data.

6.7 Discussion.

This chapter has introduced the makeup of the offshore platform considered within this thesis. Accidental hydrocarbon releases may occur in one of three modules: separation, compression and wellhead. The schematic diagrams of these modules are provided in Appendix A.

SAROS is a methodology for determining the frequency of an explosion occurring and the magnitude of overpressure expected. An outline of the SAROS code has been given, more details on the calculations involving the fluid release may be found in Chapter 7 and those for the probability calculations in Chapter 8. The limitations of SAROS have been described, these will be addressed in the following chapters.

7 introduces two methods for calculating the leak flow rate of the hydrocarbon release.

7.6 compares the results obtained from SAROS when the leak contribution is varied.

7.8 provides a comparison between the results from the two temperature state models.

8 introduces a more accurate method for calculating the frequencies of explosions.

9 addresses the assumption of assuming uniform concentration throughout the module.

10 analyses the effects of having small inaccuracies within the empirical data.
7. Modelling the release.

7.1 Introduction.

To calculate the frequency of an explosion resulting from an accidental leak of gas, the nature of the release must be determined. Leaks are expected to develop at flange failures on pipe work or process vessels yielding holes with diameters of the order of millimetres. The vessel may be at high pressure, containing a mixture of gas, condensate and oil.

Two methods for modelling the release are presented in this chapter. The first model assumes no heat input into the system therefore there will be changing temperature throughout the duration of the leak. This model was originally developed by Andrews and Smith (1994)[3]. The second model addresses this assumption by assuming that there is sufficient heat transfer into the system to keep the temperature constant during the initial stages of the release. It is expected that in reality the situation will lie somewhere between the two with there being some heat input to the system. Hence the models will provide upper and lower bounds for the frequency. The differences between these bounds will indicate whether the simplifying assumptions made in the original model were valid. Alongside the temperature state of the system during the leak, the constituents of the release were varied and their results compared.

7.2 Calculation procedures.

Both models share some basic assumptions:

1. Although the vessel/pipe-work may contain a mixture of gas, condensate and oil (e.g. in the separator), only gas and condensate contribute to the generation of the gas cloud. (Oil is of more concern when considering fires.)

2. Gas and condensate leak in the same proportions as they exist in the vessel.

3. Gas and condensate have different release speeds, this gives the correct interpolation
as the gas or condensate left within the vessel approach zero (Andrews and Smith (1994)\(^3\)).

4. The condensate immediately evaporates on contact with the atmosphere.

5. The gas and air mix perfectly and instantaneously on release providing uniform concentration.

6. The leak is considered to occur into a fixed specified volume.

The gas discharge rate is calculated by the laws of gas dynamics and the condensate discharge rate is calculated by assuming that there is a reservoir of ideal incompressible fluid. The average density of the gas-condensate mixture is

\[
\rho = \beta \rho_g + (1.0 - \beta) \rho_l
\]  

where \(\beta\) is the proportion of the gas (volume), and \(\rho_g\) and \(\rho_l\) are the densities of the gas and condensate (liquid) respectively. The mass of the gas-condensate mixture is \(M = \rho V\) and the rate of mass discharge is \(\frac{dM}{dt} = V \frac{\rho}{dt}\) where volume is constant due to there being no contraction or expansion of the vessel walls.

From assumptions 1, 2 and 3, the total mass flow rate is

\[
W = \beta W_g + (1.0 - \beta) W_l
\]  

where \(W_g\) is the mass flow rate of the gas and \(W_l\) is the mass flow rate of the condensate, which may be obtained from the continuity equation

\[
W_g = \rho_g \nu_g A \quad W_l = \rho_l \nu_l A
\]

where \(\nu_g\) and \(\nu_l\) are the discharge speeds of the gas and the condensate respectively and \(A\) is the area of the leak hole.

To obtain the discharge speed of the condensate Bernoulli's equation is used. For an isentropic flow this is

\[
\frac{p}{\rho_l} + \frac{\nu_l^2}{2} = constant
\]

where \(p\) is the pressure. Within the module the pressure is atmospheric, \(p_a\), and the discharge speed is \(\nu_l\), at the point of release the speed is zero and the pressure is \(p\).

\[
\frac{p_a}{\rho_l} + \frac{\nu_l^2}{2} = \frac{p}{\rho_l}
\]
Modelling the release.

Manipulation of this equation gives the discharge speed of the condensate.

$$\nu_i = \left( \frac{2p - p_a}{\rho_i} \right)^{\frac{1}{2}}$$

Hence the mass flow rate of the condensate is

$$W_i = A \left( 2(p - p_a) \rho_i \right)^{\frac{1}{2}} \quad (7.3)$$

This equation will also apply to the mass flow rate of any oil.

The discharge speed of the gas is obtained using the laws of gas dynamics. The gas is assumed to be a perfect gas

$$\frac{p}{\rho_g} = K \quad (7.4)$$

where $K$ is a constant and $\gamma$ is the ratio of specific heats $\gamma = c_p/c_v$ where $c_p$ is the specific heat capacity of the gas at constant pressure and $c_v$ is the specific heat at constant volume.

Bernoulli’s equation in compressible flow gives to the discharge speed of the gas (Equation 7.5) which leads to the gas flow rate when the flow is unchoked (Equation 7.6).

$$\nu_g^2 = 2 \left( \frac{\gamma}{\gamma - 1.0} \right) \frac{p}{\rho_g} \left[ 1.0 - \left( \frac{p_a}{p} \right)^{\frac{\gamma-1.0}{\gamma}} \right] \quad (7.5)$$

$$W_g = \left( 2A^2 \left( \frac{\gamma}{\gamma - 1.0} \right) \right) K \frac{1.0 + \gamma}{\gamma} \left[ \left( \frac{p_a}{p} \right)^{\frac{1.0-\gamma}{\gamma}} - 1.0 \right]^{\frac{1}{2}} \quad (7.6)$$

However if the gas reaches its maximum speed, the speed of sound, the flow becomes choked.

The critical pressure ratio is used to determine whether the flow is choked or unchoked. For unchoked flow this is

$$\frac{p}{p_a} < \left( \frac{\gamma + 1.0}{2} \right)^{\frac{\gamma}{\gamma-1.0}} \quad (7.7)$$

If there is choked flow the ratio $p_a/p$ has a maximum value of

$$\left( \frac{2}{1.0 + \gamma} \right)^{\frac{\gamma}{\gamma - 1.0}}$$

Substituting this maximum value into Equation 7.5 gives the maximum discharge speed of the gas as

$$\nu_{g_{\text{max}}} = \left( \frac{2\gamma p}{(1.0 + \gamma) \rho_g} \right)^{\frac{1}{2}}$$

This then may be used to give a flow rate for choked flow

$$W_g = A \left( \rho_g \gamma \left( \frac{2}{1.0 + \gamma} \right)^{\frac{1.0+\gamma}{\gamma-1.0}} \right)^{\frac{1}{2}} \quad (7.8)$$
The gas flow rate for choked flow is dependent upon the density. The density of the gas changes as the leak occurs. The flow rate may be re-expressed to eliminate dependencies on \( \rho_g \). \( \alpha \) is introduced to represent a product of constant terms such that

\[
W_g = V_g \frac{d\rho_g}{dt} = A (p \rho_g)^{\frac{1}{2}} \alpha \quad \text{where} \quad \alpha = \left( \frac{2}{1.0 + \gamma} \right)^{\frac{2(1.0 - \gamma)}{\gamma - 1.0}}
\]

The change in gas density with time is

\[
\frac{d\rho_g}{dt} = \frac{A (p \rho_g)^{\frac{1}{2}} \alpha}{V_g}
\]

Integrating to find the gas density and substituting this into the gas flow rate equation gives the flow rate of the gas independent of the change in gas density as

\[
W_g = AK^{\frac{1}{2}} \alpha \left( \frac{1.0 - \gamma}{2} \left( \frac{AK^{\frac{1}{2}} \alpha t}{V_g} \right) + \rho_g(0)^{\frac{1.0 - \gamma}{\gamma - 1.0}} \right)^{\frac{1.0 + \gamma}{1.0 - \gamma}}
\]  

(7.9)

The discharging condensate is assumed to evaporate immediately on contact with the atmosphere. The volume outflow into the module, \( W_v \) is

\[
W_v = \frac{W}{\rho_a}
\]

(7.10)

where \( \rho_a \) is the atmospheric density.

The volume concentration of gas within the module can be calculated by considering the rate of change of the gas volume in the module, \( V_{gm} \)

\[
\frac{dV_{gm}}{dt} = W_v - c_g (W_v + W_a)
\]

(7.11)

where \( c_g \) is the volume concentration of gas and \( W_a \) is the volume ventilation rate. Dividing by the total volume of the module, \( V_m \) gives

\[
\frac{dc_g}{dt} + c_g \left( \frac{W_v + W_a}{V_m} \right) = \frac{W_v}{V_m}
\]

(7.12)

### 7.3 Changing temperature - no heat input.

This section gives an overview of the main calculations performed in the model designed by Andrews and Smith\(^3\). This model assumes that as a leak occurs the temperature of the leaking vessel reduces due to there being no heat transfer within the system. As temperature
Modelling the release.

reduces the pressure also reduces. The ratio of condensate to gas will change as a leak occurs, because as the pressure is reduced the condensate evaporates which increases the gas/condensate ratio. The gas does not behave adiabatically because an exchange of entropy between the gas and condensate phases is assumed. By assuming that there is no heat input into the system the total entropy per unit mass is constant. The entropy per unit mass between the gas and liquid phases when in equilibrium is given by

\[ s_g - s_l = \frac{\lambda}{T} \]  

(7.13)

where \( \lambda \) is the latent heat and \( T \) is the temperature. The total entropy of the system is

\[ m_g s_g + m_l s_l = Ms \]  

(7.14)

where \( M = m_g + m_l \). Manipulating equations 7.13 & 7.14 leads to

\[ s_g = \frac{\lambda}{T} \left( \frac{\rho_l}{\rho} (1.0 - \beta) \right) + s \]  

(7.15)

For a two-phase mixture the Clausius-Clapyron equation can be applied

\[ \frac{dp}{dT} = \frac{\lambda}{T} \left( \frac{1}{\rho_g} - \frac{1}{\rho_l} \right)^{-1} \]  

(7.16)

The gas is assumed to be a perfect gas

\[ p = \rho_g RT \]  

(7.17)

\[ p = \rho_g^e \left( \frac{ss}{s_l} \right) \]  

(7.18)

The change in pressure with respect to time, differentiating equation 7.17, is

\[ \frac{dp}{dt} = \frac{d\rho_g}{dt} RT + R \rho_g \frac{dT}{dt} \]

This is substituted into equation 7.16 to eliminate the temperature which leads to

\[ \frac{dp}{dt} \left( 1.0 - \frac{p}{\rho} \left( \frac{1}{\rho_g} - \frac{1}{\rho_l} \right) \right) = \frac{p}{\rho_g} \frac{d\rho_g}{dt} \]  

(7.19)

Assuming that \( ds = 0 \), as the change of entropy is negligible due to no heat input, the entropy can be eliminated to obtain a relationship between the changes of gas density and mixture density. Differentiating equation 7.18 leads to

\[ \frac{dp}{dt} = \frac{\gamma p \rho_g}{\rho_g} \frac{d\rho_g}{dt} - \frac{p \lambda \rho_l}{c_v T \rho} \frac{d\beta}{dt} - \frac{\rho_l p \lambda}{c_v T^2 \rho} (1.0 - \beta) \frac{dp}{dt} - \frac{\rho_l p \lambda}{c_v T \rho} (1.0 - \beta) \frac{dT}{dt} \]  

(7.20)
From thermodynamics entropy is defined as

\[ T \, ds = dh - \frac{dp}{\rho} \]

where \( h \) is the enthalpy. But \( ds = 0 \) and \( dh = c_p \, dT \) giving

\[ c_v \, \gamma \rho = \frac{dp}{dT} \]

Manipulation of the governing equations leads to

\[
\frac{dp}{dt} \frac{\lambda}{\rho g} \left[ \frac{1}{\rho g} - \frac{1}{\rho l} \right]^{-1} = \frac{d \rho_g}{dT} \left[ \frac{\rho}{\rho g} \left( 1.0 - \frac{\rho}{\lambda} \left( \frac{1}{\rho g} - \frac{1}{\rho l} \right) \right)^{-1} \left( \frac{\rho c_v}{\rho g} + \frac{\rho_l}{T} (1.0 - \beta) \left[ \frac{1}{\rho g} - \frac{1}{\rho l} \right] \right) \right. \\
- \frac{c_v \gamma \rho}{\rho g} - \frac{\lambda \beta \rho_l}{T (\rho g - \rho l)} \right]
\]

Solving these equations numerically provides new proportions and flow rates at incremented time steps.

### 7.4 Constant temperature - total heat input.

This section describes an alternative method to model the release. Consider a pressurised container which may contain a mixture of gas, condensate and oil in equilibrium. The assumption is made that the mixture is kept at a constant temperature throughout the leak process. The leak is assumed to consist of either gas and condensate or gas only. The oil is neglected in terms of leak flow and blowdown flow and only serves to reduce the volume of the container. To use the original model and consider \( \frac{dT}{dt} = 0.0 \) will not suffice, since density changes are calculated from equations originating from the Clausius Clapyron which assumes a change in temperature. Therefore an alternative method must be found. The mixture is assumed to be in 2 phase equilibrium, under such conditions the pressure is a function of the temperature, hence for a given temperature there is a given pressure. For the temperature and consequently pressure to be constant, whilst there is a leak there must be evaporation of the condensate to maintain the equilibrium. Once all the condensate has evaporated there is no longer a 2 phase mixture and the pressure begins to decrease.

Two situations are considered in the modelling. The first is a gas only release when condensate is present in the section. The second is a gas and condensate release. When there is no condensate within the section the temperature can not be kept constant hence the modelling does not change in this case.
7.4.1 Gas only leak.

If the leak is gas only whilst there is condensate in the section the discharge mass flow rate is $W = W_g$. This is a constant flow rate until the condensate has evaporated. The time at which all condensate has evaporated can be calculated by considering the changes in the volume and mass of gas within the vessel. The new volume of gas after a small time $\delta t$ is the original volume of gas plus the volume created from the evaporation of condensate.

$$V'_g = V_g + \frac{\delta m_{le}}{\rho_l} \quad (7.22)$$

where $\delta m_{le}$ is the mass of condensate evaporated.

The new mass of gas after $\delta t$ is

$$m'_g = m_g - \delta m_{gl} - \delta m_{gb} + \delta m_{le} \quad (7.23)$$

where $\delta m_{gl}$ is the mass of gas leaked and $\delta m_{gb}$ is the mass of gas blown down. As $\rho_g$ is constant whilst liquid remains dividing equation 7.23 by equation 7.22 and rearranging leads to the rate of evaporation

$$\frac{dm_{le}}{dt} = \frac{\frac{dm_{gl}}{dt} + \frac{dm_{gb}}{dt}}{1.0 - \frac{\rho_g}{\rho_l}} \quad (7.24)$$

Equation 7.24 will only be true if the blowdown has activated otherwise

$$\frac{dm_{le}}{dt} = \frac{dm_{gl}}{dt} = \frac{dm_{gb}}{dt} = \frac{W}{1.0 - \frac{\rho_g}{\rho_l}} \quad (7.25)$$

where $W_b$ is the blowdown flow rate.

If $t_d$ is the time at which the blowdown activates then the rates of evaporation are

$$t < t_d \quad \frac{dm_{le}}{dt} = \frac{-W}{1.0 - \frac{\rho_g}{\rho_l}} \quad (7.26)$$

$$t > t_d \quad \frac{dm_{le}}{dt} = \frac{-W - W_b}{1.0 - \frac{\rho_g}{\rho_l}} \quad (7.27)$$

Integrating Equation 7.27 with respect to time under the condition that the time of evaporation will occur when the mass of the liquid is zero gives the time of evaporation to be

$$t_{evap} = \frac{m_l(0)\left(1.0 - \frac{\rho_g}{\rho_l}\right) + W_b t_d}{W + W_b} \quad (7.28)$$
after this time the pressure and the density of the gas will decrease.

A differential equation exists to give the concentration of gas within the module

$$\frac{d c_g}{dt} + c_g \left( \frac{W_v + W_a}{V_m} \right) = \frac{W_v}{V_m} \tag{7.29}$$

where $V_m$ is the volume of the module, $W_v$ is the volume outflow into the module, $W_a$ is the volume discharge rate out of the module and $c_g$ is the concentration of gas.

$$W_v = \frac{W}{\rho_a}$$

Before the condensate evaporates equation 7.29 can be solved analytically

$$c_g = \frac{W_v}{W_v + W_a} \left[ 1.0 - e \left( -\left( \frac{W_v + W_a}{V_m} \right) t \right) \right] \tag{7.30}$$

Rearranging will give the time for any given concentration.

$$t = \frac{V_m}{W_a + W_v} \left[ \ln \left( \frac{W_v}{W_v - c_g (W_v + W_a)} \right) \right] \tag{7.31}$$

so if $t < t_{\text{evap}}$ the limits of the concentration bands (upper and lower flammable limits) can be converted into volume concentrations and substituted into equation 7.31 to determine the time at which these limits are reached. To determine whether $t < t_{\text{evap}}$ then the maximum concentration should be calculated.

$$c_{g_{\text{max}}} = \frac{W_v}{W_v + W_a} \left[ 1.0 - e \left( -\left( \frac{W_v + W_a}{V_m} \right) t_{\text{evap}} \right) \right] \tag{7.32}$$

Once the condensate has evaporated $W_v$ is no longer constant and so equation 7.29 must be solved numerically.

### 7.4.2 Gas and condensate leak.

Under the assumption that both gas and condensate can leak it is assumed that the leak flow is a combination of gas and condensate in the same proportions as the contents of the section in terms of volume.

$$W = \beta W_g + (1.0 - \beta) W_l \tag{7.33}$$

Whilst there is condensate in the section the flow rates of the gas and liquid are constant due to the constant density. But due to the evaporation of the condensate $\beta$ will increase with
Modelling the release.

time. This time dependence can be determined by considering the changes in the volume and mass of gas. The new volume of gas after time $\delta t$

$$V_g' = V_g + \frac{\delta m_{ll}}{\rho_l} + \frac{\delta m_{le}}{\rho_l} + \frac{\delta m_{lb}}{\rho_l}$$  \hspace{1cm} (7.34)

The new mass of gas after $\delta t$

$$m_g' = m_g - \delta m_{gl} - \delta m_{gb} + \delta m_{le}$$  \hspace{1cm} (7.35)

where $\delta m_{ll}$ is the mass of the condensate leaked and $\delta m_{lb}$ is the mass of the condensate blown down. Equations 7.34 and 7.35 only apply if the blowdown has activated, i.e., $t > t_d$.

Because the density of gas is constant, equations 7.34 and 7.35 can be used to determine the rate of evaporation.

- $t < t_d$

$$\frac{dm_{le}}{dt} = \frac{\rho_g (1.0 - \beta) W_l + \rho_l \beta W_g}{(\rho_l - \rho_g)}$$  \hspace{1cm} (7.36)

- $t > t_d$

$$\frac{dm_{le}}{dt} = \frac{\rho_g (1.0 - \beta) (W_l + W_{gb}) + \rho_l \beta (W_g + W_{gb})}{(\rho_l - \rho_g)}$$  \hspace{1cm} (7.37)

To determine $\beta$'s dependence on time consider the original definition of $\beta$

$$\beta = \frac{\text{volume of gas}}{\text{total volume}}$$

and differentiate with respect to time, then equate with either equation 7.36 or equation 7.37 depending on whether the blowdown has activated, this leaves a differential equation for $\beta$

- $t < t_d$

$$\frac{d\beta}{dt} = \frac{\beta W_g + (1.0 - \beta) W_l}{V (\rho_l - \rho_g)}$$  \hspace{1cm} (7.38)

- $t > t_d$

$$\frac{d\beta}{dt} = \frac{\beta (W_g + W_{gb}) + (1.0 - \beta) (W_l + W_{gb})}{V (\rho_l - \rho_g)}$$  \hspace{1cm} (7.39)

These can be solved to give

- $t < t_d$

$$\beta(t) = \left( \beta(0) + \frac{W_l}{W_g - W_l} \right) e^{\left(\frac{W_g - W_l}{V (\rho_l - \rho_g)}t\right)} - \frac{W_l}{W_g - W_l}$$  \hspace{1cm} (7.40)
• $t > t_d$

$$ \beta(t) = \left( \beta(t_d) + \frac{W_l + W_{lb}}{W_g + W_{gb} - W_l - W_{lb}} \right) e^{\left( \frac{W_g + W_{gb} - W_l - W_{lb}}{V_{p} - p_{p}} \right) (t_d - t)} \tag{7.41} $$

These are now substituted into the mass flow rate which is not constant hence a time stepping process is necessary to calculate the concentration of gas in the module.

The change in the volume of gas in the module is

$$ \frac{dV_{gm}}{dt} = W_v - c_g (W_v + W_a) \tag{7.42} $$

This gives the new volume of gas in the module which allows the calculation of the concentration.

As soon as there is only gas remaining in the section the pressure and densities will decrease. This means that the flow rate is solely gas where $W_g$ is either of the form of equations 7.9 or 7.6 depending on the flow being choked or unchoked. As the flow is not constant time stepping is again required.

### 7.5 The leak flow inventory.

The leaking sections can contain any mixture of gas, condensate and crude oil. The original model, (model 1), assumes that gas, condensate and oil all leak into the module in proportion to the mixture left within the leaking section. The condensate evaporates within the atmosphere and is considered along with the gas to effect the gas concentration of the module. The leakage of oil is considered to change the volume and proportions within the section, but has no effect on the concentration of gas in the module. Model 2 considers the leakage of gas and condensate. Oil is neglected and is only considered to reduce the volume within the leaking section. The leak is again assumed to be in proportion to the gas and condensate in the section. Model 3 considers a leak of gas only. Whilst gas is leaking the condensate is evaporating providing further gas.

Models 4 and 5 are constant temperature models. Model 4 considers the leakage of gas and condensate. Oil is neglected and is only considered to reduce the volume within the
leaking section. The leak is again assumed to be in proportion to the gas and condensate in the section. Model 5 considers a leak of gas only. Whilst gas is leaking the condensate is evaporating providing further gas. In all models whatever is considered to be the leak flow is also the blowdown flow.

The results are presented in three sections. The first section compares results from running the changing temperature model with different leak flow inventories. The second section compares the results of the constant temperature model with different leak flow inventories. The third section compares the two temperature state models with the most appropriate leak inventory.

7.6 Leak inventory comparison with the changing temperature model.

The 3 models considered in this section assume a change of temperature during the leak flow, relating to the decreasing pressure. The models differ only in the contents of the leak. (The form of the mixture blowing down to flare is assumed to mimic the form of the leak.)

Model 1 Gas, Condensate and Oil all leak into the module in proportion to the mixture left within the leaking section

Model 2 Gas and condensate leak into the module in proportion to the gas and condensate mixture left within the leaking section. Oil is neglected from the leak flow, but is considered to reduce the volume of the leaking section.

Model 3 Gas leaks into the module. The condensate is assumed to evaporate within the leaking section producing more gas and again the oil serves only to reduce the volume.

7.6.1 The separation module.

A leak detected in the separation module originates from either section 1 or section 3, the atmospheric and inlet separators. The volume of section 1 is 108.52 m$^3$ of which gas occupies 51.49 m$^3$ with oil occupying the remaining 57.03 m$^3$. Section 3 has a volume of 166.29 m$^3$. 
with 78.02 m³ of gas and 88.27 m³ of oil. Due to the amount of oil in the sections it is expected that model 1 will have significantly different results to models 2 and 3.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original modelling</td>
</tr>
<tr>
<td></td>
<td>model 1</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.25564×10⁻⁶</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.30446×10⁻⁷</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.14318×10⁻¹⁰</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.34135×10⁻⁵</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.36996×10⁻⁵</td>
</tr>
</tbody>
</table>

Table 7.1: Explosion frequency contributions from leaks on section 1 (per year) - comparison between models 1, 2 and 3.

Section 1 may connect to sections 3, 4, 5, 6 and 12. Should an isolation valve fail between sections the inventory of the leak will include the contents of the section adjacent to that valve. Sections 4, 5, 6 and 12 all contain a mixture of gas, oil and condensate therefore significant differences were expected between the different leak inventory models.

The gas only release, model 3, generates similar results to the gas, condensate and oil release, model 1. For section 1 the gas and condensate model, model 2, has the lowest explosion frequency. However the frequency of explosions prior to mitigation is higher than the other models with the frequency of mitigated explosions being lower.

The gas cloud within the module is formed from the leaking gas and condensate, assuming instant evaporation of the condensate. The leak is assumed to be in proportion to the contents of the contributing sections. For model 1 oil leaks but does not contribute to the gas cloud, however its proportion must be taken into account. The flow rate of the gas cloud mixture is

\[ \beta_g W_g + \beta_l W_l \quad \text{where} \quad \beta_g + \beta_l + \beta_o = 1 \]

For model 2 the oil does not leak so the proportions of the oil is taken to be zero. The values of the proportions of the gas and condensate are therefore higher leading to a higher leak flow rate than model 1. For model 3 the oil and condensate do not leak therefore the flow rate consists of gas only, \( W_g \). Due to the flow rate of the condensate being much higher
than that of gas the flow rate of model 3 is much lower than that of model 2. The possible inventory combinations connected with section 1 do not have a high proportion of condensate compared to those of the oil and gas so the flow rate for model 1 are dominated by the flow of gas. This leads to similar results between models 1 and 3. The higher flow rates of model 2 cause the gas cloud to build up quicker allowing more chance of an explosion prior to mitigation.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original modelling</td>
</tr>
<tr>
<td></td>
<td>model 1</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.27343x10^{-6}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.80344x10^{-7}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.43493x10^{-11}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.36032x10^{-5}</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.39570x10^{-5}</td>
</tr>
</tbody>
</table>

Table 7.2: Explosion frequency contributions from leaks on section 3 (per year) - comparison between models 1, 2 and 3.

Section 3 connects with sections 5 and 9. Section 5 contains gas, condensate and oil, whereas section 9 contains gas only. For section 3 the gas and condensate release model has the highest explosion frequency. As for section 1 the frequency of explosions occurring prior to mitigation are greatest for model 2 and the frequency of mitigated explosions are lowest.

<table>
<thead>
<tr>
<th>Model</th>
<th>Module explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.76566x10^{-5}</td>
</tr>
<tr>
<td>2</td>
<td>0.66656x10^{-5}</td>
</tr>
<tr>
<td>3</td>
<td>0.77142x10^{-5}</td>
</tr>
</tbody>
</table>

Table 7.3: The total explosion frequencies for the separation module (per year) - comparison between models 1, 2 and 3.

From Table 7.3 it can be seen that model 2 the gas and condensate release produces the lowest explosion frequency for the module with model 3 the gas only release producing the
highest frequency. The gas and condensate release leads to lower frequencies of explosions occurring due to a leak on section 1 but higher frequencies for explosions due to leaks on section 3.

Since the contents of sections 1 and 3 is a mixture of oil and gas it would be expected that there would be no significant difference between models 2 and 3, but isolation valves are not failsafe. A failure of isolation valves leads to the contents of other sections affecting the leak. Sections 1 and 3 are connected via such valves to sections 4, 5, 6, 9 and 12 which do contain condensate, leading to the difference in the models. Table 7.4 shows the importance of failures of the isolation valves in their contribution to an explosive situation.

<table>
<thead>
<tr>
<th>Connecting sections</th>
<th>Isolation valves</th>
<th>Importance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>model 1</td>
</tr>
<tr>
<td>1 3</td>
<td>34XV033</td>
<td>2.75</td>
</tr>
<tr>
<td>1 4</td>
<td>34XV090/001</td>
<td>22.31</td>
</tr>
<tr>
<td>1 5</td>
<td>35XV186</td>
<td>16.42</td>
</tr>
<tr>
<td>1 6</td>
<td>35XV092</td>
<td>6.80</td>
</tr>
<tr>
<td>1 12</td>
<td>41XV201</td>
<td>2.26</td>
</tr>
<tr>
<td>3 5</td>
<td>35XV125/149</td>
<td>17.34</td>
</tr>
<tr>
<td>3 9</td>
<td>33XV001</td>
<td>2.78</td>
</tr>
</tbody>
</table>

Table 7.4: The importance of the isolation valves in the separation module (percentage) - comparison between models 1, 2 and 3.

Isolation valves 34XV090 and 34XV001 connect section 1 to section 4, these are the most critical valves in the module for models 1 and 3. Over 20% of explosions occurring in the separation module are due to leaks on section 1 combined with the inventory of section 4 due to isolation failure. This is significantly reduced for model 2, this may be due to the high flow rates produced which leave less time within the explosive range. The isolation valve with the lowest contribution in models 1 and 3 is 41XV201 with an importance of 2.26% and 2.19% respectively. Using model 2 this increases to 6.44%, leaving valve 34XV033 between sections 1 and 3 as the least critical.

The criticality of each of the blowdown valves is tabulated in Table 7.5. The blowdown valve on section 3, 34XV031 is the most important for each model. Blowdown valves act to reduce
the pressure within the leaking section, should they fail there is no escape route for the gas or any relief to the pressure apart from through the leak hole. The different release models allow the mixture of blowdown fluids to be in the same proportion as the leak flow. The gas, condensate and oil release has an effectively reduced blowdown hole due to the oil, as soon as oil is restricted from blowing down the gas may depressurise faster as more of it can escape. The failure of the valve then becomes more critical.

<table>
<thead>
<tr>
<th>Section</th>
<th>Blowdown valve</th>
<th>Importance Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>model 1</td>
</tr>
<tr>
<td>3</td>
<td>34XV031</td>
<td>3.21</td>
</tr>
<tr>
<td>4</td>
<td>35XV044</td>
<td>0.429</td>
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<tr>
<td>4</td>
<td>35XV103</td>
<td>0.408</td>
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<tr>
<td>5</td>
<td>35XV171</td>
<td>0.636</td>
</tr>
<tr>
<td>5</td>
<td>35XV157</td>
<td>0.875</td>
</tr>
<tr>
<td>6</td>
<td>35XV277</td>
<td>0.207</td>
</tr>
<tr>
<td>6</td>
<td>35XV279</td>
<td>0.230</td>
</tr>
<tr>
<td>12</td>
<td>41XV002</td>
<td>0.041</td>
</tr>
</tbody>
</table>

Table 7.5: The importance of the blowdown valves in the separation module (percentage) - comparison between models 1, 2 and 3.

The isolation valves and blowdown valves will not always fail. The percentages of explosions originating from leaks on sections 1 and 3 when the isolation and blowdown systems work as designed are shown in Table 7.6. Many more explosions are attributed to section 3 when the isolation and blowdown systems work than section 1, indicating that sections adjoining section 3 have less influence on explosion frequency than those connected to section 1. For model 2 more importance is given to both sections under these categories suggesting that the importance of the isolation valves failing becomes less critical. Using model 1 1.18% of explosions occur due to a leak on section 1 when blowdown and isolation work, therefore most occasions when a leak occurs on this section, the contents of other sections influence the leak.
Table 7.6: The importance of the sections in the separation module when the isolation and blowdown works as designed (percentage) - comparison between models 1, 2 and 3.

Table 7.7 shows the percentage of explosions attributed to each of the mitigation categories. Mitigated explosions contribute the most to the explosion frequency calculations. For each model leaks on section 3 have a greater likelihood of resulting in an explosion. For model 2 the importance of section 3 decreases.

Table 7.7: Total importance measures for the categories of explosions in the separation module (percentage) - comparison of models 1, 2 and 3.

The range of overpressures generated is depicted in Figure 7.1a. The range of overpressures generated and the magnitude of the exceedence frequencies are similar for each model. Figure 7.1b shows the lower overpressures generated which have fairly high exceedence frequencies. The gas, condensate and oil release model, model 1, generates higher exceedence frequencies for this range of overpressures than the other two models, with model 2, gas and condens-
sate release, having the lower exceedence frequencies. However the critical overpressures are around 3 bar, at which point the platform may collapse or have its integrity seriously damaged. Figure 7.1c shows the exceedence frequencies of the higher overpressures. There is no structure to which model produces the higher and lower exceedence frequencies of the overpressures. At around 3 bar the gas and condensate model has the lowest exceedence frequency and the gas model has the highest.
Modelling the release.

a) The range of overpressures generated

Overpressure (bar)

b) The lower overpressures generated

Overpressure (bar)

c) The higher overpressures generated

Overpressure (bar)

Figure 7.1: Comparison of the overpressure exceedence for the separation module using models 1, 2 and 3.
7.6.2 The compression module.

Sections 4, 5, 6 and 8 (all compressors) can leak directly into the compression module. Pressures of these sections are high, sections 4, 5 and 6 are divided into subsections relating to different pressure values, some of these subsections contain a mixture of gas and condensate. Section 8 is also divided into subsections but these contain only gas. Model 3 therefore is expected to produce different results for all sections except section 8.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original modelling</td>
</tr>
<tr>
<td></td>
<td>model 1</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.36978 x10^-6</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.33777 x10^-6</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.50945 x10^-11</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.60035 x10^-5</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.67111 x10^-5</td>
</tr>
</tbody>
</table>

Table 7.8: Explosion frequency contributions from leaks on section 4 (per year) - comparison between models 1, 2 and 3.

Models 1 and 2 produce similar results for section 4. Isolation valve 35XV104 connects this section to section 5 which contains gas only. Valves 34XV090 and 34XV001 connect to section 1 which has a mixture of gas and oil. Therefore a leak on section 4 may involve gas, condensate or oil. The contribution of the oil to the leak must be negligible as the results for models 1 and 2 are very similar. However model 2 does appear to have a higher flow rate, as before, leading to a higher frequency of explosions occurring prior to mitigation activating and lower frequency of mitigated explosions. The failure of the valves between sections 1 and 4 contributes approximately 2% to the frequency of explosions within the module bearing out the assumption of a negligible oil contribution. Model 3 neglects the condensate leaking, this leads to lower flow rates which steadily increase the gas cloud and therefore the chance of an explosion. For section 4 the gas only release model, model 3, has the highest explosion frequency, with model 2 having the lowest.

Section 5 connects to sections 1, 3, 4 and 6, leading to combinations containing gas condens-
Modelling the release.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Original modelling</th>
<th>Revised leak flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 1</td>
<td>model 2</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.75120 × 10^{-6}</td>
<td>0.74552 × 10^{-6}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.68405 × 10^{-6}</td>
<td>0.70662 × 10^{-6}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.13361 × 10^{-10}</td>
<td>0.12659 × 10^{-10}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.12198 × 10^{-4}</td>
<td>0.12078 × 10^{-4}</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.13633 × 10^{-4}</td>
<td>0.13530 × 10^{-4}</td>
</tr>
</tbody>
</table>

Table 7.9: Explosion frequency contributions from leaks on section 5 (per year) - comparison between models 1, 2 and 3.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Original modelling</th>
<th>Revised leak flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 1</td>
<td>model 2</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.45962 × 10^{-6}</td>
<td>0.46250 × 10^{-6}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.63053 × 10^{-6}</td>
<td>0.63419 × 10^{-6}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.43807 × 10^{-11}</td>
<td>0.43852 × 10^{-11}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.72514 × 10^{-5}</td>
<td>0.72972 × 10^{-5}</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.83416 × 10^{-5}</td>
<td>0.83939 × 10^{-5}</td>
</tr>
</tbody>
</table>

Table 7.10: Explosion frequency contribution from leaks on section 6 (per year) - comparison between models 1, 2 and 3.

sate and oil hence there are differences between the results of the three models. Model 2 has the lowest explosion frequency contribution and model 3 has the highest. With model 3 the flow rate is reduced, prolonging the length of time it takes to exhaust the gas, so that the concentration stays within the explosive range for a longer period. The lower flow rate also means that it takes longer for the gas cloud to build up to a flammable concentration level. This may account for the low frequency of explosions occurring prior to mitigation and high frequency of mitigated explosions and those occurring if the mitigation fails to be maintained with model 3 compared to models 1 and 2. The higher flow rate of model 2 yields a greater frequency of explosions occurring prior to mitigation and a lower frequency of the other categories.
Modelling the release.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Original modelling model 1</th>
<th>Revised leak flow model 2</th>
<th>Revised leak flow model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>mitigation fails to activate</td>
<td>$0.11795 \times 10^{-6}$</td>
<td>$0.11795 \times 10^{-6}$</td>
<td>$0.11808 \times 10^{-6}$</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>$0.76433 \times 10^{-6}$</td>
<td>$0.76433 \times 10^{-6}$</td>
<td>$0.76538 \times 10^{-6}$</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>$0.31731 \times 10^{-12}$</td>
<td>$0.31731 \times 10^{-12}$</td>
<td>$0.31833 \times 10^{-12}$</td>
</tr>
<tr>
<td>mitigated</td>
<td>$0.12584 \times 10^{-5}$</td>
<td>$0.12584 \times 10^{-5}$</td>
<td>$0.12596 \times 10^{-5}$</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>$0.21407 \times 10^{-5}$</td>
<td>$0.21407 \times 10^{-5}$</td>
<td>$0.21431 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Table 7.11: Explosion frequency contribution from leaks on section 8 (per year) - comparison between models 1, 2 and 3.

Section 6 connects to sections 1, 5, 7, 8 and 12 which again gives combinations with mixtures of gas, condensate and oil. As for section 5 model 3 has the highest frequency of an explosion, however the lowest is generated by model 1. In this case the explosions prior to mitigation have a higher frequency of occurrence with model 2 than with model 1 due to a higher release rate, but unlike other cases the mitigated explosions are not reduced. This indicates that the concentration profile from model 1 did not reach the flammable region in some cases whereas the higher release rates of model 2 cause the concentration to be flammable. Explosions when the mitigation system fails to activate are dependent upon the whole time the concentration is within the flammable region, hence for the frequency of such explosions to be larger for model 2 than model 1, the time within the explosive range must be larger. Section 8 connects to sections 6, 10, 11 and 13. None of these sections contain oil hence a leak on section 8 will make the same contribution to the explosion frequency whether using models 1 or 2. However there is condensate in section 6, the failure of isolation valve 35XV306 will join the inventory of section 6 to that of section 8, introducing condensate to the leak flow. The removal of condensate from the leak flow, model 3, generates slight differences in the results. For section 8 model 3 leads to the highest explosion frequencies. Table 7.12 shows the total explosion frequencies for the module. Overall model 2 has the lowest explosion frequency and model 3 has the highest. This follows the pattern demonstrated for the separation module.

Since sections 4, 5, 6 and 8, the sections that may leak directly into the compression module, contain only gas and condensate, it would be expected that models 1 and 2 would produce the same results. However these sections are connected by isolation valves to other sections.
Modelling the release.

<table>
<thead>
<tr>
<th>Model</th>
<th>Module explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$0.30827 \times 10^{-4}$</td>
</tr>
<tr>
<td>2</td>
<td>$0.30776 \times 10^{-4}$</td>
</tr>
<tr>
<td>3</td>
<td>$0.33835 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 7.12: The total explosion frequencies for the compression module (per year) - comparison between models 1, 2 and 3.

that also contain oil. The percentage of explosions that occur in the compression module when the isolation and blowdown systems work as designed are shown in Table 7.13. Due to the individual sections containing no oil the percentage of explosions occurring when the isolation and blowdown work are identical for models 1 and 2. For model 3 more importance is given to sections 4 and 6.

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>16.6</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>34.3</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>6.1</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>16.6</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>34.3</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>6.1</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>18.7</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>32.8</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table 7.13: The importance of the sections in the compression module when the isolation and blowdown works as designed (percentage) - comparison between models 1, 2 and 3.

In all cases leaks on section 5 are the most critical. Since over 30% of explosions occur due to leaks on section 5 when the safety systems activate this suggests that the sections connecting to section 5 have less influence on the explosion frequency for the module than
those connecting to the other sections. Table 7.14 shows the importance of the isolation valves. High importance shows that the explosion frequency is influenced by that connecting section.

<table>
<thead>
<tr>
<th>Connecting sections</th>
<th>Isolation valves</th>
<th>Importance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>model 1</td>
</tr>
<tr>
<td>4 1</td>
<td>34XV090/001</td>
<td>1.907</td>
</tr>
<tr>
<td>4 5</td>
<td>35XV104</td>
<td>3.70</td>
</tr>
<tr>
<td>5 1</td>
<td>35XV186</td>
<td>1.15</td>
</tr>
<tr>
<td>5 3</td>
<td>35XV125/149</td>
<td>2.43</td>
</tr>
<tr>
<td>5 6</td>
<td>35XV172</td>
<td>4.96</td>
</tr>
<tr>
<td>6 1</td>
<td>35XV092</td>
<td>0.487</td>
</tr>
<tr>
<td>6 7</td>
<td>XVX3</td>
<td>2.92</td>
</tr>
<tr>
<td>6 8</td>
<td>35XV306</td>
<td>0.360</td>
</tr>
<tr>
<td>6 12</td>
<td>41XV053</td>
<td>0.503</td>
</tr>
<tr>
<td>8 10</td>
<td>35XV383</td>
<td>0.016</td>
</tr>
<tr>
<td>8 11</td>
<td>N1</td>
<td>0.060</td>
</tr>
<tr>
<td>8 13</td>
<td>90XV6/7</td>
<td>0.303</td>
</tr>
</tbody>
</table>

Table 7.14: The importance of the isolation valves in the compression module (percentage) - comparison between models 1, 2 and 3.

Isolation valve 35XV172, connecting sections 5 and 6, is the most critical valve. Failure of this valve contributes approximately 5% to the frequency with models 1 and 2. This value increases for model 3 with a decrease in the importance of valves 34XV090 and 34XV001 between section 1 and 4. The importance of the isolation valves within the compression module are insignificant compared to those in the separation module. Due to the high pressures within sections 4, 5, 6 and 8 in the compression module, explosive scenarios are produced without the addition of further material making the importance of the isolation failures insignificant.

The pressures driving the leak flow may be diminished with the aid of blowdown valves which act to relieve the pressure of the section. The criticality of these valves is shown in Table 7.15.
Table 7.15: The importance of the blowdown valves in the compression module (percentage) - comparison between models 1, 2 and 3.

Blowdown valve 35XV279 on section 6 is the most critical, although the percentage of explosions attributed to its failure are negligible compared to those which occur when the blowdown works.

The mitigation state of the explosion is identified in the frequencies, this is also the case in Table 7.16 where the percentages of the explosions occurring in each section are listed according to the mitigation status.

In all models leaks on section 5 contribute the most to the explosion frequency. Leaks on section 8 appear to be negligible compared to other sections.

Figure 7.2a shows the range of overpressures generated within the compression module when a gas cloud builds up. The exceedence frequencies of the overpressures are similar for each model, although it does appear that the gas only release, model 3, generates lower exceedence frequencies of the overpressures than the other two models. Figure 7.2b shows a close up of the lower overpressures generated. The lowest overpressures have a higher frequency of
Modelling the release.

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Category of explosion</th>
<th>mitigation fails to activate</th>
<th>prior to mitigation</th>
<th>mitigation not maintained</th>
<th>mitigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>1.19</td>
<td>1.09</td>
<td>0.165×10^{-4}</td>
<td>19.48</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.44</td>
<td>2.22</td>
<td>0.433×10^{-4}</td>
<td>39.57</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.49</td>
<td>2.04</td>
<td>0.142×10^{-4}</td>
<td>23.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.383</td>
<td>2.48</td>
<td>0.103×10^{-5}</td>
<td>4.08</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>1.20</td>
<td>1.10</td>
<td>0.159×10^{-4}</td>
<td>19.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.42</td>
<td>2.29</td>
<td>0.411×10^{-4}</td>
<td>39.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.50</td>
<td>2.06</td>
<td>0.142×10^{-4}</td>
<td>23.71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.383</td>
<td>2.48</td>
<td>0.103×10^{-5}</td>
<td>4.08</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>1.26</td>
<td>0.09</td>
<td>0.499×10^{-4}</td>
<td>21.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.39</td>
<td>1.02</td>
<td>0.634×10^{-4}</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.50</td>
<td>1.76</td>
<td>0.208×10^{-4}</td>
<td>24.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.35</td>
<td>2.26</td>
<td>0.941×10^{-6}</td>
<td>3.72</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.16: Total importance measures for the categories of explosions in the compression module (percentage) - comparison of models 1, 2 and 3.

exceedence when using model 3, until approximately 0.025 bar. Any overpressures above this value have a lower frequency of exceedence for model 3 than models 1 and 2. The gas and condensate release, model 2, closely mirrors the exceedence frequency distribution of the overpressures generated by model 1, however the exceedence frequencies with model 2 are slightly higher. Figure 7.2c shows the exceedence frequencies of the overpressures centred around 3 bar.
Modelling the release.

Figure 7.2: Comparison of the overpressure exceedence for the compression module with models 1, 2 and 3.
7.6.3 The wellhead module.

Leaks in the wellhead module originate in section 9, 10 or 11, each of which contains only gas. Via the failure of isolation valves these sections may connect to sections 3, 8, 14, 15 and 16. Sections 3 and 14 contain a mixture of gas and oil, therefore neglecting oil from the model is expected to have some influence on the results. Sections 8, 15 and 16 contain only gas. In any combination there is no condensate available to leak into this module, hence models 2 and 3 should produce identical results.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original modelling</td>
</tr>
<tr>
<td></td>
<td>model 1</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.10630x10^-7</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.14597x10^-7</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.42827x10^-12</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.23093x10^-6</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.25615x10^-6</td>
</tr>
</tbody>
</table>

Table 7.17: Explosion frequency contribution from leaks in section 9 (per year) - comparison between models 1, 2 and 3.

Section 9 connects to section 3 via isolation valve 33XV001 and section 14 via valve WELL19, these sections contain oil therefore giving differences between models 1 and 2. As there is no condensate in these sections there is no difference between models 2 and 3. All the models generate a flow rate entirely dependent on the flow rate of gas multiplied by the proportion of gas within that section. For models 2 and 3 this proportion is 1, but for model 1 it depends on the proportion of oil therefore giving a lower flow rate for model 1. As the results for all categories of explosions are higher for model 1 than models 2 and 3 this suggests that the higher flow rates lead to a gas cloud concentration outside the flammable region whereas the lower flow rate of model 1 generates a gas cloud whose concentration remains within the explosive region for a longer period of time. The results from the three models are identical for section 10, this is because the only possible connection is to section 8 which also contains only gas. Section 11 connects to sections 8 and 16 which only contain gas therefore leading to identical results between the models. It can be seen that the explosion
Table 7.18: Explosion frequency contribution from leaks in section 10 (per year) - comparison of models 1, 2 and 3.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
<th>Original modelling</th>
<th>Revised leak flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>model 1</td>
<td>model 2</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.12951x10^{-7}</td>
<td>0.12951x10^{-7}</td>
<td>0.12951x10^{-7}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.48445x10^{-8}</td>
<td>0.48445x10^{-8}</td>
<td>0.48445x10^{-8}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.25378x10^{-12}</td>
<td>0.25378x10^{-12}</td>
<td>0.25378x10^{-12}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.29427x10^{-6}</td>
<td>0.29427x10^{-6}</td>
<td>0.29427x10^{-6}</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.31207x10^{-6}</td>
<td>0.31207x10^{-6}</td>
<td>0.31207x10^{-6}</td>
</tr>
</tbody>
</table>

Table 7.19: Explosion frequency contribution from leaks in section 11 (per year) - comparison between models 1, 2 and 3.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
<th>Original modelling</th>
<th>Revised leak flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>model 1</td>
<td>model 2</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.26400x10^{-7}</td>
<td>0.26400x10^{-7}</td>
<td>0.26400x10^{-7}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.11970x10^{-8}</td>
<td>0.11970x10^{-8}</td>
<td>0.11970x10^{-8}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.10228x10^{-12}</td>
<td>0.10228x10^{-12}</td>
<td>0.10228x10^{-12}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.59777x10^{-6}</td>
<td>0.59777x10^{-6}</td>
<td>0.59777x10^{-6}</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.63614x10^{-6}</td>
<td>0.63614x10^{-6}</td>
<td>0.63614x10^{-6}</td>
</tr>
</tbody>
</table>

Table 7.20: The total explosion frequencies for the wellhead module (per year) - comparison between models 1, 2 and 3.

<table>
<thead>
<tr>
<th>Model</th>
<th>Module explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.12044x10^{-5}</td>
</tr>
<tr>
<td>2</td>
<td>0.11883x10^{-5}</td>
</tr>
<tr>
<td>3</td>
<td>0.11883x10^{-5}</td>
</tr>
</tbody>
</table>
frequency contributions only change for section 9 as this is the section connecting to the oil. Changes in the model have no influence on the contributions from sections 10 and 11 as these sections involve only gas. Table 7.20 shows the explosion frequencies for the module using each model. As predicted models 2 and 3 give identical results. The overall explosion frequency for the module is reduced when the oil is removed from the model.

The differences in the models comes from failure of isolation valves 33XV001 and WELL19. Table 7.21 shows the contribution that explosions when the valves fail make to the overall explosion frequency for the module.

<table>
<thead>
<tr>
<th>Connecting sections</th>
<th>Isolation valves</th>
<th>Importance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>model 1</td>
</tr>
<tr>
<td>9 3</td>
<td>33XV001</td>
<td>15.78</td>
</tr>
<tr>
<td>9 14</td>
<td>WELL19</td>
<td>0.272</td>
</tr>
<tr>
<td>10 8</td>
<td>35XV383</td>
<td>0.063</td>
</tr>
<tr>
<td>10 15</td>
<td>WELL2</td>
<td>0.032</td>
</tr>
<tr>
<td>11 8</td>
<td>N1</td>
<td>52.82</td>
</tr>
<tr>
<td>11 16</td>
<td>WELL5</td>
<td>0.160</td>
</tr>
</tbody>
</table>

Table 7.21: The importance of the isolation valves in the wellhead module (percentage) - comparison between models 1, 2 and 3.

When oil is neglected from the model the percentage of explosions due to leaks on section 9 when the isolation fails is reduced. In all models the failure of the non return valve N1, connecting section 11 to section 8, accounts for over 50% of the explosions. The isolation may work as designed therefore meaning that a leak on section 9 involves only the contents of section 9. Table 7.22 gives the percentage of explosions which occur when this is the case.
Modelling the release.

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>5.24</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>25.82</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>5.31</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>26.17</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>5.31</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>26.17</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 7.22: The importance of the sections in the wellhead module when the isolation and blowdown works as designed (percentage) - comparison between models 1, 2 and 3.

If the isolation valves work as designed and a leak occurs on section 11 then there is no contribution to the explosion frequency due to the gas cloud never building up to concentration levels within the flammable region.

The pressure of the section is relieved using blowdown valves should a leak occur. The importance of these valves is given in Table 7.23.

<table>
<thead>
<tr>
<th>Section</th>
<th>Blowdown valve</th>
<th>Importance Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>model 1</td>
</tr>
<tr>
<td>3</td>
<td>34XV031</td>
<td>0.439</td>
</tr>
<tr>
<td>8</td>
<td>35XV422</td>
<td>1.93</td>
</tr>
<tr>
<td>8</td>
<td>35XV382</td>
<td>1.11</td>
</tr>
</tbody>
</table>

Table 7.23: The importance of the blowdown valves in the wellhead module (percentage) - comparison between models 1, 2 and 3.

The blowdown valve 35XV422 on section 8 is the most critical, since the majority of the explosions occur when the gas cloud is influenced by the contents of this section it would be expected that this valve is important. Blowdown valve 34XV031 reduces in importance when oil is removed from the model. This valve is on section 3 which contains oil and therefore has
Modelling the release.

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Category of explosion</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mitigation fails to activate</td>
<td>prior to mitigation</td>
<td>mitigation not maintained</td>
<td>mitigated</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>9</td>
<td>0.883</td>
<td>1.21</td>
<td>0.356×10⁻⁴</td>
<td>19.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.07</td>
<td>0.40</td>
<td>0.211×10⁻⁴</td>
<td>24.43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>2.19</td>
<td>0.99</td>
<td>0.849×10⁻⁴</td>
<td>49.63</td>
<td></td>
</tr>
<tr>
<td>2 &amp; 3</td>
<td>9</td>
<td>0.838</td>
<td>1.02</td>
<td>0.334×10⁻⁴</td>
<td>18.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.09</td>
<td>0.40</td>
<td>0.214×10⁻⁴</td>
<td>24.76</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>2.22</td>
<td>1.01</td>
<td>0.861×10⁻⁴</td>
<td>50.31</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.24: Total importance measures for the categories of explosions in the wellhead module (percentage) - comparison of models 1, 2 and 3.

less influence on the explosion frequency when oil is not considered. The blowdown valves in the wellhead module are not as critical as those in the other modules, the reliability of the isolation valves is much more important.

Table 7.24 shows the percentages of explosions categorised according to the type of explosion. The most explosions occur due to leaks originating on section 11.

The frequency of the exceedence of the overpressures produced are shown in Figure 7.3a these appear to be very similar for each model. The close up of the lower overpressures, Figure 7.3b, does indeed show the frequencies of exceedence to be identical, however the larger overpressures, Figure 7.3c, have a lower frequency of exceedence when oil is neglected from the model.
Modelling the release.

Figure 7.3: Comparison of the overpressure exceedence for the wellhead module for models 1, 2 and 3.
7.6.4 Conclusion of the leak inventory comparison with the changing temperature models.

Model 2 generates higher release rates therefore in most cases the concentration rises rapidly through the flammable region earlier than model 1. Due to this the explosions prior to the mitigation activating have a higher frequency of occurrence than for model 1. In general the total explosion frequency is lower for model 2 than model 1, although this does depend on the inventory combination within the sections leaking. Model 3 involves only gas releasing which has a lower exit speed than the condensate hence the concentration is slower to rise and slower to leave the flammable region leading to a higher explosion frequency.

Models 2 and 3 appear to provide the upper and lower bounds for the explosion frequency. Model 1 is a feasible model but is also the least likely scenario. The relative densities of gas, condensate and oil mean that oil is most likely to settle at the base of the vessel and so reducing the likelihood of a leak involving oil. Since oil is not a consideration in the explosive mixture contributing to the gas cloud this model is neglected in favour of model 2 or 3.

Model 3 provides higher frequencies of explosions due to the longer time taken to release the gas, hence it may be sensible to opt for this model as it errs on the side of caution. However a leak of condensate contributes to the gas cloud by evaporation and so to ignore this in the leak could reduce the amount of mixture within the gas cloud. Therefore model 2, the gas and condensate release, is taken as the standard model for future work in this project.

7.7 Leak inventory comparison with the constant temperature model.

These results are obtained when the program is altered to assume that there is constant temperature in the leaking vessel throughout the leak process. The models under consideration are models 4 and 5, a leak inventory including oil has been neglected.

Model 4 Gas and Condensate leak into the module in proportion to the gas and condensate mixture left in the leaking section. Any oil in the section serves to reduce the volume of the section.
Model 5 Gas leaks into the module. Condensate evaporates during the leak process.

7.7.1 The separation module.

The separation module can have an explosive concentration of gas within it due to leaks from sections 1 and 3, the atmospheric and inlet separators. These sections contain only gas and oil, therefore at first glance it could be suggested that the 2 models will not differ due to a lack of condensate, however sections 1 and 3 connect, via isolation valves, to sections 4, 5, 6, 9 and 12 which do contain condensate. Failure of an isolation valve will lead to condensate being introduced, hence differences between the models.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 4</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>$0.25166 \times 10^{-6}$</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>$0.72961 \times 10^{-7}$</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>$0.89196 \times 10^{-11}$</td>
</tr>
<tr>
<td>mitigated</td>
<td>$0.33173 \times 10^{-5}$</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>$0.36419 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Table 7.25: Explosion frequency contributions from leaks in section 1 (per year) - comparison between models 4 and 5.

The gas and condensate release of model 4 provides a higher frequency of an explosion occurring due to a leak on section 1 than the gas only release of model 5. The frequency of explosions prior to mitigation are higher for model 4, but the mitigated explosions and explosions when the mitigation is not maintained have lower frequencies of occurrence. The frequencies of explosions when the mitigation fails to activate are directly dependent on the time spent within the flammable region. As the frequencies are very similar for both models, this indicates that the time spent within the explosive range is the same for both models. The frequency of explosions prior to mitigation being higher for model 4 suggests that more time is spent within the explosive range before the mitigation activates but less is spent after this.
Modelling the release.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 4</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.37588×10^-6</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.28162×10^-6</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.64599×10^-11</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.47821×10^-5</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.54396×10^-5</td>
</tr>
</tbody>
</table>

Table 7.26: Explosion frequency contributions from leaks in section 3 (per year) - comparison between models 4 and 5.

For section 3 the explosion frequency contributions are higher for model 4 than model 5 for all categories of explosions except those when the mitigation is not maintained.

<table>
<thead>
<tr>
<th>Model</th>
<th>Module explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.90815×10^-5</td>
</tr>
<tr>
<td>5</td>
<td>0.87009×10^-5</td>
</tr>
</tbody>
</table>

Table 7.27: The total explosion frequencies for the separation module (per year) - comparison between models 4 and 5.

The total explosion frequencies for leaks into the separation module are shown in Table 7.27 for models 4 and 5. It can be seen that the gas and condensate release of model 4 produces higher explosion frequencies than the gas only release of model 5. The explosion frequency results demonstrated for the separation module with the constant temperature model contradict those gained for the changing temperature model. With constant temperature the driving pressure remains constant whilst condensate remains in the section. For this to occur evaporation of the condensate must take place, once the condensate has evaporated the pressure reduces. With a gas only release the flow rate is lower as there is no contribution from the condensate which has a higher release rate than gas. With a lower flow rate the time for the condensate to evaporate is slower therefore the pressure remains constant for a longer period. Therefore a gas and condensate release expels the fluids quickly initially then the pressure drops off and the flow rate reduces, however the gas only release starts off slower but remains at constant pressure for a longer period. Such a scenario could result in
the gas only model exhausting its supply faster and therefore spending less time within the explosive range. The percentages of explosions due to each section are illustrated in Table 7.28, categorised into types of explosions.

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Category of explosion</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mitigation fails to activate</td>
<td>prior to mitigation</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2.77</td>
<td>0.803</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.14</td>
<td>3.10</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>2.89</td>
<td>0.257</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.02</td>
<td>2.85</td>
</tr>
</tbody>
</table>

Table 7.28: Total importance measures for the category of explosions in the separation module (percentages) - comparison between models 4 and 5.

The majority, over 50%, of explosions occur in the separation module due to leaks in section 3. With model 5 the importance of section 3 falls as that of section 1 rises this indicates that the condensate has more effect for leaks from section 3, so that when this is removed the importance of section 3 decreases.

With the isolation and blowdown system working as designed section 3 contributes over 30% to the explosion frequency, see Table 7.29. This sections contribution increases when the leak ignores the condensate as sections containing condensate reduce their importance when it is neglected. Leaks occurring on section 1 with no contribution from another section due to closure of the isolation valves do not generate gas clouds within the explosive range for either model.

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>30.76</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>32.10</td>
</tr>
</tbody>
</table>

Table 7.29: The importance of the sections in the separation module when the isolation and blowdown works as designed (percentage) - comparison between models 4 and 5.
Modelling the release.

Due to model 5 neglecting condensate from the release it is expected that the isolation valves that connect to those sections containing condensate would reduce in their importance. However from Table 7.30 it can be seen that this is not strictly the case. Section 4 contains condensate yet its importance increases dramatically when condensate is removed from the leak. Unlike the changing temperature models, when the section contains condensate yet the release is gas only the constant temperature model still relies heavily on the amount of condensate. The condensate keeps the pressure constant and therefore in most cases provides a higher flow rate and so exhausts the section quicker.

<table>
<thead>
<tr>
<th>Connecting sections</th>
<th>Isolation valves</th>
<th>Importance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>model 4</td>
</tr>
<tr>
<td>1 3</td>
<td>34XV033</td>
<td>2.74</td>
</tr>
<tr>
<td>1 4</td>
<td>34XV090/001</td>
<td>7.92</td>
</tr>
<tr>
<td>1 5</td>
<td>35XV186</td>
<td>17.63</td>
</tr>
<tr>
<td>1 6</td>
<td>35XV092</td>
<td>9.18</td>
</tr>
<tr>
<td>1 12</td>
<td>41XV201</td>
<td>7.03</td>
</tr>
<tr>
<td>3 5</td>
<td>35XV125/149</td>
<td>16.55</td>
</tr>
<tr>
<td>3 9</td>
<td>33XV001</td>
<td>2.98</td>
</tr>
</tbody>
</table>

Table 7.30: The importance of the isolation valves in the separation module (percentage) - comparison between models 4 and 5.

Isolation valve 35XV186 between sections 1 and 5 is the most critical valve for model 4, followed by 35XV125 and 35XV149 between sections 3 and 5. For model 5 these valves are still important however the most critical valves are 34XV090 and 34XV001 between sections 1 and 4.

As section 3 contributes the most to the explosion frequency it is not surprising that the blowdown valve on this section is the most critical. When using the gas only release of model 5 the importance of the blowdown valves on section 4 increase. The percentages of explosions occurring when blowdown valves fail are compared in Table 7.31.
Table 7.31: The importance of the blowdown valves in the separation module (percentage) - comparison between models 4 and 5.

The exceedence frequencies of the overpressures generated are depicted in Figure 7.4a over the whole range of those generated. The higher exceedence frequencies are associated with the lower overpressures as seen in Figure 7.4b. It appears that the majority of the time the gas only release of model 5 generates higher exceedence frequencies of overpressures. The critical overpressures are the higher ones shown in Figure 7.4c.
Modelling the release.

Figure 7.4: Comparison of the overpressure exceedence for the separation module with models 4 and 5.
7.7.2 The compression module.

Leaks in the compression module originate from sections 4, 5, 6 and 8. These sections contain gas and condensate, hence due to the presence of condensate it is assumed that the 2 models will produce significantly different results.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 4</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.49557×10^{-6}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.34172×10^{-6}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.76631×10^{-11}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.81566×10^{-5}</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.89939×10^{-5}</td>
</tr>
</tbody>
</table>

Table 7.32: Explosion frequency contributions from leaks in section 4 (per year) - comparison between models 4 and 5.

The frequencies of explosions on section 4 are higher for model 4 than for model 5. This is due to section 4, and section 5 which it may link with, having condensate within them. This means that not only will the pressure be constant but the flow rate will be larger due to the influence of the condensate. The frequency of explosions when the mitigation fails to activate is higher for the gas and condensate release of model 4 indicating that with this model the gas concentration remains within the flammable region for a longer period of time than the gas only release of model 5. The frequency of explosions occurring prior to mitigation is also larger for model 4, therefore the concentration rose into the flammable region earlier than for model 5.
Modelling the release.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 4</td>
<td>model 5</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>$0.14860 \times 10^{-5}$</td>
<td>$0.87152 \times 10^{-6}$</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>$0.70692 \times 10^{-6}$</td>
<td>$0.29603 \times 10^{-6}$</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>$0.46248 \times 10^{-10}$</td>
<td>$0.24730 \times 10^{-10}$</td>
</tr>
<tr>
<td>mitigated</td>
<td>$0.24776 \times 10^{-4}$</td>
<td>$0.14650 \times 10^{-5}$</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>$0.26968 \times 10^{-4}$</td>
<td>$0.15817 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 7.33: Explosion frequency contributions from leaks on section 5 (per year) - comparison between models 4 and 5.

For section 5 the explosion frequency for model 4 is higher than that for model 5. Again the results indicate that the concentration of the gas cloud is within the explosive range for a longer period of time and enters it earlier.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 4</td>
<td>model 5</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>$0.98743 \times 10^{-6}$</td>
<td>$0.71837 \times 10^{-6}$</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>$0.63425 \times 10^{-6}$</td>
<td>$0.56297 \times 10^{-6}$</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>$0.15379 \times 10^{-10}$</td>
<td>$0.13465 \times 10^{-10}$</td>
</tr>
<tr>
<td>mitigated</td>
<td>$0.16279 \times 10^{-4}$</td>
<td>$0.11756 \times 10^{-4}$</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>$0.17921 \times 10^{-4}$</td>
<td>$0.13038 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 7.34: Explosion frequency contributions from leaks on section 6 (per year) - comparison between models 4 and 5.

For section 6 the explosion frequencies of each of the categories is higher with model 4 than with model 5. This indicates a longer period within the explosive range and also higher concentration level generation.
Modelling the release.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 4</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>$0.12114 \times 10^{-6}$</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>$0.76016 \times 10^{-6}$</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>$0.40518 \times 10^{-12}$</td>
</tr>
<tr>
<td>mitigated</td>
<td>$0.13172 \times 10^{-5}$</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>$0.21985 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Table 7.35: Explosion frequency contributions from leaks on section 8 (per year) - comparison between model 4 and 5.

Explosions occurring due to leaks on section 8 have similar frequencies of occurrence with models 4 and 5. This is due to the low amounts of condensate that may contribute to the leak. The condensate does affect the calculation of the release rate. It appears that the higher release rate causes the condensate to evaporate rapidly dropping the pressure of the leak and the flow rate whereas the lower release rates do not lead to such a quick evaporation and hence keep the leak at constant pressure longer, therefore in turn leading to a quicker exhaustion of the gas. Model 4 keeps the concentration level within the flammable region for longer, however the high release rates send this concentration above the upper flammable limit before mitigation activates. With model 5 the upper flammable limit is not exceeded as quickly, hence giving a higher frequency of explosions occurring prior to the mitigation activating with model 5 rather than with model 4 as seen in previous cases.

<table>
<thead>
<tr>
<th>Model</th>
<th>Module explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$0.56081 \times 10^{-4}$</td>
</tr>
<tr>
<td>5</td>
<td>$0.38830 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 7.36: The total explosion frequencies for the compression module (per year) - comparison between models 4 and 5.

The explosion frequencies are higher when using model 4 than for model 5. This suggests that neglecting the condensate will affect the concentration levels.

The percentages of explosions due to a leak in each section are illustrated in Table 7.37,
Modelling the release.

categorised into types of explosions. In both models leaks occurring on section 5 have the
greater importance. For model 5 this importance reduces whilst the rest of the sections
increase in their percentage contribution.

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Category of explosion</th>
<th>mitigation fails to activate</th>
<th>prior to mitigation</th>
<th>mitigation not maintained</th>
<th>mitigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4</td>
<td></td>
<td>0.884</td>
<td>0.609</td>
<td>0.137x10^-4</td>
<td>14.54</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>2.65</td>
<td>1.26</td>
<td>0.825x10^-4</td>
<td>44.18</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>1.76</td>
<td>1.13</td>
<td>0.274x10^-4</td>
<td>29.06</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>0.22</td>
<td>1.35</td>
<td>0.722x10^-6</td>
<td>2.35</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td></td>
<td>1.10</td>
<td>0.058</td>
<td>0.446x10^-4</td>
<td>18.88</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>2.24</td>
<td>0.762</td>
<td>0.637x10^-4</td>
<td>37.72</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>1.85</td>
<td>1.45</td>
<td>0.347x10^-4</td>
<td>30.28</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>0.31</td>
<td>1.96</td>
<td>0.104x10^-5</td>
<td>3.38</td>
</tr>
</tbody>
</table>

Table 7.37: Total importance measures for the category of explosions in the compression
module (percentages) - comparison between models 4 and 5.

The contributions of each of these sections takes into account any adjacent sections if the
isolation valves have failed. Table 7.38 gives the percentage of explosions which occur when
the safety systems are working so any explosive mixture produced is solely down to the
section with the leak.
Table 7.38: The importance of the sections in the compression module when the isolation and blowdown works as designed (percentage)- comparison between models 4 and 5.

Section 5 has the highest contribution to the frequency of explosions when its safety systems work as designed. As this section generates explosive gas clouds on its own the isolation valves connecting it to other sections are likely to be critical as further leak inventory may prolong the time at which the concentration is within the explosive range. From Table 7.39 it can be seen that this hypothesis was correct.
Table 7.39: The importance of the isolation valves in the compression module (percentage) - comparison between models 4 and 5.

Isolation valve 35XV172 connecting sections 5 and 6 is the most critical for both models. The blowdown valves act to reduce the pressure of the section therefore reducing the frequency of an explosion. As most explosions are likely to occur from section 5 and the isolation valves are the most critical between sections 5 and 6, then it follows that the blowdown valves in section 5 and 6 are the most important, Table 7.40.
Modelling the release.

<table>
<thead>
<tr>
<th>Section</th>
<th>Blowdown valve</th>
<th>Importance Measure</th>
<th>model 4</th>
<th>model 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>34XV031</td>
<td>0.093</td>
<td>0.063</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>35XV044</td>
<td>0.712</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>35XV103</td>
<td>0.682</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>35XV171</td>
<td>2.28</td>
<td>1.76</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>35XV157</td>
<td>2.88</td>
<td>1.89</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>35XV277</td>
<td>2.57</td>
<td>2.99</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>35XV279</td>
<td>3.08</td>
<td>3.36</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>35XV419</td>
<td>0.068</td>
<td>0.096</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>35XV422</td>
<td>0.279</td>
<td>0.401</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>35XV382</td>
<td>0.194</td>
<td>0.279</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>41XV002</td>
<td>0.012</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>90XV011</td>
<td>0.002</td>
<td>0.002</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.40: The importance of the blowdown valves in the compression module (percentage) - comparison between models 4 and 5.

The frequency of exceedence of the overpressures is shown in Figures 7.5a, b, c. The gas and condensate release of model 4 yields a higher frequency of exceedence of the overpressures throughout the range. This observation is in contrast to that of the separation module.
Modelling the release.

Figure 7.5: Comparison of the overpressure exceedence for the compression module with models 4 and 5.
7.7.3 The wellhead module.

The wellhead module has sections 9, 10 and 11 that can leak directly into the module. These sections contain only gas and have no links to sections containing condensate therefore there are no differences between models 4 and 5. The following tables have been inserted for reference as no comparison may be made apart from to state that both models provide identical results.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 4</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.10069×10^{-7}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.11958×10^{-7}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.40976×10^{-12}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.22061×10^{-6}</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.24263×10^{-6}</td>
</tr>
</tbody>
</table>

Table 7.41: Explosion frequency contributions from leaks on section 9 (per year) - comparison between models 4 and 5.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 4</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.12920×10^{-7}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.44783×10^{-8}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.25423×10^{-12}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.29393×10^{-6}</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.31133×10^{-6}</td>
</tr>
</tbody>
</table>

Table 7.42: Explosion frequency contributions from leaks on section 10 (per year) - comparison between models 4 and 5.
Modelling the release.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>protection fails to activate</td>
<td>0.26194x 10^{-7}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.11770x 10^{-7}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.10098x 10^{-11}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.59322x 10^{-6}</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.63119x 10^{-6}</td>
</tr>
</tbody>
</table>

Table 7.43: Explosion frequency contributions from leaks on section 11 (per year) - comparison between models 4 and 5.

Approximately 50% of the explosions originate from leaks in section 11.

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Explosion Type</th>
<th>Mitigation fails to activate</th>
<th>Prior to Mitigation</th>
<th>Mitigation not maintained</th>
<th>Mitigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>4,5</td>
<td>9</td>
<td>0.850</td>
<td>1.01</td>
<td>0.346x 10^{-4}</td>
<td>18.61</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.09</td>
<td>0.378</td>
<td>0.215x 10^{-4}</td>
<td>24.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>2.21</td>
<td>0.993</td>
<td>0.852x 10^{-4}</td>
<td>50.06</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.44: Total importance measures for the category of explosions in the wellhead module (percentage) - comparison between models 4 and 5.

<table>
<thead>
<tr>
<th>Connecting sections</th>
<th>Isolation valves</th>
<th>Importance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>3</td>
<td>33XV001</td>
</tr>
<tr>
<td>9</td>
<td>14</td>
<td>WELL19</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>35XV383</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>WELL2</td>
</tr>
<tr>
<td>11</td>
<td>8</td>
<td>N1</td>
</tr>
<tr>
<td>11</td>
<td>16</td>
<td>WELL5</td>
</tr>
</tbody>
</table>

Table 7.45: The importance of the isolation valves in the wellhead module (percentage) - comparison between models 4 and 5.
Modelling the release.

The failure of the non return valve N1 accounts for over 50% of the explosions in the wellhead module.

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>4,5</td>
<td>9</td>
<td>5.32</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>26.17</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 7.46: The importance of the sections in the wellhead module when the isolation and blowdown works as designed (percentage)- comparison between models 4 and 5.

<table>
<thead>
<tr>
<th>Section</th>
<th>Blowdown valve</th>
<th>Importance Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>model 4</td>
</tr>
<tr>
<td>3</td>
<td>34XV031</td>
<td>0.479</td>
</tr>
<tr>
<td>8</td>
<td>35XV422</td>
<td>1.94</td>
</tr>
<tr>
<td>8</td>
<td>35XV382</td>
<td>1.11</td>
</tr>
</tbody>
</table>

Table 7.47: The importance of the blowdown valves in the wellhead module (percentage) - comparison between models 4 and 5.
Modelling the release.

Figure 7.6: Comparison of the overpressure exceedence for the wellhead module with models 4 and 5.
7.7.4 Conclusion of the leak inventory comparison with the constant temperature models.

The conclusion must be drawn from the results of the separation and compression modules as there were no differences between the models on the wellhead module.

In general the gas and condensate release of model 4 yields higher frequencies of explosions than the gas only release of model 5. The condensate evaporates within the module to augment the gas cloud build up, therefore ignoring it may diminish the build up of the gas cloud within the module. Since model 4 generated higher frequencies, opting for this as the standard constant temperature model is erring on the side of caution.

7.8 Temperature state comparison.

In the comparison of models 1, 2 and 3 and that of models 4 and 5 the conclusion drawn is that the models with a gas and condensate release are more appropriate than the others. It was also apparent that different patterns were emerging for the changing temperature releases and the constant temperature releases. Therefore a comparison shall be made between the two temperature state models using models which both assume the same leak flow: gas and condensate release. These two models are models 2 and 4.

Model 2 Gas and Condensate release assuming a Changing Temperature scenario.
Model 4 Gas and Condensate release assuming a Constant Temperature scenario.

7.8.1 The separation module.

The separation module may have an explosion if a leak occurs from either section 1 or 3. The leak inventory may be augmented by the contents of sections 4, 5, 6, 9 and 12 which connect via isolation valves. The primary sections contain only gas and oil, however the secondary sections involve condensate.
Table 7.48: Explosion frequency contributions from leaks on section 1 (per year) - temperature state comparison.

Leaks on section 1 may involve a combination of gas and oil and, if the valves fail, condensate. The condensate in the leak causes the temperature to be kept constant for model 4, if there is no condensate the temperature and pressure can not be kept constant and the two models would produce the same results. The constant temperature model has a higher overall explosion frequency for the section. The frequency of explosions occurring when the mitigation is not activated is higher for the constant temperature model, since this depends only on the time spent within the flammable region, this model must generate concentrations which remain within the flammable limits for a longer period of time than those from the changing temperature model. The frequency of explosions occurring prior to mitigation is slightly lower for the constant temperature model, since the driving pressure of the release is initially constant this suggests that the concentration rises above the flammable limit prior to this time and before the changing temperature model therefore leaving less time for this type of explosion to occur.
Modelling the release.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 2</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.28291×10⁻⁶</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.27506×10⁻⁶</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.36246×10⁻¹¹</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.35363×10⁻⁵</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.40942×10⁻⁵</td>
</tr>
</tbody>
</table>

Table 7.49: Explosion frequency contributions from leaks on section 3 (per year) - temperature state comparison.

The frequency of explosions due to a leak on section 3 is higher for the constant temperature model than the changing temperature model. Explosions when the mitigation fails to activate have a higher frequency of occurrence indicating that more time is spent within the explosive region with the constant temperature model. As the explosions prior to mitigation have a higher frequency with the constant temperature model, this model must cause the gas cloud to reach flammable concentrations before the changing temperature model.

<table>
<thead>
<tr>
<th>Model</th>
<th>Module explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.66656×10⁻⁵</td>
</tr>
<tr>
<td>4</td>
<td>0.90815×10⁻⁵</td>
</tr>
</tbody>
</table>

Table 7.50: Total explosion frequencies for the separation module (per year) - temperature state comparison.

The overall explosion frequencies for the module, Table 7.50, show that keeping the temperature constant results in a large increase.

The models will not differ if the isolation valves work as designed preventing any condensate affecting the leak. The percentage of explosions occurring when this happens are shown in Table 7.51. With the constant temperature model such explosions reduce their importance indicating that the condensate is more important in the constant temperature model.
Table 7.51: The importance of the sections in the separation module when the isolation and blowdown works as designed (percentage) - temperature state comparison

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>2.89</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>34.79</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>30.76</td>
</tr>
</tbody>
</table>

The importance of the isolation valve failure is given in Table 7.52. The most important valves for both models are 35XV186 and 35XV125 and 35XV149 connecting sections 1 and 3 with section 5 implying that section 5 has a high release rate. With the constant temperature model the valves that connect to sections with condensate increase in their contribution to the explosion frequency. Isolation valves 34XV033 and 33XVO01 decrease in their contribution due to containing no condensate.

<table>
<thead>
<tr>
<th>Connecting sections</th>
<th>Isolation valves</th>
<th>Importance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>model 2</td>
</tr>
<tr>
<td>1 3</td>
<td>34XV033</td>
<td>2.88</td>
</tr>
<tr>
<td>1 4</td>
<td>34XV090/001</td>
<td>8.67</td>
</tr>
<tr>
<td>1 5</td>
<td>35XV186</td>
<td>13.95</td>
</tr>
<tr>
<td>1 6</td>
<td>35XV092</td>
<td>7.49</td>
</tr>
<tr>
<td>1 12</td>
<td>41XV201</td>
<td>6.44</td>
</tr>
<tr>
<td>3 5</td>
<td>35XV125/149</td>
<td>16.10</td>
</tr>
<tr>
<td>3 9</td>
<td>33XVO01</td>
<td>3.10</td>
</tr>
</tbody>
</table>

Table 7.52: The importance of the isolation valves in the separation module (percentage) - temperature state comparison.

The contribution to the explosion frequency made by failure of the blowdown valves is shown in Table 7.53.
Modelling the release.

<table>
<thead>
<tr>
<th>Section</th>
<th>Blowdown valve</th>
<th>Importance Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>34XV031</td>
<td>8.29</td>
</tr>
<tr>
<td>4</td>
<td>35XV044</td>
<td>0.163</td>
</tr>
<tr>
<td>4</td>
<td>35XV103</td>
<td>0.158</td>
</tr>
<tr>
<td>5</td>
<td>35XV171</td>
<td>0.555</td>
</tr>
<tr>
<td>5</td>
<td>35XV157</td>
<td>0.698</td>
</tr>
<tr>
<td>6</td>
<td>35XV277</td>
<td>0.226</td>
</tr>
<tr>
<td>6</td>
<td>35XV279</td>
<td>0.203</td>
</tr>
<tr>
<td>12</td>
<td>41XV002</td>
<td>0.169</td>
</tr>
</tbody>
</table>

Table 7.53: The importance of the blowdown valves in the separation module (percentage) - temperature state comparison.

The percentages of explosions occurring are split into category of explosion and originating section in Table 7.54. It can be seen that the constant temperature model yields a larger percentage of explosions due to leaks on section 1 and a lower percentage for those on section 3. This may be because section 1 involves leaks with a greater proportion of condensate.

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Category of explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mitigation fails to activate</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2.67</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.24</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2.77</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.14</td>
</tr>
</tbody>
</table>

Table 7.54: Importance measures for the categories of explosions in the separation module (percentage) - temperature state comparison.

The frequencies of exceedence for the overpressures are depicted in Figure 7.7. The constant temperature model has a higher frequency of exceedence over the whole range of the overpressures.
Modelling the release.

Figure 7.7: Comparison of the overpressure exceedence for the separation module using the two temperature state models.
7.8.2 The compression module.

The compression module has explosive situations developed from leaks on sections 4, 5, 6 and 8.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 2</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.36976x10⁻⁶</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.34156x10⁻⁶</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.49201x10⁻¹¹</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.59993x10⁻⁵</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.67106x10⁻⁵</td>
</tr>
</tbody>
</table>

Table 7.55: Explosion frequency contributions from leaks on section 4 (per year) - temperature state comparison.

Section 4 contains gas and condensate and may connect to sections 1 and 5 due to isolation failure, where section 5 also contains gas and condensate. The explosion frequencies are higher for the constant temperature model due to the large proportion of condensate available.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 2</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.74552x10⁻⁶</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.70662x10⁻⁶</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.12659x10⁻¹⁰</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.12078x10⁻⁴</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.13530x10⁻⁴</td>
</tr>
</tbody>
</table>

Table 7.56: Explosion frequency contributions from leaks on section 5 (per year) - temperature state comparison.

The explosion frequencies for sections 5 and 8 are higher for the constant temperature model.
Modelling the release.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 2</td>
<td>model 4</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>$0.46250 \times 10^{-6}$</td>
<td>$0.98743 \times 10^{-6}$</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>$0.63419 \times 10^{-6}$</td>
<td>$0.63425 \times 10^{-6}$</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>$0.43852 \times 10^{-11}$</td>
<td>$0.15379 \times 10^{-10}$</td>
</tr>
<tr>
<td>mitigated</td>
<td>$0.72972 \times 10^{-11}$</td>
<td>$0.16299 \times 10^{-11}$</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>$0.83939 \times 10^{-5}$</td>
<td>$0.13038 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 7.57: Explosion frequency contributions from leaks on section 6 (per year) - temperature state comparison.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model 2</td>
<td>model 4</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>$0.11795 \times 10^{-6}$</td>
<td>$0.12114 \times 10^{-6}$</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>$0.76433 \times 10^{-6}$</td>
<td>$0.76016 \times 10^{-5}$</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>$0.31731 \times 10^{-12}$</td>
<td>$0.40518 \times 10^{-12}$</td>
</tr>
<tr>
<td>mitigated</td>
<td>$0.12584 \times 10^{-5}$</td>
<td>$0.13172 \times 10^{-5}$</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>$0.21407 \times 10^{-5}$</td>
<td>$0.21985 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Table 7.58: Explosion frequency contributions from leaks on section 8 (per year) - temperature state comparison.

The constant temperature model produces the highest explosion frequencies for section 8. However due to the low proportion of condensate that may leak from this section there is negligible difference between the models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Module explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$0.30776 \times 10^{-4}$</td>
</tr>
<tr>
<td>4</td>
<td>$0.56081 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 7.59: The total explosion frequencies for the compression module (per year) - temperature state comparison.

The explosion frequencies are higher when using model 4 than for model 2. This suggests
that the condensate has a greater effect when using the constant temperature model. The condensate within the section keeps the pressure constant hence driving the release at a greater rate and causing more time to be spent within the explosive range.

The percentages of explosions due to a leak in each section are illustrated in Table 7.60, categorised into types of explosions. In both models leaks occurring on section 5 have the greater importance. For the constant temperature model this importance increases along with the percentage of section 6 whilst the sections 4 and 8 decrease in their percentage contribution.

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Category of explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mitigation fails to activate</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.42</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.383</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>0.884</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.65</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.76</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Table 7.60: Total importance measures for the category of explosions in the compression module (percentages) - temperature state comparison.

The contributions of each of these sections takes into account any adjacent sections if the isolation valves have failed. Table 7.61 gives the percentage of explosions which occur when the safety systems are working so any explosive mixture produced is solely down to the section with the leak.
Table 7.61: The importance of the sections in the compression module when the isolation and blowdown works as designed (percentage)- temperature state comparison.

Section 5 has the highest contribution to the frequency of explosions when its safety systems work as designed. As this section generates explosive gas clouds on its own the isolation valves connecting it to other sections are likely to be critical as further leak inventory may prolong the time at which the concentration is within the explosive range. Table 7.62 shows the percentage of explosions occurring due to isolation failure.
Isolation valve 35XV172 connecting sections 5 and 6 is the most critical for both models. The blowdown valves act to reduce the pressure of section therefore reducing the frequency of an explosion. As most explosions are likely to occur from section 5 and the isolation valves are the most critical between sections 5 and 6, then it follows that the blowdown valves in section 5 and 6 are the most important, Table 7.40.

Table 7.62: The importance of the isolation valves in the compression module (percentage) - temperature state comparison.

<table>
<thead>
<tr>
<th>Connecting sections</th>
<th>Isolation valves</th>
<th>Importance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>model 2</td>
</tr>
<tr>
<td>4 1</td>
<td>34XV090/001</td>
<td>1.908</td>
</tr>
<tr>
<td>4 5</td>
<td>35XV104</td>
<td>3.67</td>
</tr>
<tr>
<td>5 1</td>
<td>35XV186</td>
<td>1.03</td>
</tr>
<tr>
<td>5 3</td>
<td>35XV125/149</td>
<td>2.21</td>
</tr>
<tr>
<td>5 6</td>
<td>35XV172</td>
<td>4.92</td>
</tr>
<tr>
<td>6 1</td>
<td>35XV092</td>
<td>0.657</td>
</tr>
<tr>
<td>6 7</td>
<td>XVX3</td>
<td>2.94</td>
</tr>
<tr>
<td>6 8</td>
<td>35XV306</td>
<td>0.361</td>
</tr>
<tr>
<td>6 12</td>
<td>41XV053</td>
<td>0.508</td>
</tr>
<tr>
<td>8 10</td>
<td>35XV383</td>
<td>0.016</td>
</tr>
<tr>
<td>8 11</td>
<td>N1</td>
<td>0.060</td>
</tr>
<tr>
<td>8 13</td>
<td>90XV6/7</td>
<td>0.304</td>
</tr>
</tbody>
</table>
Table 7.63: The importance of the blowdown valves in the compression module (percentage) - temperature state comparison.

<table>
<thead>
<tr>
<th>Section</th>
<th>Blowdown valve</th>
<th>Importance Measure model 2</th>
<th>Importance Measure model 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>34XV031</td>
<td>0.075</td>
<td>0.093</td>
</tr>
<tr>
<td>4</td>
<td>35XV044</td>
<td>1.23</td>
<td>0.712</td>
</tr>
<tr>
<td>4</td>
<td>35XV103</td>
<td>1.20</td>
<td>0.682</td>
</tr>
<tr>
<td>5</td>
<td>35XV171</td>
<td>2.32</td>
<td>2.28</td>
</tr>
<tr>
<td>5</td>
<td>35XV157</td>
<td>2.69</td>
<td>2.88</td>
</tr>
<tr>
<td>6</td>
<td>35XV277</td>
<td>2.68</td>
<td>2.57</td>
</tr>
<tr>
<td>6</td>
<td>35XV279</td>
<td>2.78</td>
<td>3.08</td>
</tr>
<tr>
<td>7</td>
<td>35XV419</td>
<td>0.062</td>
<td>0.068</td>
</tr>
<tr>
<td>8</td>
<td>35XV422</td>
<td>0.420</td>
<td>0.279</td>
</tr>
<tr>
<td>8</td>
<td>35XV382</td>
<td>0.30</td>
<td>0.194</td>
</tr>
<tr>
<td>12</td>
<td>41XV002</td>
<td>0.01</td>
<td>0.012</td>
</tr>
<tr>
<td>13</td>
<td>90XV011</td>
<td>0.002</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Figure 7.8 shows the frequency of exceedence of the overpressures produced when an explosion occurs in the compression module. Throughout the range of overpressures produced the constant temperature model has a higher frequency of exceedence.
Modelling the release.

Figure 7.8: Comparison of the overpressure exceedence for the compression module with models 2 and 4.
7.8.3 The wellhead module.

The wellhead module contains section 9, 10 and 11. These sections only contain gas and no connecting sections contain condensate. As there is no condensate in the sections the constant temperature model can not use the evaporation of the condensate as a means of keeping the temperature and hence pressure constant. This should mean that the results are identical as both models act as changing temperature models. However different calculation procedures are employed giving slightly different results.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 2</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.99635 x 10^{-8}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.12174 x 10^{-7}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.39648 x 10^{-12}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.21795 x 10^{-6}</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.24008 x 10^{-6}</td>
</tr>
</tbody>
</table>

Table 7.64: Explosion frequency contributions from leaks on section 9 (per year) - temperature state comparison.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 2</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.12951 x 10^{-7}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.48445 x 10^{-8}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.25378 x 10^{-12}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.29427 x 10^{-6}</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.31207 x 10^{-6}</td>
</tr>
</tbody>
</table>

Table 7.65: Explosion frequency contributions from leaks on section 10 (per year) - temperature state comparison.
Modelling the release.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 2</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>$0.26400 \times 10^{-7}$</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>$0.11970 \times 10^{-7}$</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>$0.10228 \times 10^{-11}$</td>
</tr>
<tr>
<td>mitigated</td>
<td>$0.59777 \times 10^{-6}$</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>$0.63614 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Table 7.66: Explosion frequency contributions from leaks on section 11 (per year) - temperature state comparison.

<table>
<thead>
<tr>
<th>Model</th>
<th>Module explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$0.12044 \times 10^{-5}$</td>
</tr>
<tr>
<td>4</td>
<td>$0.11852 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Table 7.67: The total explosion frequencies for the wellhead module (per year) - temperature state comparison.

The explosion frequency for the changing temperature model is higher in the wellhead module.

<table>
<thead>
<tr>
<th>Connecting sections</th>
<th>Isolation valves</th>
<th>Importance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>model 2</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>33XV001</td>
</tr>
<tr>
<td>9</td>
<td>14</td>
<td>WELL19</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>35XV383</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>WELL2</td>
</tr>
<tr>
<td>11</td>
<td>8</td>
<td>N1</td>
</tr>
<tr>
<td>11</td>
<td>16</td>
<td>WELL5</td>
</tr>
</tbody>
</table>

Table 7.68: The importance of the isolation valves in the wellhead module (percentage) - temperature state comparison.

The failure of the non return valve N1 accounts for over 50% of the explosions in the wellhead
Modelling the release.

Table 7.69: The importance of the sections in the wellhead module when the isolation and blowdown works as designed (percentage) - temperature state comparison.

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>9</td>
<td>5.31</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>26.17</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>5.32</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>26.17</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 7.70: The importance of the blowdown valves in the wellhead module (percentage) - temperature state comparison.

<table>
<thead>
<tr>
<th>Section</th>
<th>Blowdown valve</th>
<th>Importance Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>model 2</td>
</tr>
<tr>
<td>3</td>
<td>34XV031</td>
<td>0.386</td>
</tr>
<tr>
<td>8</td>
<td>35XV422</td>
<td>1.96</td>
</tr>
<tr>
<td>8</td>
<td>35XV382</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Table 7.71: Importance measure for the categories of explosions in the wellhead module (percentages) - temperature state comparison.

<table>
<thead>
<tr>
<th>Model</th>
<th>Section</th>
<th>Category of explosion</th>
<th>Mitigation fails to activate</th>
<th>Prior to mitigation</th>
<th>Mitigation not maintained</th>
<th>Mitigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>9</td>
<td>Mitigation</td>
<td>0.838</td>
<td>1.02</td>
<td>0.334×10⁻⁴</td>
<td>18.34</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Mitigation</td>
<td>1.09</td>
<td>0.40</td>
<td>0.214×10⁻⁴</td>
<td>24.76</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Mitigation</td>
<td>2.22</td>
<td>1.01</td>
<td>0.861×10⁻⁴</td>
<td>50.31</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>Mitigation</td>
<td>0.849</td>
<td>1.01</td>
<td>0.346×10⁻⁴</td>
<td>18.61</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Mitigation</td>
<td>1.09</td>
<td>0.378</td>
<td>0.215×10⁻⁴</td>
<td>24.8</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Mitigation</td>
<td>2.21</td>
<td>0.993</td>
<td>0.852×10⁻⁴</td>
<td>50.06</td>
</tr>
</tbody>
</table>
Modelling the release.

The frequency of exceedence of the overpressures are shown in Figure 7.9. The changing temperature model has a slightly higher frequency of exceedence than the constant temperature model.
Modelling the release.

a) The range of overpressures generated

b) The lower overpressures generated

c) The higher overpressures generated

Figure 7.9: Comparison of the overpressure exceedence for the wellhead module with models 2 and 4.
7.8.4 Conclusion of the temperature state comparison.

Model 4 has constant temperature with a release initially driven by constant pressure. The pressure is constant whilst condensate remains in the section. Therefore the gas concentration in the module rises quicker with model 4 than with model 2, hence explosion frequencies using model 4 for the separation and compression modules are higher. For module 6 this is not the case because the driving pressure does not remain constant as no condensate is present. Sections which include more condensate account for more of the explosions when using model 4. Model 4 on the whole takes longer to run than model 2, but this is not a reason to reject it.

The true scenario will lie between the changing temperature model, which assumes that there is no heat transfer throughout the leak duration, and the constant temperature model, which assumes that there is total heat transfer. Results suggest that the constant temperature model produces higher explosion frequencies due to having a constant driving pressure for a period of time. Since reality lies between the two cases it is natural to assume that the explosion frequencies generated would lie between the results of these two models. This gives the constant temperature results as an upper bound for the frequencies of explosions with the changing temperature results being the lower bound.

7.9 Discussion.

This chapter has presented two models to calculate the leak flow rate into a module. The first model assumes that there is no heat transfer within the system, the theory behind this model is briefly discussed in Section 7.3. An alternative to this model is the constant temperature model discussed in Section 7.4. This model assumes that there is constant temperature within the section as the leak occurs. The results of the two models are compared in section 7.8. The results obtained are not dissimilar, however the constant temperature model does in general generate higher frequencies of explosions. The situation may actually involve some heat transfer taking place but not necessarily enough to retain a constant temperature throughout the leak. Hence the results obtained may be used as an upper and lower bound for the true situation.
Modelling the release.

The modelling assumes that the leak inventory is composed of the components of the leaking section in proportion to their presence. This assumption may not hold in all cases, for example if the oil has settled on the base of the vessel and a leak occurs at the top of a vessel then it may be unreasonable to assume that the oil will leak out. Sections 7.5 and 7.7 compare the results of running the changing temperature model and the constant temperature model when the leak inventory is altered. The leak inventory was assumed to consist of gas, condensate and oil releasing in proportion, gas and condensate with the oil acting only to reduce the volume of the section and a gas only release. Comparison of these models lead to a selection of the gas and condensate release as being the most appropriate.
8. Modelling the frequency of an explosion.

8.1 Introduction.

The models presented assume that once the leak occurs, the condensate evaporates on contact with the atmosphere, therefore contributing to the gas cloud. The gas concentration within the fixed volume is uniform throughout due to the assumption of immediate perfect mixing. The concentration is affected by the gas being released and the ventilation rate representing the wind effects. Initially the concentration profile is dominated by the release, at the peak of the profile the ventilation takes precedence and in the latter stages of the tail the change is solely due to the ventilation.

Ignition may only occur if the concentration of gas is between the flammable limits. If perfect mixing occurs and the gas concentration within a fixed volume is assumed constant then the concentration time history may be one of 3 forms. The situation shown in Figure 8.1 could not result in an explosion, as the concentration of gas does not build up to the flammable region. In Figure 8.2 ignition may occur between t1 and t4. However in Figure 8.3 ignition may occur in two time periods, between t1 and t2 whilst the concentration is rising and again between t3 and t4 as it falls back between the flammable limits.

![Figure 8.1: Time-concentration history, concentration below explosive range.](image)
Due to the uniform concentration within the module the ignition source is assumed to occur at a constant rate. The probability density function for the ignition source, $f_i(v)$, is therefore represented by the exponential distribution as shown in Equation 8.1.

$$f_i(v) = A_i e^{-A_i v}$$  \hspace{1cm} (8.1)

where $A_i$ is the constant ignition rate.

There are two categories of explosions dependent on the availability of the water spray system; mitigated and unmitigated. Mitigated explosions occur when the water spray is operational, for this we must consider the case when:

1. The water system is initiated then fails prior to the gas concentration decreasing below the LFL and there is an ignition prior to the deluge failure.
2. The water spray functions throughout the critical time period and an ignition occurs.

Unmitigated explosions occur when:

1. The water spray system fails to activate when the gas is detected and ignition occurs.
2. The water spray activates but the gas ignites during the delay time (prior to mitigation).
3. The water spray system activates and is fully operational but then fails followed by ignition of the gas (mitigation not maintained).

The frequency of an explosion will take one of the following forms depending on whether the water spray initially activates.

\[ f_e = P(S)\lambda_LP(E)P(WSFA) \]  
\[ f_e = P(S)\lambda_LP(E)(1 - P(WSFA)) \]

Where \( P(S) \) is the probability the event sequence, from gas detection up to but not including water spray activation, \( \lambda_L \) is the frequency of the gas leak, \( P(E) \) is the probability of ignition and \( P(WSFA) \) is the probability that the water system fails to activate.

Initial modelling assumed that an ignition may occur in the first or second time period, taking no account of previous conditions. The new approach assumes that if an ignition takes place then there can not have been a previous ignition neither can there be another ignition afterwards. Consider a scenario which involves the concentration of gas entering a specific concentration band at time \( t_1 \) leaving at \( t_2 \), reentering at \( t_3 \) and leaving at \( t_4 \) (Figure 8.4). The original modelling assumes that

\[ P(E) = P(\text{ignition between } t_1 \text{ & } t_2 \text{ OR ignition between } t_3 \text{ & } t_4) \]  

The simplest case is when the mitigation system is not activated. The probability of ignition is then dependent on the probability density function of the ignition source, \( f_i(v) \), and the time within the flammable region giving

\[ P(E) = \int_{t_1}^{t_2} f_i(v)dv + \int_{t_3}^{t_4} f_i(v)dv \]
Modelling the frequency of an explosion.

The new modelling accounts for the ignition being dependent on previous ignitions. In this case we are concerned with the times at which the flammable region is reached and exited as well as those times specific to the concentration band of interest. The times relating to the flammable region are represented as $T_1$, $T_2$, $T_3$, and $T_4$ where $T_1$ is the time that the lower flammable limit is reached and the explosive region entered, $T_2$ is the time that the upper flammable limit is reached and the explosive region is exited as the gas concentration continues to rise. As the gas concentration begins to fall the explosive region is reentered at $T_3$ and left at $T_4$. For this case the probability of ignition takes the following form.

\[
P(E) = P((\text{ignition at } v \text{ between } t_1 \& t_2 \text{ AND no ignition between } T_1 \& v) \text{ OR } (\text{ignition at } v \text{ between } t_3 \& t_4 \text{ AND no ignition between } T_1 \& v))
\]

(8.6)

![Diagram of time-concentration history](image)

Figure 8.4: Time-concentration history, concentration rising and falling through a specific concentration band when the concentration exceeds the explosive range.

Considering an ignition occurring when the mitigation system is not activated for the situation depicted in Figure 8.4 when the concentration exceeds the upper flammable limit, the probability of ignition occurring is

\[
P(E) = \int_{t_1}^{t_2} f_i(v) \left[1 - \int_{T_1}^{v} f_i(s)ds\right] dv + \\
\int_{t_3}^{t_4} f_i(v) \left[1 - \int_{T_1}^{T_2} f_i(s)ds - \int_{T_3}^{v} f_i(s)ds\right] dv
\]

(8.7)
Modelling the frequency of an explosion.

When the concentration does not exceed the upper flammable limit, Figure 8.5, T2 & T3 do not exist therefore the probability of ignition occurring becomes

$$P(E) = \int_{T1}^{T2} f_i(v) \left[ 1 - \int_{T1}^{v} f_i(s) ds \right] dv + \int_{T3}^{T4} f_i(v) \left[ 1 - \int_{T1}^{v} f_i(s) ds \right] dv$$  \hspace{1cm} (8.8)

The explosions may be categorised depending on the mitigation situation. This allows the overpressure distribution to be calculated. The mitigation situations considered are

1. Mitigation systems fail to activate
2. Prior to mitigation systems activating
3. Mitigation system begins but is not maintained
4. Mitigation system activates

### 8.2 Explosions when the mitigation system fails to activate.

The frequency of explosions occurring when the mitigation system fails to activate is given by

$$f_e = P(S)\lambda_L P(E)P(WSFA)$$  \hspace{1cm} (8.9)
Modelling the frequency of an explosion.

The probability of ignition occurring depends only on the time period within the explosive range and the probability density function of the ignition source. For the original modelling it does not matter whether a previous explosion has occurred, therefore the times used are those relating to the concentration band being analysed. The probability of ignition occurring in concentration band \( j \) is

\[
P(E) = \int_{t_{j1}}^{t_{j2}} f_i(v)dv + \int_{t_{j3}}^{t_{j4}} f_i(v)dv \quad (8.10)
\]

For the revised modelling the probability of ignition occurring in a specific concentration band is dependent on whether any previous explosions have occurred, the situation in Figure 8.4 gives the probability of an ignition occurring in concentration band \( j \) as

\[
P(E) = \int_{t_{j1}}^{t_{j2}} f_i(v) \left[1 - \int_{T1}^{T2} f_i(s)ds \right] dv + \int_{t_{j3}}^{t_{j4}} f_i(v) \left[1 - \int_{T1}^{T2} f_i(s)ds - \int_{T3}^{T2} f_i(s)ds \right] dv \quad (8.11)
\]

This equation represents the probability of an ignition, in concentration band \( j \), occurring if ignition has occurred at time \( v \) between \( t_{j1} \) and \( t_{j2} \) given that ignition has not occurred previously (i.e. from entering the flammable region at \( T1 \) until \( v \)) or ignition has occurred at \( v \) between \( t_{j3} \) and \( t_{j4} \) given that it has not already occurred (i.e. between \( T1 \) and \( T2 \) and between \( T3 \) and \( v \)).

For the situation in Figure 8.5, where the concentration level never exceeds the upper flammable limit \( T2 \) and \( T3 \) do not exist so the probability of an ignition occurring in band \( j \) is

\[
P(E) = \int_{t_{j1}}^{t_{j2}} f_i(v) \left[1 - \int_{T1}^{T2} f_i(s)ds \right] dv + \int_{t_{j3}}^{t_{j4}} f_i(v) \left[1 - \int_{T1}^{T2} f_i(s)ds \right] dv \quad (8.12)
\]

When band \( j \) is the band where the concentration ceases to rise and begins its descent there is only one time period in which an ignition may occur giving the probability of an ignition occurring as

\[
P(E) = \int_{t_{j1}}^{t_{j4}} f_i(v) \left[1 - \int_{T1}^{T2} f_i(s)ds \right] dv \quad (8.13)
\]
8.3 Explosions prior to the mitigation systems activating.

The frequency of explosions occurring prior to the activation of the mitigation system is given by

\[ f_e = P(S)\lambda_L P(E)(1 - P(WSFA)) \]  \hspace{1cm} (8.14)

The form of \( P(E) \), the probability of ignition, is dependent on the activation time of the mitigation, \( t_a \).

For the situation of Figure 8.4 where each concentration band \( j \) has times \( t_{j1}, t_{j2}, t_{j3} \) and \( t_{j4} \) associated with it and the flammable region is entered and the upper flammable limit exceeded giving times \( T1, T2, T3 \) and \( T4 \), there are certain situations which need to be considered separately, these involve when activation takes place.

if \( t_a < t_{j1} \)

\[ P(E) = 0 \]  \hspace{1cm} (8.15)

An ignition may not occur in this concentration range as it was not reached prior to the mitigation system activating.

if \( t_{j1} < t_a < t_{j2} \)

\[ P(E) = \int_{t_{j1}}^{t_a} f_i(v) \left[ 1 - \int_{T1}^{v} f_i(s) ds \right] dv \]  \hspace{1cm} (8.16)

Ignition may only occur after \( t_{j1} \) and prior to \( t_a \) but must not have occurred previously under any conditions.

if \( t_{j2} < t_a < t_{j3} \)

\[ P(E) = \int_{t_{j1}}^{t_{j2}} f_i(v) \left[ 1 - \int_{T1}^{v} f_i(s) ds \right] dv \]  \hspace{1cm} (8.17)

Since activation has occurred after the concentration band has been exceeded but prior to it being reentered, ignition may occur between \( t_{j1} \) and \( t_{j2} \).

if \( t_{j3} < t_a < t_{j4} \)

\[ P(E) = \int_{t_{j1}}^{t_{j2}} f_i(v) \left[ 1 - \int_{T1}^{v} f_i(s) ds \right] dv + \int_{t_{j3}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T1}^{T2} f_i(s) ds - \int_{T3}^{v} f_i(s) ds \right] dv \]  \hspace{1cm} (8.18)
Modelling the frequency of an explosion.

Ignition may occur between $t_{j1}$ and $t_{j2}$ or between $t_{j3}$ and $t_a$.

If $t_{j4} < t_a$

$$P(E) = \int_{t_{j1}}^{t_{j2}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s)ds \right] dv + \int_{t_{j3}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{T_2} f_i(s)ds - \int_{T_2}^{v} f_i(s)ds \right] dv$$  \hspace{1cm} (8.19)

Ignition may occur at any period within the concentration band as the mitigation system does not activate until after the concentration has dropped below this range.

For the situation in Figure 8.5 there is no exceedence of the upper flammable limit so $T_2$ and $T_3$ do not exist. When band $j$ is exceeded the probabilities of ignition are as above with

$$\left[ 1 - \int_{T_1}^{T_2} f_i(s)ds - \int_{T_2}^{v} f_i(s)ds \right]$$ replaced by $$\left[ 1 - \int_{T_1}^{v} f_i(s)ds \right]$$

When band $j$ is the band where the concentration ceases to rise and begins its descent the probabilities of ignition are

If $t_a < t_{j1}$

$$P(E) = 0$$  \hspace{1cm} (8.20)

If $t_{j1} < t_a < t_{j4}$

$$P(E) = \int_{t_{j1}}^{t_a} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s)ds \right] dv$$  \hspace{1cm} (8.21)

If $t_{j4} < t_a$

$$P(E) = \int_{t_{j1}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s)ds \right] dv$$  \hspace{1cm} (8.22)

8.4 Explosions when the mitigation begins but is not maintained.

These explosions depend on the activation time, $t_a$ and on the probability density function of the mitigation failure, $f_{ws}(u)$. The failure of the mitigation system is assumed to be a
constant rate so the probability density function of the mitigation failure takes an exponential form as shown in Equation 8.23.

\[
f_{ws}(u) = \lambda_w e^{-\lambda_w u} \tag{8.23}
\]

The activation time in relation to the entrance and exit times for the concentration bands must first be considered to determine whether the mitigation has begun. Secondly each time period within the calculation is considered to assess whether the mitigation system fails.

if \( t_a < t_{j1} \)

\[
P(E) = \int_{t_a}^{t_{j1}} f_{ws}(u) \left[ \int_{t_{j1}}^{t_{j2}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s) ds \right] dv + \right. \\
\int_{t_{j1}}^{t_{j3}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s) ds - \int_{T_2}^{v} f_i(s) ds \right] dv \right] du + \\
\int_{t_{j1}}^{t_{j4}} f_{ws}(u) \left[ \int_{t_{j3}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s) ds - \int_{T_2}^{v} f_i(s) ds \right] dv \right] du + \\
\int_{t_{j3}}^{t_{j4}} f_{ws}(u) \left[ \int_{t_{j1}}^{t_{j3}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s) ds - \int_{T_2}^{v} f_i(s) ds \right] dv \right] du + \\
\int_{t_{j3}}^{t_{j4}} f_{ws}(u) \left[ \int_{t_{j3}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s) ds - \int_{T_2}^{v} f_i(s) ds \right] dv \right] du \tag{8.24}
\]

The failure of the mitigation system must be considered in all time periods from \( t_a \) to \( t_{j1} \) through to \( t_{j3} \) to \( t_{j4} \). If the mitigation system has failed during one of these time periods then ignition may occur at any reasonable time period following this provided it has not previously occurred. For example the mitigation system may fail between the activation time and the time at which the concentration level is reached, so an ignition may occur at any time within the concentration range. The mitigation system may fail between \( t_{j1} \) and \( t_{j2} \) and therefore ignition may occur at any time from this point whilst the concentration is within the explosive range.

if \( t_{j1} < t_a < t_{j2} \)

\[
P(E) = \int_{t_a}^{t_{j2}} f_{ws}(u) \left[ \int_{t_{j1}}^{t_{j2}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s) ds \right] dv + \right. \\
\int_{t_{j1}}^{t_{j3}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s) ds - \int_{T_2}^{v} f_i(s) ds \right] dv \right] du + \\
\int_{t_{j3}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s) ds - \int_{T_2}^{v} f_i(s) ds \right] dv \]
Modelling the frequency of an explosion.

\[
\int_{t_{j2}}^{t_{j3}} f_{ws}(u) \left[ \int_{t_{j3}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{T_2} f_i(s) ds - \int_{T_3}^{v} f_i(s) ds \right] dv \right] du + \\
\int_{t_{j3}}^{t_{j4}} f_{ws}(u) \left[ \int_{t_{j1}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{T_2} f_i(s) ds - \int_{T_3}^{v} f_i(s) ds \right] dv \right] du \quad (8.25)
\]

If the mitigation system is not activated until after the concentration has entered the explosive range then it can not fail until after this reducing the amount of time in which this type of ignition may occur.

if \( t_{j2} < t_a < t_{j3} \)

\[
P(E) = \int_{t_a}^{t_{j3}} f_{ws}(u) \left[ \int_{t_{j3}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{T_2} f_i(s) ds - \int_{T_3}^{v} f_i(s) ds \right] dv \right] du + \\
\int_{t_{j3}}^{t_{j4}} f_{ws}(u) \left[ \int_{t_{j1}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{T_2} f_i(s) ds - \int_{T_3}^{v} f_i(s) ds \right] dv \right] du \quad (8.26)
\]

if \( t_{j3} < t_a < t_{j4} \)

\[
P(E) = \int_{t_a}^{t_{j4}} f_{ws}(u) \left[ \int_{t_{j1}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{T_2} f_i(s) ds - \int_{T_3}^{v} f_i(s) ds \right] dv \right] du \quad (8.27)
\]

if \( t_{j4} < t_a \)

\[
P(E) = 0 \quad (8.28)
\]

The mitigation system has been activated after the concentration has dropped below the lower flammable limit for this concentration range, therefore an ignition can not occur when the mitigation has been activated but not maintained.

For the situation in Figure 8.5 explosions in band \( j \) are as above with

\[
\left[ 1 - \int_{T_1}^{T_2} f_i(s) ds - \int_{T_3}^{v} f_i(s) ds \right] \quad \text{replaced by} \quad \left[ 1 - \int_{T_1}^{v} f_i(s) ds \right]
\]

When band \( j \) is the band where the concentration ceases to rise and begins its descent the probabilities of explosions are

if \( t_a < t_{j1} \)

\[
P(E) = \int_{t_a}^{t_{j1}} f_{ws}(u) \left[ \int_{t_{j1}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s) ds \right] dv \right] du + \\
\int_{t_{j1}}^{t_{j4}} f_{ws}(u) \left[ \int_{u}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s) ds \right] dv \right] du \quad (8.29)
\]

\[166\]
Modelling the frequency of an explosion.

if $t_{j1} < t_a < t_{j4}$

$$P(E) = \int_{t_a}^{t_{j4}} f_{ws}(u) \left[ \int_{u}^{t_{j4}} f_{i}(v) \left[ 1 - \int_{T1}^{v} f_{i}(s) ds \right] dv \right] du$$ (8.30)

if $t_{j4} < t_a$

$$P(E) = 0$$ (8.31)

8.5 Explosions when the mitigation is activated.

These explosions again depend on the activation time and the failure frequency of the mitigation systems. If the mitigation system has failed then ignition must have occurred previously for a mitigated explosion to take place, therefore each time range must be considered to determine when the failures occur.

For the case depicted in Figure 8.4

if $t_a < t_{j1}$

$$P(E) = \left[ 1 - \int_{t_a}^{t_{j4}} f_{ws}(u) du \right] \left[ \int_{t_{j1}}^{t_{j2}} f_{i}(v) \left[ 1 - \int_{T1}^{v} f_{i}(s) ds \right] dv \right]$$

$$+ \int_{t_{j1}}^{t_{j2}} f_{i}(v) \left[ 1 - \int_{T1}^{T2} f_{i}(s) ds - \int_{T3}^{v} f_{i}(s) ds \right] dv$$

$$+ \int_{t_{j1}}^{t_{j2}} f_{ws}(u) \left[ \int_{t_{j1}}^{u} f_{i}(v) \left[ 1 - \int_{T1}^{v} f_{i}(s) ds \right] dv \right] du$$

$$+ \int_{t_{j1}}^{t_{j2}} f_{ws}(u) \left[ \int_{t_{j1}}^{t_{j2}} f_{i}(v) \left[ 1 - \int_{T1}^{v} f_{i}(s) ds \right] dv \right] du$$

$$+ \int_{t_{j1}}^{t_{j3}} f_{ws}(u) \left[ \int_{t_{j1}}^{t_{j2}} f_{i}(v) \left[ 1 - \int_{T1}^{v} f_{i}(s) ds \right] dv \right] du$$

$$+ \int_{t_{j1}}^{u} f_{i}(v) \left[ 1 - \int_{T1}^{T2} f_{i}(s) ds - \int_{T3}^{v} f_{i}(s) ds \right] dv$$ (8.32)

The first term in this equation represents there being no failure of the mitigation system whilst the concentration is within the specific band, hence an ignition is possible throughout the range. The remaining terms consider the possible periods that failure may occur and determine the probability of an ignition appropriately.
if \( t_{j1} < t_a < t_{j2} \)

\[
P(E) = \left[ 1 - \int_{t_a}^{t_{j4}} fis(u)du \right] \left[ \int_{t_{j3}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s)ds \right] dv \right] \\
+ \int_{t_{j3}}^{t_{j4}} fis(u) \left[ \int_{t_{j3}}^{v} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s)ds \right] dv \right] du \\
\]  
(8.33)

if \( t_{j2} < t_a < t_{j3} \)

\[
P(E) = \left[ 1 - \int_{t_a}^{t_{j4}} fis(u)du \right] \left[ \int_{t_{j3}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{T_2} f_i(s)ds - \int_{T_3}^{v} f_i(s)ds \right] dv \right] \\
+ \int_{t_{j3}}^{t_{j4}} fis(u) \left[ \int_{t_{j3}}^{v} f_i(v) \left[ 1 - \int_{T_1}^{T_2} f_i(s)ds - \int_{T_3}^{v} f_i(s)ds \right] dv \right] du \\
\]  
(8.34)

if \( t_{j3} < t_a < t_{j4} \)

\[
P(E) = \left[ 1 - \int_{t_a}^{t_{j4}} fis(u)du \right] \left[ \int_{t_{j3}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{T_2} f_i(s)ds - \int_{T_3}^{v} f_i(s)ds \right] dv \right] \\
+ \int_{t_{a}}^{t_{j4}} fis(u) \left[ \int_{t_{a}}^{v} f_i(v) \left[ 1 - \int_{T_1}^{T_2} f_i(s)ds - \int_{T_3}^{v} f_i(s)ds \right] dv \right] du \\
\]  
(8.35)

if \( t_{j4} < t_a \)

\[
P(E) = 0 \\
(8.36)
\]

The mitigation system has not activated whilst the concentration was between the flammable limits therefore a mitigated ignition can not occur.

For the situation in Figure 8.5 explosions in band \( j \) are as above with

\[
\left[ 1 - \int_{T_1}^{T_2} f_i(s)ds - \int_{T_3}^{v} f_i(s)ds \right] \quad \text{replaced by} \quad \left[ 1 - \int_{T_1}^{v} f_i(s)ds \right]
\]

When band \( j \) is the band where the concentration ceases to rise and begins its descent the probabilities of explosions are
if $t_a < t_{j1}$

$$P(E) = \left[ 1 - \int_{t_a}^{t_{j4}} f_{ws}(u) du \right] \left[ \int_{t_{j1}}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{u} f_i(s) ds \right] dv \right]$$

$$+ \int_{t_{j1}}^{t_{j4}} f_{ws}(u) \left[ \int_{t_{j1}}^{u} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s) ds \right] dv \right] du \quad (8.37)$$

if $t_{j1} < t_a < t_{j4}$

$$P(E) = \left[ 1 - \int_{t_a}^{t_{j4}} f_{ws}(u) du \right] \left[ \int_{t_a}^{t_{j4}} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s) ds \right] dv \right]$$

$$+ \int_{t_a}^{t_{j4}} f_{ws}(u) \left[ \int_{t_a}^{u} f_i(v) \left[ 1 - \int_{T_1}^{v} f_i(s) ds \right] dv \right] du \quad (8.38)$$

if $t_{j4} < t_a$

$$P(E) = 0 \quad (8.39)$$

### 8.6 Results.

The new calculations should increase the accuracy of the model as the frequency calculations now take into account previous ignitable situations. The simplification made in the original model of ignoring the previous conditions of the gas cloud with respect to the ignition source has been replaced with a more complex method accounting for previous conditions. The new method introduces a dependency into the calculations, ruling out the chance that more than one ignition may occur within the same gas cloud. The new method is physically correct but leads to more complex calculations which rely on knowing the entrance and exit times corresponding to the flammable region and not just those for the specific concentration bands. The results are presented for each module; separation, compression and wellhead. The revised probability modelling was combined with both temperature state models. Model 2 was the changing temperature state with a gas and condensate release and model 4 was the constant temperature release with the gas and condensate release. Due to the relatively small differences between the probability models the explosion frequency tables for the modules are shown instead of those for the individual sections within the modules.
8.6.1 The separation module.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Original modelling</th>
<th>Revised modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>mitigation fails to activate</td>
<td>0.46059×10^{-6}</td>
<td>0.46043×10^{-6}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.34814×10^{-6}</td>
<td>0.34814×10^{-6}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.97447×10^{-11}</td>
<td>0.97360×10^{-11}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.58569×10^{-5}</td>
<td>0.58547×10^{-5}</td>
</tr>
<tr>
<td><strong>Total explosion frequency</strong></td>
<td>0.66656×10^{-5}</td>
<td>0.66633×10^{-5}</td>
</tr>
</tbody>
</table>

Table 8.1: Explosion frequency for the separation module (per year) with the changing temperature model - comparison of the two probability models.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Original modelling</th>
<th>Revised modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>mitigation fails to activate</td>
<td>0.62753×10^{-6}</td>
<td>0.62725×10^{-6}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.35458×10^{-6}</td>
<td>0.35458×10^{-6}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.15380×10^{-10}</td>
<td>0.15363×10^{-10}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.80994×10^{-5}</td>
<td>0.80956×10^{-5}</td>
</tr>
<tr>
<td><strong>Total explosion frequency</strong></td>
<td>0.90815×10^{-5}</td>
<td>0.90775×10^{-5}</td>
</tr>
</tbody>
</table>

Table 8.2: Explosion frequency for the separation module (per year) with the constant temperature model - comparison of the two probability models.
## 8.6.2 The compression module.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Original modelling</th>
<th>Revised modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>mitigation fails to activate</td>
<td>0.16957×10^{-5}</td>
<td>0.16954×10^{-5}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.24467×10^{-5}</td>
<td>0.24467×10^{-5}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.22282×10^{-10}</td>
<td>0.22262×10^{-10}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.26633×10^{-4}</td>
<td>0.26627×10^{-4}</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.30776×10^{-4}</td>
<td>0.30769×10^{-4}</td>
</tr>
</tbody>
</table>

Table 8.3: Explosion frequency for the compression module (per year) with the changing temperature model - comparison of the two probability models.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Original modelling</th>
<th>Revised modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>mitigation fails to activate</td>
<td>0.30901×10^{-5}</td>
<td>0.30889×10^{-5}</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.24431×10^{-5}</td>
<td>0.24430×10^{-5}</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.69696×10^{-10}</td>
<td>0.69624×10^{-10}</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.50548×10^{-4}</td>
<td>0.50528×10^{-4}</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.56081×10^{-4}</td>
<td>0.56060×10^{-4}</td>
</tr>
</tbody>
</table>

Table 8.4: Explosion frequency for the compression module (per year) with the constant temperature model - comparison of the two probability models.
8.6.3 The wellhead module.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original modelling</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.49314x10^-7</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.28988x10^-7</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.16730x10^-11</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.11100x10^-5</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.12044x10^-5</td>
</tr>
</tbody>
</table>

Table 8.5: Explosion frequency for the wellhead module (per year) with the changing temperature model - comparison of the two probability models.

<table>
<thead>
<tr>
<th>Type of explosion</th>
<th>Explosion frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original modelling</td>
</tr>
<tr>
<td>mitigation fails to activate</td>
<td>0.49184x10^-7</td>
</tr>
<tr>
<td>prior to mitigation</td>
<td>0.28206x10^-7</td>
</tr>
<tr>
<td>mitigation not maintained</td>
<td>0.16738x10^-11</td>
</tr>
<tr>
<td>mitigated</td>
<td>0.11078x10^-5</td>
</tr>
<tr>
<td>Total explosion frequency</td>
<td>0.11852x10^-5</td>
</tr>
</tbody>
</table>

Table 8.6: Explosion frequency for the wellhead module (per year) with the constant temperature model - comparison of the two probability models.

8.7 Discussion.

This chapter has presented a new approach for determining the frequencies of explosion based on the times at which the concentration is between the flammable limits and the constant ignition rate. The original modelling assumes that as long as the concentration is between the flammable limits an ignition can occur. The new approach takes into account previous ignitions. For an ignition to occur there can have been no previous ignitions, if there have been ignitions resulting in explosions then the gas cloud no longer remains. Such an approach is more accurate in its modelling and is expected to produce lower explosion...
Modelling the frequency of an explosion.

frequencies.

For all three modules and both models there are negligible differences between the frequencies gained with the original probability modelling and those with the revised probability modelling. The more accurate modelling of the revised probability calculations yields slightly lower explosion frequencies than the original calculations as expected. Hence the original modelling was providing an over estimation of the explosion frequencies. Since this model takes less computations and provides an upper bound, it is reasonable to say that the simplification assumption was valid.
9. Modelling the dispersion of the flammable gas cloud.

9.1 Introduction.

A current assumption in the SAROS modelling is that when the gas is released it immediately mixes perfectly with the air in the module to provide a uniform concentration throughout the module. The concentration is dependent upon the gas release rate, relative volume of the module and the ventilation rate. As long as the concentration is within the flammable limits and an ignition source occurs an explosion is possible. This is an over simplification, it would be more accurate if the dispersion of the gas within the air could be modelled. The larger the gas cloud the greater the chance of encountering an ignition source.

The only way to effectively model the gas dispersion from a time dependent release source into a semi confined region full of obstacles, of the detail required on an offshore platform, is through computational fluid dynamics (CFD). CFD is the analysis of fluid flow, heat transfer and related phenomena using numerical techniques and computers. CFD plays a major part in engineering design due to its ability to predict the behaviour of designs prior to construction, therefore it can save time and money by reducing the need to build prototypes.

CFD begins by setting up the equations necessary to solve the specific problem. It is based on solving the time dependent Navier Stokes transport equations. These equations have the form

\[
\frac{\partial}{\partial t} (\rho \phi_i) + \nabla \cdot (\rho \phi_i \mathbf{u}) - \nabla \cdot (\Gamma_i \nabla \phi_i) = \text{source}
\]  

(9.1)

These are solved by converting them to a numerical form using a discretisation scheme and employing a suitable solution algorithm.
9.2 Defining the problem.

The problem that requires solution is calculating the concentration levels of gas within a module which has a volume of magnitude of the order of thousands of cubic metres. The gas source is a leaking pipe or pressurised vessel, the magnitude of the leak hole is of the order of millimetres.

For simplicity the assumption is made that the release is only gas, but this can be expanded to include liquid. The gas is natural gas in the context of offshore platforms. The composition of natural gas is approximately 95% methane with the other 5% made up of various denser products, for simplification we assume that we are dealing with a methane release. The module contains air at atmospheric pressure (101325 Pascals).

The species transport equation requires solving to determine the concentration, this has the following form

\[ \frac{\partial}{\partial t} (\rho m_j) + \nabla \cdot (\rho m_j u) - \nabla \cdot (\Gamma_j \nabla m_j) = \text{source} \]  

(9.2)

where \( m_j \) is the mass fraction of species \( j \). When there are \( n \) species, \((n-1)\) species transport equations require solution due to

\[ m_n = 1 - \sum_{j=1}^{(n-1)} m_j \]  

(9.3)

In this case there are 2 species, air and methane, so only one species transport equation requires solution. The source term is the volume flow rate into the module. \( \Gamma_j \) is the diffusion coefficient which is a constant relating the transport of a species to the concentration gradient ensuring that the total net transport of molecules is zero. As there are 2 gases the binary diffusion coefficient is employed which takes into account the properties of both species. By Ficks law of diffusion, that states that the current density of the flow past a plane normal to the gradient is proportional to the gradient. The diffusion coefficient is

\[ \Gamma_j = \frac{2}{3} \left( \frac{k^3}{\pi^3} \right)^{\frac{1}{2}} \left( \frac{1}{2m_a} + \frac{1}{2m_b} \right)^{\frac{1}{2}} \frac{T^3}{p} \left( \frac{\sigma_a + \sigma_b}{2} \right)^{2} \]  

(9.4)

Where \( k \) is the coefficient of thermal conductivity, \( a \) & \( b \) are subscripts for the respective species, \( \sigma \) is the molecular diameter and \( m \) is the molecular weight. The Lennard Jones parameters can be used to estimate the molecular diameters, for air \( \sigma = 3.689 \) and for methane \( \sigma = 3.796 \).
Modelling the dispersion of the flammable gas cloud.

The species equation 9.2 incorporating equation 9.4 involves the velocity, \( u \), the density, \( \rho \), the temperature, \( T \), and the pressure, \( p \), as unknowns. To solve for the velocity the momentum equations are used. The general transport equation in terms of momentum is

\[
\frac{\partial}{\partial t} (\rho u_i) + \nabla \cdot (\rho u_i u) - \nabla \cdot (\Gamma_i \nabla u_i) = \text{source} \tag{9.5}
\]

\( \frac{\partial}{\partial t} (\rho u_i) + \nabla \cdot (\rho u_i u) \) is the rate of increase of momentum of a fluid particle. This is equal to the sum of forces on the fluid particle, of which there are surface forces and body forces. Surface forces include viscosity, shear stresses and pressure, whilst the body force is gravity.

\[
\nabla \cdot (\Gamma_i \nabla u_i) + \text{source} = -\nabla p - \rho g + \text{effects of stresses} \tag{9.6}
\]

\( g = \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} \)

where

\[
effect \ of \ stresses = \frac{\partial r_{xx}}{\partial x} + \frac{\partial r_{xy}}{\partial y} + \frac{\partial r_{xz}}{\partial z} \quad \text{for the } x \text{ component of momentum} \tag{9.7}
\]

The gas is likely to be compressible, therefore the continuity equation is

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{9.8}
\]

The gas is taken to be an ideal gas, i.e., one which obeys Boyle’s law where the pressure is inversely proportional to the volume. The equation of state for an ideal gas is

\[
p = \rho R T \tag{9.9}
\]

In order to solve for the temperature the energy transport equation for enthalpy requires a solution.

\[
\frac{\partial}{\partial t} (\rho h) + \nabla \cdot (\rho hu) - \nabla \cdot (\Gamma_h \nabla h) = \text{source} \tag{9.10}
\]

In this case the diffusion coefficient is the coefficient of thermal conductivity, the source includes pressure, body forces and stresses.

\[
\frac{\partial}{\partial t} (\rho h) + \nabla \cdot (\rho hu) - \nabla \cdot (k \nabla h) = \frac{\partial p}{\partial t} + \nabla \cdot (u.T) - \rho g \tag{9.11}
\]

The stresses are part of a matrix, \( T \)

\[
T = \begin{pmatrix} \tau_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \tau_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \tau_{zz} \end{pmatrix}
\]
Modelling the dispersion of the flammable gas cloud.

The temperature is then found from

\[ T = \frac{h - m_{fu}H_{fu}}{\bar{c}_p} \]  

(9.12)

where \( m_{fu} \) is the mass fraction of the gas, \( H_{fu} \) is the calorific value of the fuel.

\[ \bar{c}_p = \frac{1}{T - T_{ref}} \int_{T_{ref}}^{T} c_p dT \]  

(9.13)

where

\[ c_p = \sum_{j} m_j c_j \]  

(9.14)

\( c_j \) is the specific heat capacity of species \( j \) at constant pressure.

The flow may be turbulent, which means that the velocity components vary very rapidly in both space and time. Therefore the flow behaviour is random and chaotic. In order to determine whether flow is turbulent the Reynolds number is calculated

\[ Re = \frac{\rho v_{ref} D}{\mu} \]  

(9.15)

where \( D \) is the characteristic length, usually taken to be the inlet diameter, \( v_{ref} \) is the characteristic velocity, usually the velocity at the inlet. If \( Re > 1000 \) then the flow is assumed turbulent, requiring turbulent transport equations to be solved.

The turbulent flow is assumed to be homogeneous, which means quantitatively the turbulence has the same structure in all parts of the flow field. All variables relating to the fluid can be divided into a mean component and a randomly fluctuating component.

\[ \phi_i = \bar{\phi}_i + \phi'_i \]  

(9.16)

where the mean component is calculated using space averaging for homogeneous turbulence. Both the average and the fluctuating components satisfy the continuity equations. Solving the original Navier Stokes equations, using \( u_i \), and capturing the effects of turbulence would require a very fine mesh and a vast number of iterations. With the present computing resources available it would take billions of years to obtain an accurate and converged solution. To overcome this problem semi empirical turbulence modelling techniques are employed which involve solving the appropriate transport equations with equation 9.16 substituted. Applying the averaging forms of variables in the general scalar transport equation introduces a turbulent diffusive flux.

\[ \bar{\rho u_i \phi'} \]  

(9.17)
Physically this means that the major effects of turbulence are to enhance the mixing of the fluid.

A turbulence model must be chosen which fulfils the following required attributes.

**Accuracy** the degree of closure and empiricism

**Wide applicability** to a number of flow scenarios and flow speeds

**Simplicity** for easy coding and understanding

**Economical** to reduce computational time and effort

The most effective turbulence model available is the $k - \epsilon$ turbulence model which assumes that the turbulent transport is analogous to molecular transport. This is the most commonly used model due to its ability to most closely match the criteria. Two equations along with empirical constants are employed in this method, due to the models wide usage experimentally derived and validated constants are well known and utilised. $k$ is the turbulent kinetic energy which provides a measure of the velocity fluctuations and is defined by

$$k = \frac{1}{2} u'_i u'_i$$

(9.18)

$\epsilon$ is the viscous dissipation

$$\epsilon = \frac{\mu}{\rho} \frac{\partial u'_i}{\partial x_j} \frac{\partial u'_i}{\partial x_j}$$

(9.19)

The turbulent viscosity, $\mu_t$ was defined by Prandtl Kolmogorov to be

$$\mu_t = C_\mu \frac{k^2}{\epsilon}$$

(9.20)

where $C_\mu$ is a constant.

The transport equations for $k$ and $\epsilon$ are

$$\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} + p - \rho \epsilon$$

(9.21)

$$\frac{\partial \rho \epsilon}{\partial t} + \frac{\partial}{\partial x_i} (\rho \epsilon u_i) = \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_i} + \frac{C_1 \rho \epsilon p}{k} - \frac{C_2 \rho \epsilon^2}{k}$$

(9.22)

The constants have been determined via computer optimisation by considering 2 dimensional wall boundary layers. These are $C_1 = 1.44 \quad C_2 = 1.92 \quad C_\mu = 0.09 \quad \sigma_k = 1.0 \quad \sigma_\epsilon = 1.3.$
Solving for \( k \) and \( \epsilon \) gives \( \mu_t \) which is used in the Reynolds stresses

\[
\frac{\partial}{\partial x_i} \left( \mu_t \frac{\partial \bar{u}_i}{\partial x_i} \right) = \frac{\partial}{\partial x_j} \left( \rho \bar{u}_i \bar{u}_j \right)
\]

This gives \( \bar{u}_i \) and \( u'_i \) and hence give \( u_i \) allowing the applicable set of transport equations to be solved.

### 9.3 Discretising the transport equations.

The Navier Stokes transport equations are partial differential equations which must be solved numerically over the whole domain of interest. The transformation of the partial differential equations to a numerical analogue of the equation is done using the finite volume method. This method divides the domain of interest into discrete control volumes. Rectangular Cartesian coordinates or cylindrical coordinates may be used to setup the nodal points, ensuring that all geometries can be modelled effectively. The control volumes are setup around each node, with the boundaries of the volumes being midway between adjacent nodes. In three dimensions there are six neighbouring nodes, east, west, north, south, top and bottom as seen in Figure 9.1.

![Figure 9.1: A conventional node in 3 dimensions.](image-url)
Modelling the dispersion of the flammable gas cloud.

In each control volume the partial differential equations are discretised to algebraic form relating the variables to the values in the neighbouring volumes. These equations can then be solved numerically. Scalar variables such as pressure, density, temperature etc., are evaluated at the nodal points. If the velocities are defined at the scalar grid nodes the influence of the pressure is not properly represented in the discretised momentum equations[59], so a staggered grid centred around the control volume faces is used to calculate the velocity. An interpolation scheme must then be utilised to define the velocity at the nodes.

A discretisation scheme requires conservativeness, boundedness and transportiveness to ensure that the numerical solutions are realistic.

**Conservativeness:** For the variable under consideration, \( \phi \), to be conservative for the whole solution domain the flux of \( \phi \) leaving a control volume must be equal to the flux of \( \phi \) entering the adjacent control volume through the adjoining face. Hence the flux must be represented in a consistent manner, i.e., by the same expression in each pair of adjacent control volumes. Overall the fluxes must cancel out leaving a net flux of zero.

**Boundedness:** When solving equations for \( \phi \) the process begins with an estimate then an iterative technique is used to converge to a correct solution. Matrix coefficients should therefore be diagonally dominant, for this to be the case the source terms must be negative. If there are no source terms \( \phi \) should be bounded by the boundary values. For boundedness all coefficients of the discretised equations should have the same sign. If a discretisation scheme does not satisfy boundedness then the solution may never converge or may take a long time to do so.

**Transportiveness:** This is the relationship between the magnitude of the Peclet number and the direction of the flow. The Peclet number is the ratio of convection to diffusion

\[
P e = \frac{\rho u \delta x}{\Gamma}
\]

where \( \delta x \) is the characteristic length, \( \rho \) is the density, \( u \) is the velocity and \( \Gamma \) is the diffusion coefficient. When \( Pe = 0 \) the flow is still and the contours of \( \phi \) are concentric circles centred around \( P \), the central node in the control volume. This is because diffusion spreads \( \phi \) equally in all directions. As \( Pe \) increases, i.e., convection increases, the contours become elliptical and the direction of spread is influenced by the direction
of flow. The effects of convection, diffusion and direction of flow, i.e., transportiveness, must be integrated into the discretisation scheme to obtain correct solutions.

Discretisation schemes include differencing schemes; central, upwind and hybrid. The central differencing scheme is not transportive and is therefore an inadequate scheme. The upwind and hybrid schemes are improved schemes however the accuracy is only first order. The power law scheme and the exponential scheme are alternative discretisation methods, however they are also first order accurate. The QUICK (quadratic upwind differencing) scheme uses a three point weighted quadratic interpolation for the cell face values and is therefore third order accurate and possesses the three attributes required.

9.4 Solving the transport equations.

Once the partial differential equations have been discretised an algorithm for solving them is required. The equations are highly non linear therefore requiring an iterative solution scheme. A SIMPLE algorithm\(^{[59]}\) is used for the solution procedure, where SIMPLE is an acronym for Semi Implicit Method for Pressure Linked Equations. This is an iterative solution strategy adopted to solve coupled pressure and velocity equations which invariably occur when a flow is incompressible. Initial guesses for the velocity and pressure fields are made which must be improved.

The SIMPLER (SIMPLE Revised) and SIMPLEC (SIMPLE Consistent) are improvements to the SIMPLE algorithm. The SIMPLE algorithm however is relatively straightforward and used in most commercial packages. The SIMPLER and SIMPLEC algorithms increase the amount of computations necessary, but improvements in convergence usually reduce the computer time. The number of iterations can not be predicted before the solution procedure begins. It will be dependent on the dimensions of the solution grid, the initial conditions, initial estimation of variables and the nature and complexity of the flow being modelled.
9.5 Use of commercial CFD packages.

To model the dispersion of the gas commercial packages were employed, due to the infeasibility of writing a specific code within the time allowed. Both FLUENT and CFX FLOW3D were used in an attempt to model the situation.

On an offshore platform the geometry is complex due to the congestion of pipe work and process vessels within a module. Because of this complexity an initial simpler model was set up. The simpler model involved the meshing of a large module which has dimensions $40m \times 20m \times 10m$ with a small inlet hole of diameter $50mm$ representing the flange failure of a pipe. The module was assumed to be semi confined with two solid walls and two open faces. The two open faces allowed for the ventilation effects. One was represented as an inlet with wind speeds of $1.7ms^{-1}$ (equivalent to 4mph) and the opposite face was represented as the outlet. The inflow was assumed to be methane with air as the ambient background fluid with the atmospheric pressure at $101325$ Pascals. The CFD packages required the physical composition of methane and the ambient fluid. From this data, Table 9.1, the binary dispersion coefficient could be calculated and the nature of the fluids could be assessed.

<table>
<thead>
<tr>
<th>Property</th>
<th>Air</th>
<th>Methane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ($kg/m^3$)</td>
<td>1.22</td>
<td>0.667</td>
</tr>
<tr>
<td>Gas constant ($J/kmolK$)</td>
<td>287</td>
<td>518</td>
</tr>
<tr>
<td>Molecular weight ($kg/kmol$)</td>
<td>28</td>
<td>16</td>
</tr>
<tr>
<td>Specific heat capacity ($J/kgK$) at constant pressure</td>
<td>1004.5</td>
<td>2136.75</td>
</tr>
<tr>
<td>Specific heat capacity ($J/kgK$) at constant volume</td>
<td>718</td>
<td>1675.55</td>
</tr>
<tr>
<td>Thermal conductivity ($mkg/s^3K$)</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Viscosity ($kg/ms$)</td>
<td>$1.8 \times 10^{-5}$</td>
<td>$1.34 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Table 9.1: The physical data for methane and air.
9.5.1 General limitations.

Using both FLUENT and CFX FLOW3D problems were encountered. These problems were due mainly to divergence occurring because of the relative scales of the leak hole specified and the module dimensions. Adaptive meshing was employed when using CFX FLOW3D as a measure to rectify this. However the processor power available was not sufficient to gain convergence over more than two iterations. To simulate the release into the simplified domain was a lengthy process, a simulation of a few seconds required hours of real time.

The problems arising on a simplification of the model prohibited attempts at the more complex cases. Therefore the resources available, in terms of computer processor power and time, proved to be major limitations in what could be achieved using commercial codes which had no specific sub models for such a simulation. Without the CFD expertise it was infeasible to write specific sub models in the time allowed. Hence correlations relating the volume to the concentration levels were not produced for a realistic scenario.

9.6 Integrating dispersion correlations into the frequency modelling.

Modelling the dispersion of the gas within the module will enable us to establish correlations for the time variation of the volume occupied by a specific concentration range of gas. The concentration contours produced as the gas enters the module will change position and shape with time. The volume encased within each concentration band will change with respect to time, such as that shown in Figure 9.2 for a specific concentration band. The exact form of this relationship will change for each scenario.
Modelling the dispersion of the flammable gas cloud.

Figure 9.2: An example of the expected growth and decay of the volume within a concentration band, using the lognormal function.

In this example the volume builds up rapidly at first due to a fast release rate. Once the leak has exhausted the volume reduces as determined by the ventilation rate. It is possible that the variation may be represented by a skewed function such as a lognormal function of the form

$$V(t) = \frac{1}{\sigma t} \exp\left(-\frac{1}{2} \left(\frac{\ln(t) - \phi}{\sigma}\right)^2\right)$$

(9.24)

Where $\phi$ and $\sigma$ are the function parameters. Such a function is capable of representing the increase of volume as the gas is released and the decrease as ventilation dominates whilst the gas is exhausted.

To calculate the frequencies of explosions an ignition density is used rather than an ignition rate. In this case the probability of ignition is dependent on the ignition density and the dispersion and concentration of the gas cloud. For a specific concentration band, $m$, the volume of gas follows a function, $V_m(t)$. The ignition rate is then

$$\lambda_i V_m(t)$$

(9.25)

Where $\lambda_i$ is the ignition rate per unit volume. This leads to a probability density function for the ignition source occurrence times of

$$f(t) = \lambda_i V_m(t) \exp \left(-\lambda_i \int_0^t V_m(u) \, du\right)$$

(9.26)

The modelling provides the times at which each concentration band develops and then disappears and the volume within this band. It is assumed that the lowest concentration band is the first to be reached and the last to be left, and that the highest is the last to be reached.

184
and the first to be left. Therefore if \( t_{Em} \) is the time band \( m \) is entered and \( t_{Lm} \) is the time band \( m \) is left, the following must apply

\[
t_{E1} < t_{E2} < \ldots < t_{L2} < t_{L1}
\]  
(9.27)

As with the probability calculations described previously, this method assumes that an ignition will only occur at time \( t \) if it has not occurred previously whilst a gas cloud existed which was within the explosive range. Previous calculations involve integrating the probability density function for the ignition source using limits of integration that relate to the times of entry and exit for each concentration band over the flammable region. In this case however it is more complex. Each concentration range has its own probability density function that depends on the volume of the gas cloud within the concentration band limits. We must therefore consider each time interval in Equation 9.27, i.e. \( t_{E1} \) to \( t_{E2} \), \( t_{E2} \) to \( t_{E3} \), etc. These are illustrated in Figure 9.3 where the variation of volume with time for each band is assumed not to intersect.

![Figure 9.3: Representation of the volume variation for each concentration band with time.](image)

Considering first the probability of a gas cloud ignition at time \( v \)

\[
P(E) = \sum_{k=m}^{n-1} \int_{t_{Ek}}^{t_{E(k+1)}} f_{im}(v) \left( 1 - \sum_{j=1}^{k} \int_{t_{Ej}}^{v} f_{ij}(s) \, ds \right) \, dv 
+ \int_{t_{E1}}^{t_{En}} f_{im}(v) \left( 1 - \sum_{j=1}^{n} \int_{t_{Ej}}^{v} f_{ij}(s) \, ds \right) \, dv 
+ \sum_{k=m}^{n-1} \int_{t_{Lk}}^{t_{L(k+1)}} f_{im}(v) \left( 1 - \sum_{j=k+1}^{n} \int_{t_{Ej}}^{t_{Lj}} f_{ij}(s) \, ds - \sum_{l=1}^{k} \int_{t_{E1}}^{v} f_{il}(s) \, ds \right) \, dv \]  
(9.28)

Where \( n \) is the number of concentration bands, \( P(E) \) is the probability of ignition whilst the concentration is in band \( m \) and \( f_{ij} \) is the probability density function for the ignition
Modelling the dispersion of the flammable gas cloud.

source for band \( j \). The first term considers the intervals between the entering times for each concentration band, for example if only the first concentration band has been reached then it is unnecessary to consider the ignition density function relating to the other bands as ignition can not yet occur within those ranges. However as the gas release develops and the higher concentration bands are entered more terms are added to account for the other ignition density functions of the other bands. The second term considers the time interval between entering and leaving the last band within the flammable limits. The final term accounts for the time intervals between the exit of each band this reduces the number of density functions that need to be considered.

To evaluate the proportions of these explosions that are unmitigated we need to consider the situation where the ignition happens before the water spray activates. The calculations for this will be as in Equation 9.28 with the limits changed to account for the time in the release at which the deluge activates. Explosions occurring after the failure of the activated water spray depend on the activation time and the failure rate of the water spray system. The deluge failure rate is assumed to be a constant leading to the failure density function of Equation 9.29.

\[
f_{\text{us}}(u) = \lambda_{\text{us}} \exp\left(-\lambda_{\text{us}} u\right)
\]  

(9.29)

The activation time with respect to the limiting times of each band is considered.

For the case when \( t_d < t_{E_m} \) the probability of ignition in band \( m \) at time \( v \) is

\[
P(E) = \int_{t_d}^{t_{E_m}} f_{\text{us}}(u) \left\{ \sum_{k=m}^{n-1} \left[ \int_{t_{E_k}}^{t_{E(k+1)}} f_{im}(v) \left( 1 - \sum_{j=1}^{k} \int_{t_{E_j}}^{v} f_{ij}(s) \, ds \right) \, dv \right] \\ + \int_{t_{E_m}}^{t_{Ln}} f_{im}(v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_j}}^{v} f_{ij}(s) \, ds \right) \, dv \right\} \, du \\
+ \sum_{j=m}^{n-1} \int_{t_{E(j+1)}}^{t_{E(j+1)}} f_{us}(u) \left\{ \sum_{k=m}^{n-1} \left[ \int_{t_{E_k}}^{t_{E(k+1)}} f_{im}(v) \left( 1 - \sum_{j=1}^{k} \int_{t_{E_l}}^{v} f_{il}(s) \, ds \right) \, dv \right] \\ + \int_{t_{E_m}}^{t_{Ln}} f_{im}(v) \left( 1 - \sum_{l=1}^{n} \int_{t_{E_l}}^{v} f_{il}(s) \, ds \right) \, dv \right\} \, du \\
+ \sum_{k=m}^{n-1} \left[ \int_{t_{E(k+1)}}^{t_{E(k+1)}} f_{im}(v) \left( 1 - \sum_{l=1}^{n} \int_{t_{E_l}}^{v} f_{ul}(s) \, ds \right) \, dv \right] \\
+ \int_{u}^{t_{E(j+1)}} f_{im}(v) \left( 1 - \sum_{j=1}^{j} \int_{t_{E_j}}^{v} f_{ul}(s) \, ds \right) \, dv \right\} \, du
\]
Modelling the dispersion of the flammable gas cloud.

\[
+ \int_{t_{E_{(k+1)}}}^{t_{E_{(k+1)}}} f_{ws} (u) \left\{ \int_{t_{E_{j}}}^{t_{E_{j}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv + \sum_{k=m}^{n-1} \left[ \int_{t_{L_{(k+1)}}}^{t_{L_{(k+1)}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv \right] \right\} \, du \\
+ \int_{t_{E_{(k+1)}}}^{t_{E_{(k+1)}}} f_{ws} (u) \left\{ \int_{t_{E_{j}}}^{t_{E_{j}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv + \sum_{k=m}^{n-1} \left[ \int_{t_{L_{(k+1)}}}^{t_{L_{(k+1)}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv \right] \right\} \, du \\
+ \sum_{j=m}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ws} (u) \left\{ \int_{t_{E_{j}}}^{t_{E_{j}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv + \sum_{k=m}^{n-1} \left[ \int_{t_{L_{(k+1)}}}^{t_{L_{(k+1)}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv \right] \right\} \, du \\
+ \sum_{j=m}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ws} (u) \left\{ \int_{t_{E_{j}}}^{t_{E_{j}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv + \sum_{k=m}^{n-1} \left[ \int_{t_{L_{(k+1)}}}^{t_{L_{(k+1)}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv \right] \right\} \, du \\
+ \sum_{j=m}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ws} (u) \left\{ \int_{t_{E_{j}}}^{t_{E_{j}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv + \sum_{k=m}^{n-1} \left[ \int_{t_{L_{(k+1)}}}^{t_{L_{(k+1)}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv \right] \right\} \, du \\

(9.30)
\]

For all other intervals Equation 9.30 is used with a change of integration limits. Similarly for ignition occurring when the water spray is active the probability of ignition when \( t_d < t_{Em} \) is:

\[
P(E) = \left[ 1 - \int_{t_d}^{t_{E_{(k+1)}}} f_{ws} (u) \, du \right] \left\{ \sum_{k=m}^{n-1} \left[ \int_{t_{E_{j}}}^{t_{E_{j}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv \right] \right\} \\
+ \int_{t_{E_{(k+1)}}}^{t_{E_{(k+1)}}} f_{ws} (u) \left\{ \int_{t_{E_{j}}}^{t_{E_{j}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv + \sum_{k=m}^{n-1} \left[ \int_{t_{L_{(k+1)}}}^{t_{L_{(k+1)}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv \right] \right\} \, du \\
+ \sum_{j=m}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ws} (u) \left\{ \int_{t_{E_{j}}}^{t_{E_{j}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv + \sum_{k=m}^{n-1} \left[ \int_{t_{L_{(k+1)}}}^{t_{L_{(k+1)}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv \right] \right\} \, du \\
+ \sum_{j=m}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ws} (u) \left\{ \int_{t_{E_{j}}}^{t_{E_{j}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv + \sum_{k=m}^{n-1} \left[ \int_{t_{L_{(k+1)}}}^{t_{L_{(k+1)}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv \right] \right\} \, du \\
+ \sum_{j=m}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ws} (u) \left\{ \int_{t_{E_{j}}}^{t_{E_{j}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv + \sum_{k=m}^{n-1} \left[ \int_{t_{L_{(k+1)}}}^{t_{L_{(k+1)}}} f_{im} (v) \left( 1 - \sum_{j=1}^{n} \int_{t_{E_{j}}}^{t_{E_{j}}} f_{ij} (s) \, ds \right) \, dv \right] \right\} \, du \\

187
9.7 Discussion.

This chapter has outlined the work necessary to use CFD proficiently applied to an offshore platform and the attempts to simplify this procedure. CFD correlations of the volume of gas enclosed at specific concentration levels with time would allow us to specify different ignition sources at different positions in time and space. Should correlations of the concentration growth with time be provided by CFD or other means, Section 9.6 provides the equations that have been developed to allow for an ignition rate density dependent on the concentration level rather than a constant ignition source within a perfectly mixed volume.

It is expected that these equations will provide a better approximation to the frequency of an explosion as they allow for a more realistic scenario to develop. However no useful correlations were obtained for numerical estimates to be obtained due to the convergence limitations and time restrictions. Although the results are likely to be more accurate, we can not state whether these will be higher or lower than those currently available. As the current modelling assumes that the concentration is uniform, it not only ignores the fact that there will be areas with a lower concentration but also areas with intense concentration. Therefore in some cases the results could presently be underestimated in others they may be overestimated.
10. Sensitivity analysis.

10.1 Introduction.

Analysis has been carried out on the consequences of varying key parameters in the model to determine the most sensitive. This analysis will highlight the effects produced should any of the data have any inaccuracies in it. The key parameters were identified to be:

- The frequency of ignition.
- The probability that the deluge system fails to operate.
- The activation time of the deluge system.
- The leak hole size distribution.
- The frequencies of occurrence of the leak holes.
- The distribution of ventilation rates.
- The failure frequency of the deluge once the deluge is operational.

The values of these parameters were varied by ±5%, ±10% and ±15%. If further analysis of the results or confirmation of a pattern was required then the parameters were varied by ±20% and ±50%.

The results were initially analysed by looking for changes in the expected frequencies of explosions and in the frequency of the overpressures obtained. A typical offshore platform is designed to withstand overpressures of up to 3 bar, therefore particular attention was paid to the frequency that the overpressures exceeded 3 bar. Secondly, the degrees of importance attributed to each of the isolation and blowdown valves were compared to determine any significant changes. The contributions to the frequency due to leaks on particular sections were also considered.
Sensitivity analysis.

To obtain a complete picture as to the nature of the effects arising from a change in a parameter two models were used. Both models assume that the leak is comprised of gas and condensate, escaping in proportion to the amounts within the vessel. The first model is the changing temperature model which assumes that there is no heat transfer within the system as the leak occurs. The second model is the constant temperature model which assumes total heat transfer within the system as the leak occurs. Should a leak occur on an offshore platform there is likely to be some, but not total, heat transfer in the system, therefore these models provide an upper and lower bound for the results. When the two models exhibit the same effect to the change in parameter we may assume that the true scenario will follow the same behaviour.

A leak may occur on an offshore platform in the separation, compression and wellhead modules. The results attributed to the three modules are all dependent on the key parameters. The modules each contain sections that may contribute to the leak and are subject to different environmental and initial conditions. Each module is considered to determine whether the changes in the parameters have similar effects in different conditions.

Within this analysis the parameters are each considered separately.

10.2 The frequency of ignition.

For all three modules, the frequency of an ignition source being in the vicinity of the gas cloud is 0.0028/hour. This was varied as shown in Table 10.1.

<table>
<thead>
<tr>
<th>Change</th>
<th>Frequency</th>
<th>Change</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5%</td>
<td>0.00294</td>
<td>-5%</td>
<td>0.00266</td>
</tr>
<tr>
<td>+10%</td>
<td>0.00308</td>
<td>-10%</td>
<td>0.00252</td>
</tr>
<tr>
<td>+15%</td>
<td>0.00322</td>
<td>-15%</td>
<td>0.00238</td>
</tr>
<tr>
<td>+20%</td>
<td>0.00336</td>
<td>-20%</td>
<td>0.00224</td>
</tr>
<tr>
<td>+50%</td>
<td>0.0042</td>
<td>-50%</td>
<td>0.0014</td>
</tr>
</tbody>
</table>

Table 10.1: The variation of ignition frequency per hour.

The results generated for the separation, compression and wellhead modules with the two
Sensitivity analysis.

different temperature state models revealed the same pattern as seen in Tables 10.2 and 10.3.

<table>
<thead>
<tr>
<th>Change</th>
<th>Separation Module</th>
<th>Compression Module</th>
<th>Wellhead Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
<td>0.4953×10^{-5}</td>
<td>0.2526×10^{-4}</td>
<td>0.1023×10^{-5}</td>
</tr>
<tr>
<td>-10%</td>
<td>0.5244×10^{-5}</td>
<td>0.2674×10^{-4}</td>
<td>0.1083×10^{-5}</td>
</tr>
<tr>
<td>-5%</td>
<td>0.5536×10^{-5}</td>
<td>0.2823×10^{-4}</td>
<td>0.1143×10^{-5}</td>
</tr>
<tr>
<td>0%</td>
<td>0.5827×10^{-5}</td>
<td>0.2971×10^{-4}</td>
<td>0.1203×10^{-5}</td>
</tr>
<tr>
<td>+5%</td>
<td>0.6118×10^{-5}</td>
<td>0.3120×10^{-4}</td>
<td>0.1263×10^{-5}</td>
</tr>
<tr>
<td>+10%</td>
<td>0.6409×10^{-5}</td>
<td>0.3269×10^{-4}</td>
<td>0.1323×10^{-5}</td>
</tr>
<tr>
<td>+15%</td>
<td>0.6700×10^{-5}</td>
<td>0.3417×10^{-4}</td>
<td>0.1383×10^{-5}</td>
</tr>
</tbody>
</table>

Table 10.2: The changes in explosion frequencies (per year) due to ignition frequency variation using the changing temperature model.

<table>
<thead>
<tr>
<th>Change</th>
<th>Separation Module</th>
<th>Compression Module</th>
<th>Wellhead Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
<td>0.7550×10^{-5}</td>
<td>0.4759×10^{-4}</td>
<td>0.9526×10^{-6}</td>
</tr>
<tr>
<td>-10%</td>
<td>0.7994×10^{-5}</td>
<td>0.5039×10^{-4}</td>
<td>0.1008×10^{-5}</td>
</tr>
<tr>
<td>-5%</td>
<td>0.8438×10^{-5}</td>
<td>0.5318×10^{-4}</td>
<td>0.1064×10^{-5}</td>
</tr>
<tr>
<td>0%</td>
<td>0.8882×10^{-5}</td>
<td>0.5598×10^{-4}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
<td>+5%</td>
<td>0.9326×10^{-5}</td>
<td>0.5878×10^{-4}</td>
<td>0.1176×10^{-5}</td>
</tr>
<tr>
<td>+10%</td>
<td>0.9769×10^{-5}</td>
<td>0.6158×10^{-4}</td>
<td>0.1232×10^{-5}</td>
</tr>
<tr>
<td>+15%</td>
<td>0.1021×10^{-5}</td>
<td>0.6438×10^{-4}</td>
<td>0.1288×10^{-5}</td>
</tr>
</tbody>
</table>

Table 10.3: The changes in explosion frequencies (per year) due to ignition frequency variation using the constant temperature model.

There is a direct correlation between the frequency of an ignition source per hour and the frequency of an explosion for the module concerned. A correlation was to be expected as the frequency of an explosion is directly dependent on the frequency of an ignition source being present. The probability of an ignition source occurring in the simplest case is described by the following equation

\[ P(E) = \int_{t_1}^{t_2} f_i(v)dv = \int_{t_1}^{t_2} \lambda_i e^{-\lambda_i v}dv = e^{-\lambda_{t_2}} - e^{-\lambda_{t_1}} \]  \hspace{1cm} (10.1)

This shows that there is an exponential relationship between \( \lambda_i \), the frequency of an ignition source being present and the probability of an ignition source occurring. For small
changes in $\lambda_i$ a linear relationship will be seen between the changes in $P(E)$. The percentage increase/decrease of the ignition frequency per hour produces the equivalent percentage increase/decrease of the module explosion frequency. For example, increasing the ignition frequency per hour by 20% increases the frequency that an explosion will occur in the module by 20%.

The importance measures of the sections and valves do not alter. This is because the frequency of ignition is a parameter of small magnitude which has an approximately linear effect. The gas leak flow and the subsequent module concentration, generated from a leak on a particular section with a certain combination of valves is derived without reference to the ignition frequency. Therefore each simulation will be the same up until the ignition frequency is introduced, this then has a linear effect, leaving the relative importance of the sections and valves unchanged.

The frequencies of the expected overpressures vary by the percentage increase/decrease of the parameter. Therefore the frequency of exceeding an overpressure of 3 bar is increased by 5% should the frequency of an ignition be increased by 5%. Figure 10.1 shows the overpressure exceedence curve centered around 3 bar for each of the modules using both of the models.

Hence it can be seen that an error of $\epsilon\%$ made in determining the ignition frequency per hour will produce results for the expected explosion frequencies and the overpressure-frequency distribution in error of $\epsilon\%$. This relationship is demonstrated for the separation, compression and wellhead modules using both temperature state models.
Sensitivity analysis.

Figure 10.1: A comparison of the exceedence frequency of the overpressures produced, due to the ignition frequency variation.
10.3 The probability that the deluge system fails to activate.

The probability that the deluge system fails to activate (unavailability of deluge) is dependent upon the module being considered. For the separation module it is originally 0.0691, for the compression module it is 0.0551 and for the wellhead module it is 0.0415. The variations are tabulated in Table 10.4.

<table>
<thead>
<tr>
<th>Separation module</th>
<th>Change</th>
<th>Unavailability</th>
<th>Change</th>
<th>Unavailability</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5%</td>
<td>0.072555</td>
<td>-5%</td>
<td>0.065645</td>
<td></td>
</tr>
<tr>
<td>+10%</td>
<td>0.07601</td>
<td>-10%</td>
<td>0.06219</td>
<td></td>
</tr>
<tr>
<td>+15%</td>
<td>0.079465</td>
<td>-15%</td>
<td>0.058735</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compression module</th>
<th>Change</th>
<th>Unavailability</th>
<th>Change</th>
<th>Unavailability</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5%</td>
<td>0.057855</td>
<td>-5%</td>
<td>0.052345</td>
<td></td>
</tr>
<tr>
<td>+10%</td>
<td>0.06061</td>
<td>-10%</td>
<td>0.04959</td>
<td></td>
</tr>
<tr>
<td>+15%</td>
<td>0.063365</td>
<td>-15%</td>
<td>0.046835</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wellhead module</th>
<th>Change</th>
<th>Unavailability</th>
<th>Change</th>
<th>Unavailability</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5%</td>
<td>0.043575</td>
<td>-5%</td>
<td>0.039425</td>
<td></td>
</tr>
<tr>
<td>+10%</td>
<td>0.04565</td>
<td>-10%</td>
<td>0.03735</td>
<td></td>
</tr>
<tr>
<td>+15%</td>
<td>0.047725</td>
<td>-15%</td>
<td>0.035275</td>
<td></td>
</tr>
</tbody>
</table>

Table 10.4: The variation of the unavailability of the deluge.

All three modules and both models produce the same pattern of variation in the frequencies of the explosions generated when the unavailability of the deluge is changed.

The total explosion frequencies for leaks attributed to specific sections and the total explosion frequency for the module do not change with variations in the unavailability of the deluge system (final column in Tables 10.5 and 10.6). However, the frequencies of explosions
Table 10.5: The changes in explosion frequencies (per year) due to the variation of the unavailability of the deluge system using the changing temperature model.
### Sensitivity analysis.

#### Separation module

<table>
<thead>
<tr>
<th>Change</th>
<th>Deluge fails to activate</th>
<th>Prior to deluge</th>
<th>Deluge not maintained</th>
<th>Mitigated</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
<td>0.5217×10^{-6}</td>
<td>0.3581×10^{-6}</td>
<td>0.1445×10^{-10}</td>
<td>0.8002×10^{-5}</td>
<td>0.8882×10^{-5}</td>
</tr>
<tr>
<td>-10%</td>
<td>0.5523×10^{-6}</td>
<td>0.3568×10^{-6}</td>
<td>0.1439×10^{-10}</td>
<td>0.7972×10^{-5}</td>
<td>0.8882×10^{-5}</td>
</tr>
<tr>
<td>-5%</td>
<td>0.5830×10^{-6}</td>
<td>0.3555×10^{-6}</td>
<td>0.1434×10^{-10}</td>
<td>0.7943×10^{-5}</td>
<td>0.8882×10^{-5}</td>
</tr>
<tr>
<td>0%</td>
<td>0.6137×10^{-6}</td>
<td>0.3542×10^{-6}</td>
<td>0.1429×10^{-10}</td>
<td>0.7914×10^{-5}</td>
<td>0.8882×10^{-5}</td>
</tr>
<tr>
<td>+5%</td>
<td>0.6444×10^{-6}</td>
<td>0.3529×10^{-6}</td>
<td>0.1423×10^{-10}</td>
<td>0.7884×10^{-5}</td>
<td>0.8882×10^{-5}</td>
</tr>
<tr>
<td>+10%</td>
<td>0.6751×10^{-6}</td>
<td>0.3516×10^{-6}</td>
<td>0.1418×10^{-10}</td>
<td>0.7855×10^{-5}</td>
<td>0.8882×10^{-5}</td>
</tr>
<tr>
<td>+15%</td>
<td>0.7058×10^{-6}</td>
<td>0.3503×10^{-6}</td>
<td>0.1413×10^{-10}</td>
<td>0.7826×10^{-5}</td>
<td>0.8882×10^{-5}</td>
</tr>
</tbody>
</table>

#### Compression module

<table>
<thead>
<tr>
<th>Change</th>
<th>Deluge fails to activate</th>
<th>Prior to deluge</th>
<th>Deluge not maintained</th>
<th>Mitigated</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
<td>0.2622×10^{-5}</td>
<td>0.2469×10^{-5}</td>
<td>0.6993×10^{-10}</td>
<td>0.5089×10^{-4}</td>
<td>0.5598×10^{-4}</td>
</tr>
<tr>
<td>-10%</td>
<td>0.2776×10^{-5}</td>
<td>0.2462×10^{-5}</td>
<td>0.6972×10^{-10}</td>
<td>0.5074×10^{-4}</td>
<td>0.5598×10^{-4}</td>
</tr>
<tr>
<td>-5%</td>
<td>0.2930×10^{-5}</td>
<td>0.2455×10^{-5}</td>
<td>0.6952×10^{-10}</td>
<td>0.5060×10^{-4}</td>
<td>0.5598×10^{-4}</td>
</tr>
<tr>
<td>0%</td>
<td>0.3084×10^{-5}</td>
<td>0.2448×10^{-5}</td>
<td>0.6932×10^{-10}</td>
<td>0.5045×10^{-4}</td>
<td>0.5598×10^{-4}</td>
</tr>
<tr>
<td>+5%</td>
<td>0.3239×10^{-5}</td>
<td>0.2440×10^{-5}</td>
<td>0.6912×10^{-10}</td>
<td>0.5030×10^{-4}</td>
<td>0.5598×10^{-4}</td>
</tr>
<tr>
<td>+10%</td>
<td>0.3393×10^{-5}</td>
<td>0.2433×10^{-5}</td>
<td>0.6891×10^{-10}</td>
<td>0.5016×10^{-4}</td>
<td>0.5598×10^{-4}</td>
</tr>
<tr>
<td>+15%</td>
<td>0.3547×10^{-5}</td>
<td>0.2426×10^{-5}</td>
<td>0.6871×10^{-10}</td>
<td>0.5001×10^{-4}</td>
<td>0.5598×10^{-4}</td>
</tr>
</tbody>
</table>

#### Wellhead module

<table>
<thead>
<tr>
<th>Change</th>
<th>Deluge fails to activate</th>
<th>Prior to deluge</th>
<th>Deluge not maintained</th>
<th>Mitigated</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
<td>0.3953×10^{-7}</td>
<td>0.2602×10^{-7}</td>
<td>0.1422×10^{-11}</td>
<td>0.1055×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
<td>-10%</td>
<td>0.4186×10^{-7}</td>
<td>0.2596×10^{-7}</td>
<td>0.1419×10^{-11}</td>
<td>0.1052×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
<td>-5%</td>
<td>0.4418×10^{-7}</td>
<td>0.2591×10^{-7}</td>
<td>0.1416×10^{-11}</td>
<td>0.1050×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
<td>0%</td>
<td>0.4651×10^{-7}</td>
<td>0.2585×10^{-7}</td>
<td>0.1413×10^{-11}</td>
<td>0.1048×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
<td>+5%</td>
<td>0.4883×10^{-7}</td>
<td>0.2580×10^{-7}</td>
<td>0.1410×10^{-11}</td>
<td>0.1046×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
<td>+10%</td>
<td>0.5116×10^{-7}</td>
<td>0.2574×10^{-7}</td>
<td>0.1407×10^{-11}</td>
<td>0.1043×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
<td>+15%</td>
<td>0.5348×10^{-7}</td>
<td>0.2568×10^{-7}</td>
<td>0.1404×10^{-11}</td>
<td>0.1041×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
</tbody>
</table>

Table 10.6: The changes in explosion frequencies (per year) due to the variation of the unavailability of the deluge system using the constant temperature model.
are categorised dependent on the state of the mitigation system at the point that ignition occurs. Explosions may occur when the deluge system fails to activate, prior to the deluge system activating, when the deluge system is not maintained or when the deluge system is fully operational. The frequency of the deluge system failing to activate affects the type of explosion expected, as demonstrated in Tables 10.5 and 10.6.

When determining the frequency of an explosion, the failure rate of the deluge system is introduced following the calculation of the release rates and hence the times at which an explosion is possible. Combining the probability that ignition occurs, the probability of the leak scenario arising, the frequency of the leak and the probability that the deluge system fails to activate gives the frequency of an explosion occurring during a specific concentration level. The frequency of an explosion occurring given that the deluge fails to activate is

\[
\text{Frequency of an explosion} = P(E) P(S) \lambda_L P(WSFA)
\]

Where \(P(E)\) is the probability that the ignition occurs, \(P(S)\) is the probability that the scenario arises, \(\lambda_L\) is the frequency of occurrence of the leak hole and \(P(WSFA)\) is the probability of the deluge failing to activate.

The other types of explosions all assume that the deluge system does initially activate therefore the frequency of an explosion has the probability that the deluge system activates as a multiplication factor.

\[
\text{Frequency of an explosion} = P(E) P(S) \lambda_L (1 - P(WSFA))
\]

When the unavailability of the deluge is increased the frequency of explosions occurring when the deluge fails to activate is increased by the same percentage (second column in Tables 10.5 and 10.6). For example, increasing the unavailability of the deluge by 10% for the compression module using the changing temperature model gives the frequency of an explosion occurring when the deluge system fails to activate of \(0.18013 \times 10^{-5}\) per year compared to the original value of \(0.16375 \times 10^{-5}\) per year. This is a 10% increase \((0.16375 \times 10^{-5} \times 1.1 = 0.18013 \times 10^{-5})\).

The frequencies of explosions from the other categories decrease proportionally, but not at the same percentage as the increase in the variable. The frequency of these explosions is decreased by

\[
\left(1 - \frac{(1 - (1 + a)P(WSFA))}{(1 - P(WSFA))}\right) \times 100\%
\]
Sensitivity analysis.

Where \((a \times 100)\%\) is the increase of the unavailability of deluge.

For example the unavailability of the deluge system for the separation module is 0.0691, increasing this by 10% gives 0.07601. The frequency of an explosion when the deluge system fails to activate increases by 10%. The frequency of explosions prior to the deluge activating, when the deluge is not maintained and when the deluge system operates continuously decrease by \((1 - \frac{1-0.07601}{1-0.0691})\) 100% = 0.742%.

The importance measures do not alter for isolation and blowdown valve contributions to the expected explosion frequency, however they do change for the category of explosions generated. The values with which leaks on particular sections contribute to the explosion frequencies remain unaltered.

The frequencies of exceedence of the overpressures vary according to the variation in the unavailability of the deluge. Figure 10.2 demonstrates the effects for each of the modules with both temperature state models.

Mitigation systems act to reduce the overpressures generated by a gas cloud. Therefore increasing the unavailability of the deluge system decreases the mitigation causing the frequency of higher overpressures to increase.
Sensitivity analysis.

Figure 10.2: A comparison of the exceedence frequency of the overpressures produced, due to variation of the unavailability of deluge.
10.4 The activation time for the deluge.

The activation time for the deluge was originally determined to be 45 seconds for all modules. This has been varied to give the values in Table 10.7. The special case of reducing the time taken to 30 seconds (i.e. percentage decrease of 33.33%) was also considered.

<table>
<thead>
<tr>
<th>Change</th>
<th>Time</th>
<th>Change</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5%</td>
<td>47.25</td>
<td>-5%</td>
<td>42.75</td>
</tr>
<tr>
<td>+10%</td>
<td>49.5</td>
<td>-10%</td>
<td>40.5</td>
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<tr>
<td>+15%</td>
<td>51.75</td>
<td>-15%</td>
<td>38.25</td>
</tr>
<tr>
<td>+50%</td>
<td>67.5</td>
<td>-50%</td>
<td>22.5</td>
</tr>
</tbody>
</table>

Table 10.7: The variation of the time to activate the deluge system in seconds.

The total explosion frequencies for the modules and the individual sections do not vary. However the frequencies of the category of explosions will be influenced. From Tables 10.8 and 10.9 it can be seen that the frequencies of explosions when the deluge fails to activate will not be affected by the activation time of the deluge system. The frequencies of the other categories of explosions will alter as demonstrated in the tables.

The frequencies of explosions prior to the deluge commencing demonstrate the greatest change where the frequencies increase as the activation time increases. These are dependent on the time of activation relative to the times at which the gas concentration reaches the explosive range. The calculations have a contribution which takes the following form.

\[
\text{if } t_1 < t_a < t_2 \text{ then } P(E) = \int_{t_1}^{t_a} f_i(v) \, dv
\]

Where \( t_1 \) is the time the concentration band is reached, \( t_2 \) is the time the band is exceeded, \( t_a \) is the activation time of the deluge and \( f_i(v) \) is the probability density function for the ignition source. Therefore increasing the activation time of the deluge leads to a general increase in the likelihood of such explosions occurring.

The frequencies of explosions when the deluge is not maintained are dependent on the activation time as shown for the case when \( t_a < t_1 \).

\[
P(E) = \int_{t_a}^{t_1} w_s(u) \left[ \int_{t_1}^{t_2} f_i(v) \, dv + \int_{t_3}^{t_a} f_i(v) \, dv \right] \, du +
\]
### Separation module

<table>
<thead>
<tr>
<th>Change</th>
<th>Deluge fails to activate</th>
<th>Prior to deluge</th>
<th>Deluge not maintained</th>
<th>Mitigated</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
<td>0.4026 x 10^{-6}</td>
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<td>0.1081 x 10^{-10}</td>
<td>0.5354 x 10^{-5}</td>
<td>0.5827 x 10^{-5}</td>
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<td>-10%</td>
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<td>0.8023 x 10^{-7}</td>
<td>0.1078 x 10^{-10}</td>
<td>0.5344 x 10^{-5}</td>
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</tr>
<tr>
<td>-5%</td>
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<td>0.9508 x 10^{-7}</td>
<td>0.1074 x 10^{-10}</td>
<td>0.5329 x 10^{-5}</td>
<td>0.5827 x 10^{-5}</td>
</tr>
<tr>
<td>0%</td>
<td>0.4026 x 10^{-6}</td>
<td>0.1093 x 10^{-6}</td>
<td>0.1071 x 10^{-10}</td>
<td>0.5315 x 10^{-5}</td>
<td>0.5827 x 10^{-5}</td>
</tr>
<tr>
<td>+5%</td>
<td>0.4026 x 10^{-6}</td>
<td>0.1234 x 10^{-6}</td>
<td>0.1068 x 10^{-10}</td>
<td>0.5301 x 10^{-5}</td>
<td>0.5827 x 10^{-5}</td>
</tr>
<tr>
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<td>0.1379 x 10^{-6}</td>
<td>0.1065 x 10^{-10}</td>
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<tr>
<td>+15%</td>
<td>0.4026 x 10^{-6}</td>
<td>0.1527 x 10^{-6}</td>
<td>0.1062 x 10^{-10}</td>
<td>0.5271 x 10^{-5}</td>
<td>0.5827 x 10^{-5}</td>
</tr>
</tbody>
</table>

### Compression module

<table>
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<tr>
<th>Change</th>
<th>Deluge fails to activate</th>
<th>Prior to deluge</th>
<th>Deluge not maintained</th>
<th>Mitigated</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
<td>0.1391 x 10^{-5}</td>
<td>0.2026 x 10^{-5}</td>
<td>0.2197 x 10^{-10}</td>
<td>0.2630 x 10^{-4}</td>
<td>0.2971 x 10^{-4}</td>
</tr>
<tr>
<td>-10%</td>
<td>0.1391 x 10^{-5}</td>
<td>0.2169 x 10^{-5}</td>
<td>0.2181 x 10^{-10}</td>
<td>0.2615 x 10^{-4}</td>
<td>0.2971 x 10^{-4}</td>
</tr>
<tr>
<td>-5%</td>
<td>0.1391 x 10^{-5}</td>
<td>0.2313 x 10^{-5}</td>
<td>0.2166 x 10^{-10}</td>
<td>0.2601 x 10^{-4}</td>
<td>0.2971 x 10^{-4}</td>
</tr>
<tr>
<td>0%</td>
<td>0.1391 x 10^{-5}</td>
<td>0.2456 x 10^{-5}</td>
<td>0.2151 x 10^{-10}</td>
<td>0.2587 x 10^{-4}</td>
<td>0.2971 x 10^{-4}</td>
</tr>
<tr>
<td>+5%</td>
<td>0.1391 x 10^{-5}</td>
<td>0.2601 x 10^{-5}</td>
<td>0.2136 x 10^{-10}</td>
<td>0.2572 x 10^{-4}</td>
<td>0.2971 x 10^{-4}</td>
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<tr>
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<td>0.2756 x 10^{-5}</td>
<td>0.2121 x 10^{-10}</td>
<td>0.2557 x 10^{-4}</td>
<td>0.2971 x 10^{-4}</td>
</tr>
<tr>
<td>+15%</td>
<td>0.1391 x 10^{-5}</td>
<td>0.2919 x 10^{-5}</td>
<td>0.2106 x 10^{-10}</td>
<td>0.2540 x 10^{-4}</td>
<td>0.2971 x 10^{-4}</td>
</tr>
</tbody>
</table>

### Wellhead module

<table>
<thead>
<tr>
<th>Change</th>
<th>Deluge fails to activate</th>
<th>Prior to deluge</th>
<th>Deluge not maintained</th>
<th>Mitigated</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
<td>0.4994 x 10^{-7}</td>
<td>0.2793 x 10^{-7}</td>
<td>0.1667 x 10^{-11}</td>
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<td>0.1203 x 10^{-5}</td>
</tr>
<tr>
<td>-10%</td>
<td>0.4994 x 10^{-7}</td>
<td>0.2925 x 10^{-7}</td>
<td>0.1661 x 10^{-11}</td>
<td>0.1124 x 10^{-5}</td>
<td>0.1203 x 10^{-5}</td>
</tr>
<tr>
<td>-5%</td>
<td>0.4994 x 10^{-7}</td>
<td>0.3052 x 10^{-7}</td>
<td>0.1654 x 10^{-11}</td>
<td>0.1123 x 10^{-5}</td>
<td>0.1203 x 10^{-5}</td>
</tr>
<tr>
<td>0%</td>
<td>0.4994 x 10^{-7}</td>
<td>0.3141 x 10^{-7}</td>
<td>0.1647 x 10^{-11}</td>
<td>0.1122 x 10^{-5}</td>
<td>0.1203 x 10^{-5}</td>
</tr>
<tr>
<td>+5%</td>
<td>0.4994 x 10^{-7}</td>
<td>0.3229 x 10^{-7}</td>
<td>0.1641 x 10^{-11}</td>
<td>0.1121 x 10^{-5}</td>
<td>0.1203 x 10^{-5}</td>
</tr>
<tr>
<td>+10%</td>
<td>0.4994 x 10^{-7}</td>
<td>0.3318 x 10^{-7}</td>
<td>0.1634 x 10^{-11}</td>
<td>0.1120 x 10^{-5}</td>
<td>0.1203 x 10^{-5}</td>
</tr>
<tr>
<td>+15%</td>
<td>0.4994 x 10^{-7}</td>
<td>0.3406 x 10^{-7}</td>
<td>0.1628 x 10^{-11}</td>
<td>0.1119 x 10^{-5}</td>
<td>0.1203 x 10^{-5}</td>
</tr>
</tbody>
</table>

Table 10.8: The changes in explosion frequencies due to the variation of the activation time of the deluge system using the changing temperature model.
Sensitivity analysis.

<table>
<thead>
<tr>
<th>Change</th>
<th>Deluge fails to activate</th>
<th>Prior to deluge</th>
<th>Deluge not maintained</th>
<th>Mitigated</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
<td>0.6137x10^{-6}</td>
<td>0.2682x10^{-6}</td>
<td>0.1443x10^{-10}</td>
<td>0.8000x10^{-5}</td>
<td>0.8882x10^{-5}</td>
</tr>
<tr>
<td>-10%</td>
<td>0.6137x10^{-6}</td>
<td>0.2967x10^{-6}</td>
<td>0.1438x10^{-10}</td>
<td>0.7971x10^{-5}</td>
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</tr>
<tr>
<td>-5%</td>
<td>0.6137x10^{-6}</td>
<td>0.3252x10^{-6}</td>
<td>0.1433x10^{-10}</td>
<td>0.7943x10^{-5}</td>
<td>0.8882x10^{-5}</td>
</tr>
<tr>
<td>0%</td>
<td>0.6137x10^{-6}</td>
<td>0.3542x10^{-6}</td>
<td>0.1429x10^{-10}</td>
<td>0.7914x10^{-5}</td>
<td>0.8882x10^{-5}</td>
</tr>
<tr>
<td>+5%</td>
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<td>0.3841x10^{-6}</td>
<td>0.1424x10^{-10}</td>
<td>0.7884x10^{-5}</td>
<td>0.8882x10^{-5}</td>
</tr>
<tr>
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<td>0.6137x10^{-6}</td>
<td>0.4135x10^{-6}</td>
<td>0.1419x10^{-10}</td>
<td>0.7854x10^{-5}</td>
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</tr>
<tr>
<td>+15%</td>
<td>0.6137x10^{-6}</td>
<td>0.4427x10^{-6}</td>
<td>0.1415x10^{-10}</td>
<td>0.7825x10^{-5}</td>
<td>0.8882x10^{-5}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Change</th>
<th>Deluge fails to activate</th>
<th>Prior to deluge</th>
<th>Deluge not maintained</th>
<th>Mitigated</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
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<td>0.2039x10^{-5}</td>
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<td>-5%</td>
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<td>0.2325x10^{-5}</td>
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<td>0%</td>
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<td>0.5089x10^{-4}</td>
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<td>0.5075x10^{-4}</td>
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<td>0.6904x10^{-10}</td>
<td>0.5043x10^{-4}</td>
<td>0.5598x10^{-4}</td>
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</table>

<table>
<thead>
<tr>
<th>Change</th>
<th>Deluge fails to activate</th>
<th>Prior to deluge</th>
<th>Deluge not maintained</th>
<th>Mitigated</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.2508x10^{-7}</td>
<td>0.1432x10^{-11}</td>
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<td>0.1120x10^{-5}</td>
</tr>
<tr>
<td>-10%</td>
<td>0.4651x10^{-7}</td>
<td>0.2554x10^{-7}</td>
<td>0.1425x10^{-11}</td>
<td>0.1048x10^{-5}</td>
<td>0.1120x10^{-5}</td>
</tr>
<tr>
<td>-5%</td>
<td>0.4651x10^{-7}</td>
<td>0.2583x10^{-7}</td>
<td>0.1419x10^{-11}</td>
<td>0.1048x10^{-5}</td>
<td>0.1120x10^{-5}</td>
</tr>
<tr>
<td>0%</td>
<td>0.4651x10^{-7}</td>
<td>0.2585x10^{-7}</td>
<td>0.1413x10^{-11}</td>
<td>0.1048x10^{-5}</td>
<td>0.1120x10^{-5}</td>
</tr>
<tr>
<td>+5%</td>
<td>0.4651x10^{-7}</td>
<td>0.2587x10^{-7}</td>
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<td>0.2589x10^{-7}</td>
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<tr>
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<td>0.2591x10^{-7}</td>
<td>0.1395x10^{-11}</td>
<td>0.1048x10^{-5}</td>
<td>0.1120x10^{-5}</td>
</tr>
</tbody>
</table>

Table 10.9: The changes in explosion frequencies due to the variation of the activation time of the deluge system using the constant temperature model.
Sensitivity analysis.

\[
\begin{align*}
&\int_{t_1}^{t_2} f_{ws}(u) \left[ \int_{t_1}^{t_2} f_i(v) dv + \int_{t_3}^{t_4} f_i(v) dv \right] du + \\
&\int_{t_2}^{t_3} f_{ws}(u) \left[ \int_{t_3}^{t_4} f_i(v) dv \right] du + \int_{t_3}^{t_4} f_{ws}(u) \left[ \int_{t_1}^{t_2} f_i(v) dv \right] du
\end{align*}
\]

Where \( f_{ws}(v) \) is the probability density function of the failure of the deluge system.

The frequencies of explosions which are mitigated are also dependent on the activation time of the deluge as shown.

\[
P(E) = \left[ 1 - \int_{t_a}^{t_4} f_{ws}(u) du \right] \left[ \int_{t_1}^{t_2} f_i(v) dv + \int_{t_3}^{t_4} f_i(v) dv \right] + \\
\int_{t_1}^{t_2} f_{ws}(u) \left[ \int_{t_1}^{t_2} f_i(v) dv \right] du + \int_{t_2}^{t_3} f_{ws}(u) \left[ \int_{t_1}^{t_2} f_i(v) dv \right] du + \\
\int_{t_3}^{t_4} f_{ws}(u) \left[ \int_{t_1}^{t_2} f_i(v) dv + \int_{t_3}^{t_4} f_i(v) dv \right] du
\]

In both of these cases if \( t_a \) is greater than the times \( t_1, t_2, t_3 \) or \( t_4 \) then the frequency becomes more dependent on the activation time. However it is unlikely that this will occur with regularity therefore changing the activation time has less effect than for the frequency of explosions prior to the deluge commencing. In general an increase in the activation time leads to a decrease in the frequencies of explosions occurring when the deluge system is not maintained and when the deluge system is fully operational.

Although the wellhead module is not typical some interesting results may be seen when this module is investigated more thoroughly. Gas clouds in the wellhead module arise due to leaks occurring on sections 9, 10 or 11.

Looking closely at the gas cloud build up for sections 10 and 11 shows that no matter what combination of valves work or fail or leak hole sizes exist, the concentration with respect to time will appear as Figure 10.3, where the concentration exceeds the upper flammable limit. Results also show that the activation time occurs between \( t_2 \) and \( t_3 \). Therefore all explosions prior to mitigation must occur between \( t_1 \) and \( t_2 \) and all explosions which are mitigated or when the deluge is not maintained must occur between \( t_3 \) and \( t_4 \).

For section 10, \( t_2 \) has a maximum of 33.7s and \( t_3 \) has a minimum of 177s, so to affect the frequencies of explosions occurring prior to the mitigation activating the activation time must be reduced below 33.7s or increased above 177s. Reducing the activation time to 30s reduces the explosion frequencies prior to deluge in the 13 – 14% and 14 – 15% concentration bands, see Table 10.10.
Sensitivity analysis.

Figure 10.3: The concentration within the module with time, exceeding the flammable region.

Table 10.10: The frequency of explosions occurring prior to deluge due to section 10 in the wellhead module when the activation time of deluge is 30 seconds.
Sensitivity analysis.

Figure 10.4: The effects of mitigating the gas cloud.

The frequencies of the explosions when deluge is not maintained and when it operates perfectly increase in all bands when the time is lowered suggesting that the deluge has a mitigating effect, as depicted in Figure 10.4, which suppresses the concentration rise whilst retaining the possibility of an explosion occurring. For section 11, $t_2$ has a maximum of 41.9s and $t_3$ has a minimum of 483s. Therefore increasing the activation time within our percentage limits has no effect. Decreasing the time by more than 10% reduces the frequencies of explosions prior to deluge in the latter concentration bands and increases the frequencies of explosions when the deluge is not maintained and when the deluge operates fully in all bands. Reducing the activation time to 30s affects the explosion frequencies prior to deluge in the 11 – 12% concentration band and upwards, Table 10.11.

Section 9 may lead to a concentration profile of Figure 10.3 or Figure 10.5. Due to the mixture of profiles obtained increasing or decreasing the activation time results in a change of frequency. In general the frequency of the explosions prior to mitigation, increase with an increase in time and the explosions when the deluge is not maintained or when it is fully operational, decrease with an increase in time. The overpressures obtained for the wellhead module do not differ significantly with the change of parameter as seen in Figure 10.6(c and f).
Sensitivity analysis.

### Table 10.11: The frequency of explosions occurring prior to deluge due to section 11 in the wellhead module when the activation time of deluge is 30 seconds.

<table>
<thead>
<tr>
<th>Concentration level</th>
<th>Frequency of explosion</th>
</tr>
</thead>
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<td></td>
<td>45 seconds</td>
</tr>
<tr>
<td>5-6 %</td>
<td>0.1038x10^{-8}</td>
</tr>
<tr>
<td>6-7 %</td>
<td>0.1056x10^{-8}</td>
</tr>
<tr>
<td>7-8 %</td>
<td>0.1103x10^{-8}</td>
</tr>
<tr>
<td>8-9 %</td>
<td>0.1089x10^{-8}</td>
</tr>
<tr>
<td>9-10 %</td>
<td>0.1170x10^{-8}</td>
</tr>
<tr>
<td>10-11 %</td>
<td>0.1164x10^{-8}</td>
</tr>
<tr>
<td>11-12 %</td>
<td>0.1211x10^{-8}</td>
</tr>
<tr>
<td>12-13 %</td>
<td>0.1278x10^{-8}</td>
</tr>
<tr>
<td>13-14 %</td>
<td>0.1317x10^{-8}</td>
</tr>
<tr>
<td>14-15 %</td>
<td>0.1360x10^{-8}</td>
</tr>
</tbody>
</table>

Figure 10.5: The concentration within the module with time, remaining within the flammable region.
However, the wellhead module is not typical, the separation and compression modules contain sections demonstrating profiles such as those shown for section 9. No direct relationship between the parameter variation and the change in frequency is obvious. In general it can be said that increasing the time increases the frequency of explosions occurring prior to the deluge activating, but decreases the frequency of explosions occurring when the mitigation is not maintained and when the mitigation system operates continuously. The frequency of exceedence of the overpressures for the separation and compression modules increase with an increase to the activation time, Figure 10.6(a,b,d,& e). The importance measures for the valves do not alter, but the contribution to the frequency for the categories of explosions do. As demonstrated by the Tables 10.8 and 10.9, the frequency of an explosion for the module has a greater contribution from mitigated explosions and a lower contribution from explosions occurring prior to the deluge activating when the activation time is decreased.
Figure 10.6: A comparison of the exceedence frequency of the overpressures produced, due to the variation of the deluge activation time.
10.5 The leak hole size distribution.

Leaks typically appear as a result of flange failures, the sizes of the holes are therefore small in comparison with the dimensions of the modules. Not every size of hole can be considered, however from observational data, the hole sizes have been divided into three groups. Each member of a group has been assigned the average value for that group. The average leak hole diameters are taken to be 18\( mm \), 50\( mm \) and 100\( mm \) for all of the modules. These hole sizes have been varied as shown in Table 10.12.

<table>
<thead>
<tr>
<th>Change</th>
<th>Hole 1</th>
<th>Hole 2</th>
<th>Hole 3</th>
<th>Change</th>
<th>Hole 1</th>
<th>Hole 2</th>
<th>Hole 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5%</td>
<td>18.9</td>
<td>52.5</td>
<td>105</td>
<td>-5%</td>
<td>17.1</td>
<td>47.5</td>
<td>95</td>
</tr>
<tr>
<td>+10%</td>
<td>19.8</td>
<td>55</td>
<td>110</td>
<td>-10%</td>
<td>16.2</td>
<td>45</td>
<td>90</td>
</tr>
<tr>
<td>+15%</td>
<td>20.7</td>
<td>57.5</td>
<td>115</td>
<td>-15%</td>
<td>15.3</td>
<td>42.5</td>
<td>85</td>
</tr>
</tbody>
</table>

Table 10.12: The variation of leak hole diameters.

In order to determine the frequency of an explosion, the frequency of ignition occurring is required. This is dependent upon the times at which the concentration level of gas-in-air, of concern, is reached. The leak hole size controls the rates that the gas and condensate are able to escape, hence influencing the gas cloud build up with time. Therefore the hole sizes will, indirectly, affect the explosion frequencies expected.

In general a larger hole size results in a lower time period within the explosive range. For most sections the smallest hole size of 18\( mm \) diameter leads to a concentration profile of Figure 10.5, whereas the holes of diameters 50\( mm \) and 100\( mm \) have profiles of Figure 10.3.

Both temperature state models provide comparable results for the wellhead module but not for the separation and compression modules, Tables 10.13 and 10.14. For the wellhead module the increase in the hole sizes leads to a decrease in the explosion frequencies generated whilst a decrease in the hole sizes leads to an increase in the explosion frequencies for both models. For the separation module decreasing the hole sizes decreases the explosion frequencies, increasing the hole sizes also leads to a decrease in explosion frequencies centred about the \(-10\%\) level for the constant temperature model and the \(5\%\) level for the changing temperature model. The compression module demonstrates a pattern of increase in the explosion frequencies as the hole size distribution increases for the changing temperature.
model up to the 10% level. For the constant temperature model there appears to be a critical region within which the frequency of an explosion fluctuates. The differences between the models is because the temperature state of the model controls the release flow of gas into the module. When the section is held at constant temperature the driving pressure of the leak remains higher than that for the changing temperature model, therefore in general there is a higher release rate of gas into the module.

<table>
<thead>
<tr>
<th>Change</th>
<th>Separation Module</th>
<th>Compression Module</th>
<th>Wellhead Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
<td>0.5167x10^{-5}</td>
<td>0.2678x10^{-4}</td>
<td>0.1277x10^{-5}</td>
</tr>
<tr>
<td>-10%</td>
<td>0.5367x10^{-5}</td>
<td>0.2808x10^{-4}</td>
<td>0.1274x10^{-5}</td>
</tr>
<tr>
<td>-5%</td>
<td>0.5575x10^{-5}</td>
<td>0.2907x10^{-4}</td>
<td>0.1235x10^{-5}</td>
</tr>
<tr>
<td>0%</td>
<td>0.5827x10^{-5}</td>
<td>0.2971x10^{-4}</td>
<td>0.1203x10^{-5}</td>
</tr>
<tr>
<td>+5%</td>
<td>0.6085x10^{-5}</td>
<td>0.3002x10^{-4}</td>
<td>0.1185x10^{-5}</td>
</tr>
<tr>
<td>+10%</td>
<td>0.6041x10^{-5}</td>
<td>0.3039x10^{-4}</td>
<td>0.1174x10^{-5}</td>
</tr>
<tr>
<td>+15%</td>
<td>0.6127x10^{-5}</td>
<td>0.3008x10^{-4}</td>
<td>0.1167x10^{-5}</td>
</tr>
</tbody>
</table>

Table 10.13: The changes in explosion frequencies due to the variation of the hole size distribution using the changing temperature model.

<table>
<thead>
<tr>
<th>Change</th>
<th>Separation Module</th>
<th>Compression Module</th>
<th>Wellhead Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
<td>0.8173x10^{-5}</td>
<td>0.4917x10^{-4}</td>
<td>0.1133x10^{-5}</td>
</tr>
<tr>
<td>-10%</td>
<td>0.8517x10^{-5}</td>
<td>0.5557x10^{-4}</td>
<td>0.1129x10^{-5}</td>
</tr>
<tr>
<td>-5%</td>
<td>0.9147x10^{-5}</td>
<td>0.5379x10^{-4}</td>
<td>0.1124x10^{-5}</td>
</tr>
<tr>
<td>0%</td>
<td>0.8882x10^{-5}</td>
<td>0.5598x10^{-4}</td>
<td>0.1120x10^{-5}</td>
</tr>
<tr>
<td>+5%</td>
<td>0.8434x10^{-5}</td>
<td>0.5315x10^{-4}</td>
<td>0.1117x10^{-5}</td>
</tr>
<tr>
<td>+10%</td>
<td>0.7743x10^{-5}</td>
<td>0.5279x10^{-4}</td>
<td>0.1115x10^{-5}</td>
</tr>
<tr>
<td>+15%</td>
<td>0.7267x10^{-5}</td>
<td>0.5116x10^{-4}</td>
<td>0.1113x10^{-5}</td>
</tr>
</tbody>
</table>

Table 10.14: The changes in explosion frequencies due to the variation of the hole size distribution using the constant temperature model.

These results suggest that for each module there exists a critical level for the leak holes. As can be seen from the results there appears to be no general pattern as to the variation of the leak hole sizes. This is due to the complex interaction between the hole size and the ventilation. The hole sizes play a major part in determining the gas release rate into the
module following a leak, the rate of air changes per hour controls the dispersion of the gas from the module. The interaction between these two factors determines the times at which the concentration is at a level for ignition to occur.

The wellhead module is the simplest to analyse in detail due to there being a constant ventilation rate of 12 air changes per hour, hence shall be looked at first. Sections 10 and 11 located in the wellhead module both show that an increase of the hole sizes leads to a decrease in the explosion frequencies. This is due to the original concentration profile of Figure 10.3, increasing the hole sizes allows more gas to escape rapidly therefore leading to an earlier time for the upper flammable limit to be exceeded and hence less time in the explosive range as seen in Figure 10.7. Decreasing the hole sizes may generate a profile which still exceeds the upper flammable limit, but at a later time, the growth of the gas cloud will be slower leading to more time in the explosive range. Alternatively the profile may not exceed the upper flammable limit hence also allowing a longer period of time within the explosive range. Section 9 has the opposite effect, as the holes are made larger the explosion frequency is increased. Again this may be related to the original concentration profile of Figure 10.5. As the hole size is increased there is a faster initial release of gas leading to a higher concentration of gas within the region. The concentration profile exhibits growth, Figure 10.7, but not so much that the upper flammable limit is exceeded, therefore giving more time in the explosive range. Due to the complex coupling of the hole size and the ventilation rates in determining the overpressures, it is difficult to determine a relationship between the variation of the hole sizes and the overpressures produced.

For the wellhead module a pattern may be seen due to there only being one ventilation rate. From Figure 10.8 it can be seen that reducing the hole diameters increases the frequency with which certain overpressures are exceeded, however no formal mathematical relationship is apparent.

The compression and separation modules are more typical in that to represent the effects of natural ventilation, a distribution of air changes per hour are assumed. Sections 1 and 3, located in the separation module, and sections 4, 5, 6 and 8, located in the compression module, exhibit concentration profiles which vary between those of Figures 10.3 and 10.5 therefore making it difficult for any full analysis to be carried out. In some situations, when the hole size is decreased, an original profile of Figure 10.3 may reduce to one of Figure 10.5 which leads to a greater time within the explosive region therefore an increased chance of
Figure 10.7: The possible variation of the concentration profile occurring with the variation of the hole sizes.
explosion occurring meanwhile a profile of Figure 10.5 may be reduced to one which never enters the explosive region decreasing the chance of an explosion. This is demonstrated in Figure 10.7. Similarly increasing the hole sizes may decrease or increase the explosion frequency. Due to the interaction of these factors and the profiles obtained following a change of parameter no generalisation may be made regarding the effects.

Figure 10.8 shows the changes in the overpressure distributions obtained. Although the two temperature state models differ in the way the gas is released therefore varying the explosion frequencies obtained, the overpressure distributions are similar for each model.
Figure 10.8: A comparison of the overpressure distributions for each module, with each model when the hole sizes are varied.
10.6 The frequency of occurrence of the leak holes.

The frequency with which the hole sizes are expected is not only dependent on the module being analysed, but also on which of the sections may contribute to the leak within that module. For each module the frequencies of the leak hole sizes were altered for each section connected to that module. It was expected that there would be a straightforward pattern relating to the change in this parameter due to the frequency of occurrence of a leak being a linear multiplying factor in the model, therefore to confirm this only a small range of tests were done. Table 10.15 reflects the tests done, varying the parameter up and down by 10% and up by 50%.
Sensitivity analysis.

<table>
<thead>
<tr>
<th>Change</th>
<th>18mm</th>
<th>50mm</th>
<th>100mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0.05194</td>
<td>0.06295</td>
<td>0.00610</td>
</tr>
<tr>
<td>+10%</td>
<td>0.05713</td>
<td>0.06925</td>
<td>0.00671</td>
</tr>
<tr>
<td>-10%</td>
<td>0.04675</td>
<td>0.05666</td>
<td>0.00549</td>
</tr>
<tr>
<td>+50%</td>
<td>0.07791</td>
<td>0.09443</td>
<td>0.00919</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Change</th>
<th>18mm</th>
<th>50mm</th>
<th>100mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0.04521</td>
<td>0.02956</td>
<td>0.00267</td>
</tr>
<tr>
<td>+10%</td>
<td>0.04973</td>
<td>0.03252</td>
<td>0.00294</td>
</tr>
<tr>
<td>-10%</td>
<td>0.04069</td>
<td>0.02660</td>
<td>0.00240</td>
</tr>
<tr>
<td>+50%</td>
<td>0.06782</td>
<td>0.04434</td>
<td>0.00401</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Change</th>
<th>18mm</th>
<th>50mm</th>
<th>100mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0.05567</td>
<td>0.03532</td>
<td>0.00534</td>
</tr>
<tr>
<td>+10%</td>
<td>0.06124</td>
<td>0.03885</td>
<td>0.00588</td>
</tr>
<tr>
<td>-10%</td>
<td>0.0501</td>
<td>0.03179</td>
<td>0.00481</td>
</tr>
<tr>
<td>+50%</td>
<td>0.08351</td>
<td>0.05298</td>
<td>0.00802</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Change</th>
<th>18mm</th>
<th>50mm</th>
<th>100mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0.07285</td>
<td>0.02759</td>
<td>0.00391</td>
</tr>
<tr>
<td>+10%</td>
<td>0.08014</td>
<td>0.03035</td>
<td>0.00429</td>
</tr>
<tr>
<td>-10%</td>
<td>0.06557</td>
<td>0.02483</td>
<td>0.00352</td>
</tr>
<tr>
<td>+50%</td>
<td>0.10928</td>
<td>0.04139</td>
<td>0.00586</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Change</th>
<th>18mm</th>
<th>50mm</th>
<th>100mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0.00132</td>
<td>0.00976</td>
<td>0.00088</td>
</tr>
<tr>
<td>+10%</td>
<td>0.00146</td>
<td>0.01074</td>
<td>0.00096</td>
</tr>
<tr>
<td>-10%</td>
<td>0.00119</td>
<td>0.00879</td>
<td>0.00079</td>
</tr>
<tr>
<td>+50%</td>
<td>0.00199</td>
<td>0.01465</td>
<td>0.00131</td>
</tr>
</tbody>
</table>

Table 10.15: The variation of the frequency of occurrence of the leak holes for the separation module.

Should there have been no visible pattern further tests would have been carried out. However as expected the increase seen in the explosion frequencies and the overpressure exceedence frequencies was the percentage increase of the hole size frequency range. Table 10.16 shows the change in the explosion frequencies due to the variation for each module using the changing temperature model and Table 10.17 displays the results for the constant temperature model. These two tables demonstrate the same relationship between the variation of the parameter.
and the explosion frequencies generated. The overpressure distributions generated are shown in Figure 10.9.

<table>
<thead>
<tr>
<th>Change</th>
<th>Separation Module</th>
<th>Compression Module</th>
<th>Wellhead Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10%</td>
<td>0.5244 x 10^{-5}</td>
<td>0.2674 x 10^{-4}</td>
<td>0.1083 x 10^{-5}</td>
</tr>
<tr>
<td>0%</td>
<td>0.5827 x 10^{-5}</td>
<td>0.2971 x 10^{-4}</td>
<td>0.1203 x 10^{-5}</td>
</tr>
<tr>
<td>+10%</td>
<td>0.6409 x 10^{-5}</td>
<td>0.3276 x 10^{-4}</td>
<td>0.1323 x 10^{-5}</td>
</tr>
<tr>
<td>+50%</td>
<td>0.8740 x 10^{-5}</td>
<td>0.4457 x 10^{-4}</td>
<td>0.1805 x 10^{-5}</td>
</tr>
</tbody>
</table>

Table 10.16: The changes in explosion frequencies due to the variation of the frequency of occurrence of the leak holes using the changing temperature model.

<table>
<thead>
<tr>
<th>Change</th>
<th>Separation Module</th>
<th>Compression Module</th>
<th>Wellhead Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10%</td>
<td>0.7994 x 10^{-5}</td>
<td>0.5038 x 10^{-4}</td>
<td>0.1008 x 10^{-5}</td>
</tr>
<tr>
<td>0%</td>
<td>0.8882 x 10^{-5}</td>
<td>0.5598 x 10^{-4}</td>
<td>0.1120 x 10^{-5}</td>
</tr>
<tr>
<td>+10%</td>
<td>0.9776 x 10^{-5}</td>
<td>0.6165 x 10^{-4}</td>
<td>0.1232 x 10^{-5}</td>
</tr>
<tr>
<td>+50%</td>
<td>0.1332 x 10^{-4}</td>
<td>0.8398 x 10^{-4}</td>
<td>0.1681 x 10^{-5}</td>
</tr>
</tbody>
</table>

Table 10.17: The changes in explosion frequencies due to the variation of the frequency of occurrence of the leak holes using the constant temperature model.

The generated explosion frequencies are dependent upon the accuracy of the frequency of the leak. This study has considered an increase in the frequency of occurrence of all the sizes of holes, i.e., if the frequency of the 18 mm hole increases then so too do the frequencies of the 50 mm and 100 mm holes. The frequencies of leaks occurring are taken from empirical data, such data has inaccuracies which may mean that the leak holes have been wrongly classified in terms of average size. Such inaccuracies will alter not only the frequencies of the holes of an average size occurring but also the sizes of the average holes. Therefore the frequencies of occurrence of the holes may not change as a group, it may be more accurate to assume that if one group increases another falls. This argument also applies to the distribution of the hole sizes.
Sensitivity analysis.

a) Separation module: changing temperature model

b) Compression module: changing temperature model
c) Wellhead module: changing temperature model
d) Separation module: constant temperature model
e) Compression module: constant temperature model
f) Wellhead module: constant temperature model

Figure 10.9: A comparison of the exceedence frequency of the overpressures produced, due to the variation of the frequency of occurrence of the leak holes.
### 10.7 The distribution of ventilation rates.

The ventilation distribution for the three modules differ. For the wellhead module a constant ventilation rate of 12 air changes per hour is assumed. For the separation and compression modules the distribution has been discretised into five ventilation rates which have equal probability of occurrence of 0.2. For the separation module these are 10.5, 106.5, 210, 252 and 282 air changes per hour. For the compression module these are 33, 81.6, 157.8, 260.4 and 343.8 air changes per hour. Table 10.18 shows the changes.

<table>
<thead>
<tr>
<th>%</th>
<th>Air changes</th>
<th>%</th>
<th>Air changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5</td>
<td>11.03 111.83 220.5 264.6 296.1</td>
<td>-5</td>
<td>9.98 101.18 199.5 239.4 267.9</td>
</tr>
<tr>
<td>+10</td>
<td>11.55 117.15 231 277.2 310.2</td>
<td>-10</td>
<td>9.45 95.85 189 226.8 253.8</td>
</tr>
<tr>
<td>+15</td>
<td>12.08 122.48 241.5 289.8 324.3</td>
<td>-15</td>
<td>8.93 90.53 178.5 214.2 239.7</td>
</tr>
</tbody>
</table>

### Separation Module

<table>
<thead>
<tr>
<th>%</th>
<th>Air changes</th>
<th>%</th>
<th>Air changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5</td>
<td>34.65 85.68 165.69 273.4 361</td>
<td>-5</td>
<td>31.35 77.52 149.9 247.4 326.6</td>
</tr>
<tr>
<td>+10</td>
<td>36.3 89.76 173.6 286.4 378.2</td>
<td>-10</td>
<td>29.7 73.44 142 234.4 309.4</td>
</tr>
<tr>
<td>+15</td>
<td>37.95 93.84 181.5 299.5 395.4</td>
<td>-15</td>
<td>28.05 69.36 134.1 221.3 292.2</td>
</tr>
</tbody>
</table>

### Compression Module

<table>
<thead>
<tr>
<th>%</th>
<th>Air changes</th>
<th>%</th>
<th>Air changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5</td>
<td>12.6</td>
<td>-5</td>
<td>11.4</td>
</tr>
<tr>
<td>+10</td>
<td>13.2</td>
<td>-10</td>
<td>10.8</td>
</tr>
<tr>
<td>+15</td>
<td>13.3</td>
<td>-15</td>
<td>10.2</td>
</tr>
</tbody>
</table>

### Table 10.18: The variation of the air changes per hour.

The ventilation rate affects the gas concentration build up within the module and controls the dispersion from the module once the leaking vessel is exhausted. Increasing the ventilation rates may not have a beneficial effect. The ventilation acts to reduce the level of concentration in the module. However explosions may only occur if the concentration is within the explosive region. If the concentration has been exceeding the upper flammable limit then increasing the ventilation rate may lower the concentration to within the explosive region, thereby increasing the likelihood of an explosion occurring. Alternatively, the concentration may be
Sensitivity analysis.

reduced below the lower flammable limit therefore reducing the likelihood of an explosion.

The results obtained for the changing temperature model and the constant temperature model are presented in Tables 10.19 and 10.20 respectively.

From the final columns in Tables 10.19 and 10.20 it can be seen that there is a general decrease in the explosion frequencies when the ventilation rates are increased. For the separation module there is a general decrease for all types of explosions. For the compression and wellhead modules the frequencies of explosions occurring prior to deluge increase whilst the other categories show a decreasing trend. However there are irregularities in the results. The results generated due to the ventilation rate changes appear more complex than for the other parameter changes. First, the comparatively simple case of the wellhead module with only one ventilation rate is considered.

In this case increasing the ventilation by \( \epsilon \% \) leads to a decrease in the explosion frequencies of \( \epsilon \% \). The isolation valve failures remain with the same importance although the corresponding contributions to the explosion frequency decrease by \( \epsilon \% \).

When the ventilation rates are increased the frequencies of exceedence of the overpressures decrease. From Figure 10.10(c and f) it can be seen that the greater the decrease in the ventilation rate the greater the increase in the frequencies of exceedence and the greater the increase in the ventilation rate the lower the decrease in the frequencies of exceedence. There appears to be an increase in the overpressure exceedence frequencies of about \( \frac{3}{6} \epsilon \% \) for an increase in the ventilation rate of \( \epsilon \% \).

The contribution to the frequency of an explosion when the ventilation rate is increased differs for each section. In the wellhead module there are three sections, sections 9, 10 and 11. The explosion frequency contributions of sections 9 and 11 due to the effect of the ventilation increase should the ventilation rate increase, but for explosions due to a leak on section 10 the contributions decrease. All three sections produce initially high flow rates which in turn give high concentration levels above the explosive range and consequently short time periods for an explosion to occur. The flow rates for sections 9 and 11 are such that when the ventilation rate is increased the time that the concentration is within the explosive range is increased, therefore increasing the likelihood of an explosion. However, for section
### Sensitivity analysis.

#### Separation module

<table>
<thead>
<tr>
<th>Change</th>
<th>Deluge fails to activate</th>
<th>Prior to deluge</th>
<th>Deluge not maintained</th>
<th>Mitigated</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
<td>$0.4641 \times 10^{-6}$</td>
<td>$0.1343 \times 10^{-6}$</td>
<td>$0.1302 \times 10^{-10}$</td>
<td>$0.6119 \times 10^{-5}$</td>
<td>$0.6717 \times 10^{-5}$</td>
</tr>
<tr>
<td>-10%</td>
<td>$0.4414 \times 10^{-6}$</td>
<td>$0.1248 \times 10^{-6}$</td>
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<tr>
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<td>$0.4928 \times 10^{-5}$</td>
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<tr>
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#### Compression module

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#### Wellhead module

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<td>$0.1122 \times 10^{-5}$</td>
<td>$0.1203 \times 10^{-5}$</td>
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<td>$0.0994 \times 10^{-6}$</td>
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Table 10.19: The changes in explosion frequencies due to the variation of the ventilation rates using the changing temperature model.
### Separation module

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<td>0.8882×10^{-5}</td>
</tr>
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<td>0.3426×10^{-6}</td>
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<td>0.7840×10^{-5}</td>
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</tr>
<tr>
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<td>0.1397×10^{-10}</td>
<td>0.7695×10^{-5}</td>
<td>0.8618×10^{-5}</td>
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### Compression module

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<th>Total</th>
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<td>0.5051×10^{-4}</td>
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</tr>
<tr>
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<tr>
<td>+5%</td>
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<td>0.6636×10^{-10}</td>
<td>0.4643×10^{-4}</td>
<td>0.5130×10^{-4}</td>
</tr>
<tr>
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### Wellhead module

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<th>Deluge not maintained</th>
<th>Mitigated</th>
<th>Total</th>
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</thead>
<tbody>
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<td>0.1941×10^{-11}</td>
<td>0.1228×10^{-5}</td>
<td>0.1308×10^{-5}</td>
</tr>
<tr>
<td>-10%</td>
<td>0.5141×10^{-7}</td>
<td>0.2566×10^{-7}</td>
<td>0.1736×10^{-11}</td>
<td>0.1161×10^{-5}</td>
<td>0.1238×10^{-5}</td>
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<tr>
<td>-5%</td>
<td>0.4883×10^{-7}</td>
<td>0.2577×10^{-7}</td>
<td>0.1562×10^{-11}</td>
<td>0.1102×10^{-5}</td>
<td>0.1176×10^{-5}</td>
</tr>
<tr>
<td>0%</td>
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<td>0.2585×10^{-7}</td>
<td>0.1413×10^{-11}</td>
<td>0.1048×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
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<td>0.4441×10^{-7}</td>
<td>0.2595×10^{-7}</td>
<td>0.1285×10^{-11}</td>
<td>0.0999×10^{-6}</td>
<td>0.1070×10^{-5}</td>
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<tr>
<td>+10%</td>
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<td>0.2609×10^{-7}</td>
<td>0.1175×10^{-11}</td>
<td>0.0956×10^{-6}</td>
<td>0.1024×10^{-5}</td>
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<td>0.1079×10^{-11}</td>
<td>0.09159×10^{-6}</td>
<td>0.09829×10^{-6}</td>
</tr>
</tbody>
</table>

Table 10.20: The changes in explosion frequencies due to the variation of the ventilation rates using the constant temperature model.
The separation module is considered with five ventilation rates acting upon it. When using both temperature state models the frequency of an explosion occurring decrease for all categories with an increase in ventilation rate. In general the higher ventilation rates contribute less to the overall frequency of explosions occurring. For the lowest ventilation rate of 10.5 air changes per hour, the smallest hole produces a concentration profile as that seen in Figure 10.5, whereas the larger two hole sizes produce the profile of Figure 10.3. Increasing the ventilation rate leads to there being no explosions for the smallest hole sizes and the frequency of the profile remaining within the explosive region (Figure 10.5) increases with the frequency of the profile exceeding the range decreasing. Therefore, in general, the increase in the ventilation rate causes a decrease in the explosion frequency for the module. It appears that the frequencies of explosions occurring in the lower concentration bands increases this could be due to the ventilation prohibiting the rise of the concentration level. However in some cases the frequency of an explosion increases due to the extra time spent in the explosive range when the concentration profile does not exceed the upper flammable limit when it previously did. Due to the other factors involved no immediate pattern can be suggested to describe the relationship between the change in ventilation rate and the explosion frequency expected. The overpressure exceedence frequencies are compared in Figure 10.10(a & d). Increasing the ventilation rates leads to a decrease in the exceedence frequencies for the overpressures.

The same arguments may apply to the compression module as stated for the separation module. It appears in this case that increasing the ventilation rates leads to a decrease in explosion frequencies but decreasing the rates does not necessarily increase the explosion frequencies. To decrease the ventilation rate by 10% when using the constant temperature model incurs a decrease in the explosion frequencies when an increase was expected to follow the pattern demonstrated by the other results. However a pattern should not be expected due to the coupling between the leak flow rate and the ventilation in determining the concentration of gas within the module. The ventilation rate acts to lower the concentration of gas within the module. Certain levels of ventilation may have a detrimental effect. If the
concentration profile was originally one that exceeded the upper flammable limit, increasing the ventilation rate could reduce the concentration to within the flammable range, therefore increasing the likelihood of an explosion occurring. Alternatively a concentration profile remaining within the flammable range could be reduced below the lower flammable limit by an increase in ventilation therefore reducing the likelihood of an explosion occurring. Since the compression module involves both of these profiles then increasing the ventilation rate will in some cases reduce the explosion frequency whilst in others it will increase it. However the lower ventilation rates are more dominant in contributing to the explosion frequency therefore it seems natural to generalise and say that the more the ventilation rates are decreased the higher the explosion frequencies will become.

As with the hole size distribution there is no pattern to the decrease/increase of the over-pressure exceedence due to changes in the ventilation rates.
Figure 10.10: A comparison of the exceedence frequency of the overpressures produced, due to the variation of the ventilation rates.
10.8 The failure frequency of the deluge once operational.

The failure rate of the deluge system once operational is $9.446 \times 10^{-6}$ per hour for all modules. This parameter was varied as in Table 10.21.

<table>
<thead>
<tr>
<th>Change</th>
<th>Failure Rate</th>
<th>Change</th>
<th>Failure Rate</th>
</tr>
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<td>$1.08629 \times 10^{-5}$</td>
<td>$-15%$</td>
<td>$8.0291 \times 10^{-6}$</td>
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</table>

Table 10.21: The variation of the deluge failure rate per hour.

The failure rate of the deluge when operational is not a parameter involved in the calculation of the frequencies of explosions when the deluge system fails to activate or when the explosion occurs prior to the deluge activating. It is involved in the frequency of explosions that are mitigated and those that occur when the deluge has activated but fails prior to ignition. The calculations for the frequency of ignition when the deluge is activated but is not maintained takes the following form.

$$
P(E) = \int_{t_a}^{t_{i1}} f_{ws}(u) \left[ \int_{t_{i1}}^{t_{i2}} f_i(v)dv + \int_{t_{i3}}^{t_{i4}} f_i(v)dv \right] du + \\
\int_{t_{i2}}^{t_{i3}} f_{ws}(u) \left[ \int_{t_{i1}}^{t_{i2}} f_i(v)dv + \int_{t_{i3}}^{t_{i4}} f_i(v)dv \right] du + \\
\int_{t_{i3}}^{t_{i4}} f_{ws}(u) \left[ \int_{t_{i1}}^{t_{i4}} f_i(v)dv \right] du + \int_{t_{i3}}^{t_{i4}} f_{ws}(u) \left[ \int_{t_{i1}}^{t_{i4}} f_i(v)dv \right] du$$

(10.2)

where $f_{ws}(u)$ is the failure density function for the deluge system. The deluge system is assumed to have a constant rate of failure, $\lambda_{ws}$, leading to a probability density function for the failure of the deluge system of

$$
f_{ws}(u) = \lambda_{ws} e^{-\lambda_{ws} u}$$

(10.3)

The calculations for mitigated explosions takes the following form.

$$
P(E) = \left[ 1 - \int_{t_a}^{t_{i1}} f_{ws}(u)du \right] \left[ \int_{t_{i1}}^{t_{i2}} f_i(v)dv + \int_{t_{i3}}^{t_{i4}} f_i(v)dv \right] + \\
\int_{t_{i1}}^{t_{i2}} f_{ws}(u) \left[ \int_{t_{i1}}^{u} f_i(v)dv \right] du + \int_{t_{i2}}^{t_{i4}} f_{ws}(u) \left[ \int_{t_{i1}}^{t_{i2}} f_i(v)dv \right] du + \\
\int_{t_{i3}}^{t_{i4}} f_{ws}(u) \left[ \int_{t_{i1}}^{t_{i4}} f_i(v)dv + \int_{t_{i3}}^{u} f_i(v)dv \right] du$$

(10.4)
Sensitivity analysis.

Although both of these calculations are dependent on the failure rate of the deluge, the explosions when the deluge fails are more heavily dependent.

Changing this variable only changes the frequency of an explosion should the deluge activate but fail to be maintained as seen in Tables 10.22 and 10.23. The percentage change of the variable incurs the same percentage change in the frequency of this type of explosion. However, an explosion when the deluge is not maintained is of negligible frequency compared to the other explosion frequencies therefore there is no change in the overall explosion frequencies or the distribution of overpressure frequencies. The overpressure frequencies are shown in Figure 10.11.
Table 10.22: The changes in explosion frequencies due to the variation of the failure rate of the deluge system using the changing temperature model.
Sensitivity analysis.

<table>
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<th>Deluge fails to activate</th>
<th>Prior to deluge</th>
<th>Deluge not maintained</th>
<th>Mitigated</th>
<th>Total</th>
</tr>
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<td>0.7914×10^{-5}</td>
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</tr>
<tr>
<td>-5%</td>
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</tr>
<tr>
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</tr>
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<table>
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<th>Mitigated</th>
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<tr>
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<td>0.5598×10^{-4}</td>
</tr>
<tr>
<td>+5%</td>
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<td>0.2448×10^{-5}</td>
<td>0.7342×10^{-10}</td>
<td>0.5045×10^{-4}</td>
<td>0.5598×10^{-4}</td>
</tr>
<tr>
<td>+10%</td>
<td>0.3084×10^{-5}</td>
<td>0.2448×10^{-5}</td>
<td>0.7692×10^{-10}</td>
<td>0.5045×10^{-4}</td>
<td>0.5598×10^{-4}</td>
</tr>
<tr>
<td>+15%</td>
<td>0.3084×10^{-5}</td>
<td>0.2448×10^{-5}</td>
<td>0.8041×10^{-10}</td>
<td>0.5045×10^{-4}</td>
<td>0.5598×10^{-4}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Change</th>
<th>Deluge fails to activate</th>
<th>Prior to deluge</th>
<th>Deluge not maintained</th>
<th>Mitigated</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15%</td>
<td>0.4651×10^{-7}</td>
<td>0.2585×10^{-7}</td>
<td>0.1201×10^{-11}</td>
<td>0.1048×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
<td>-10%</td>
<td>0.4651×10^{-7}</td>
<td>0.2585×10^{-7}</td>
<td>0.1272×10^{-11}</td>
<td>0.1048×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
<td>-5%</td>
<td>0.4651×10^{-7}</td>
<td>0.2585×10^{-7}</td>
<td>0.1342×10^{-11}</td>
<td>0.1048×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
<td>0%</td>
<td>0.4651×10^{-7}</td>
<td>0.2585×10^{-7}</td>
<td>0.1413×10^{-11}</td>
<td>0.1048×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
<td>+5%</td>
<td>0.4651×10^{-7}</td>
<td>0.2585×10^{-7}</td>
<td>0.1484×10^{-11}</td>
<td>0.1048×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
<td>+10%</td>
<td>0.4651×10^{-7}</td>
<td>0.2585×10^{-7}</td>
<td>0.1554×10^{-11}</td>
<td>0.1048×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
<tr>
<td>+15%</td>
<td>0.4651×10^{-7}</td>
<td>0.2585×10^{-7}</td>
<td>0.1625×10^{-11}</td>
<td>0.1048×10^{-5}</td>
<td>0.1120×10^{-5}</td>
</tr>
</tbody>
</table>

Table 10.23: The changes in explosion frequencies due to the variation of the failure rate of the deluge system using the constant temperature model.
Figure 10.11: A comparison of the exceedence frequency of the overpressures produced, due to the variation of the failure rate of the deluge system.
10.9 Discussion.

This analysis has indicated that there are two types of parameters involved in determining the frequency of an explosion and the consequences arising therefrom. The first category include those parameters that affect the concentration build up of gas in the module. The second category include parameters that are introduced to the modelling to determine the frequency of the different categories of explosion given the time periods at which the concentration is between the flammable limits.

The first category includes the distribution of leak hole sizes and the distribution of ventilation rates. The initial environmental conditions of the leaking section, such as the pressure and temperature, combine with the leak hole to give a mass flow rate into the module. Combining this flow rate with the ventilation rate supplies a concentration within the module. Due to the reducing driving pressure of the leak, the flow rate diminishes causing the ventilation to become the dominant force in determining the concentration levels with time. Because of the influence of the initial conditions on the flow rate and the time on the system, the relationship between the concentration build up, ventilation rates and hole sizes is complex.

The first stage of calculations and parameters provide a concentration time profile. The times at which the concentration bands are reached are then used to determine the frequency of ignition occurring under the specific conditions.

The second category includes the frequency of ignition and of the leak occurring and the deluge parameters. These parameters are combined with the times at which ignition may occur to determine the frequency of an explosion occurring. The parameters in the second category have a more obvious relationship to the overall results due to them being predominantly linear multiplying factors. The frequencies of ignition and leak are linear parameters affecting the overall explosion frequencies in all categories and the overpressure distribution. The deluge parameters affect the types of explosions occurring specific to the parameter and hence affect the overall overpressure distribution.

The parameters in the second category may be seen to be the most sensitive due to the obvious effects on the overall results. However the parameters in the first category generate a change in the concentration time profile which leads to a more complex change in the
Sensitivity analysis.

explosion frequencies and overpressure distribution.

It has been seen that the two temperature state models; changing temperature throughout the release and constant temperature during the phase when both condensate and gas are within the section followed by reducing temperature when the condensate has evaporated, lead to comparable results. For the second category of parameters the two models produce identical results. The first category of parameters are those in which the concentration build up within the module is affected. However the concentration build up is dependent on the release rate of the gas into the module, the initial environmental conditions influence the release rate however they are constant in both models. The temperature state of the models combined with the initial conditions and the leak hole sizes dictates the initial release rates when the section contains condensate, therefore differences were seen between the two temperature state models when the hole sizes were varied.
11. Approaches to optimise the configuration of the safety systems.

11.1 Introduction.

On an offshore platform an accidental release of gas may lead to catastrophic consequences. Ignition of the gas may lead to an explosion which generates excessive overpressures. A platform can be designed to withstand overpressures of up to around 3 bar. Assuming that a platform has this strength limit we must minimise the likelihood of the overpressures exceeding 3 bar. SAROS is a tool which can predict the frequency of an explosion and the frequency of exceeding any level of overpressure. These predictions are based on knowledge of the safety systems in place and their reliabilities. The safety systems include isolation valves, blowdown valves, the deluge system and the gas detection system. These features have an associated unavailability, inspection interval, time to test and cost.

In order to reduce the frequency of an explosion exceeding 3 bar occurring these safety systems must have an unavailability which is as low as possible whilst retaining a reasonable cost. Inspection of the components helps to achieve low unavailabilities, however testing the components takes time and money therefore the time spent in the testing process should be as low as possible. An optimisation procedure is required to select the best possible parameters for use in the predictions. The optimisation being undertaken in this chapter provides an example to illustrate the practicality of this type of approach.

11.2 The objective function.

The objective is to minimise the frequency of an explosion generating an overpressure exceeding 3 bar i.e.,

$$\min_{\mathbf{x}} f_0(\mathbf{x})$$

(11.1)
where \( f_0(x) \) is the frequency of the overpressure exceeding 3 bar, \( x \) is the design vector which includes 9 parameters: type of isolation valve, type of blowdown valve, type of deluge system and type of detection system; inspection interval of the isolation valves, blowdown valves, deluge system and detection system; position of the isolation valves.

\( f_0(x) \) is evaluated by SAROS which is a computer program with an average running time of six hours, depending on the platform characteristics and the processor power of the computer. The SAROS data files contain information regarding the potential leak inventory, the atmospheric environment and the specifications of the module safety systems. The offshore platform is considered in terms of three modules, separation, compression and wellhead, data files must be created for each module and evaluated by the SAROS program individually. Changing one detail in the specification of the safety systems requires the creation of six new data files (two per module) and three further evaluations of SAROS. The values of \( f_0(x) \) can not be directly obtained from the output files of SAROS. The frequencies of the overpressures are generated at discrete points dictated by the concentration levels. In order to obtain results for exceeding 3 bar, interpolation between the results is required. The distribution appears to be of an exponential form, however around the 3 bar values it demonstrates an approximately linear relationship. Therefore to gain the values of exceeding 3 bar, linear interpolation between neighbouring values is employed. This process is done for each module then to obtain the frequency of exceeding 3 bar for the platform the sum of the module values is taken. The three computer runs, the linear interpolation and the summation required to obtain \( f_0(x) \) is referred to as a platform evaluation.

11.3 The components and the design vector.

There are fourteen isolation valves on the platform considered in this design exercise, for the purpose of this study each valve is assumed to be of the same type. When optimising there is a choice between three types of valve, each with a different unavailability and cost. Table 11.1 shows the unavailabilities and costs for each valve type. Choosing valves of type 1 will cost 400 units per valve, type 2 costs 300 units and type 3 costs 100 units. The inspection interval chosen for the valves affects the unavailability. Inspecting the type 1 valves every 6 months gives an unavailability of 0.01 per valve, whereas inspecting every 12 months increases this to 0.02. This gain in unavailability may be traded off against the reduction in the time spent
Approaches to optimise the configuration of the safety systems.

in the inspection process and hence the time spent with the platform off line. Each valve
takes 3 hours to inspect, therefore inspecting every 6 months means that within a year 6
hours have been spent on each valve, with 14 valves on the platform a total of 84 hours is
lost in the inspection process. An inspection every 12 months results in an off line period of
42 hours, Table 11.2. The cost for inspection is assumed to be 100 units per hour, therefore
the greater the time spent in the testing process the greater the cost of maintaining the
platform becomes.

<table>
<thead>
<tr>
<th>Valve</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unavailability (6 month inspection)</td>
<td>0.01</td>
<td>0.04</td>
<td>0.1</td>
</tr>
<tr>
<td>Unavailability (12 month inspection)</td>
<td>0.02</td>
<td>0.08</td>
<td>0.2</td>
</tr>
<tr>
<td>Cost (per valve)</td>
<td>400</td>
<td>300</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 11.1: Data for the isolation and blowdown valves.

<table>
<thead>
<tr>
<th>Inspection interval (months)</th>
<th>6</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Isolation</td>
<td>Blowdown</td>
</tr>
<tr>
<td>Time to test system (hours)</td>
<td>84</td>
<td>72</td>
</tr>
</tbody>
</table>

Table 11.2: Data for the isolation and blowdown system inspection.

There are twelve blowdown valves on the platform which are again all assumed to be the
same. The data for these valves is the same as for the isolation valves given in Tables 11.1
and 11.2. However that does not restrict us to selecting the same type of blowdown valve as
the chosen isolation valve.

Each module has a deluge system which is designed to activate on detection of a leak in
that module. There are four types of deluge system to choose from, that differ in their
unavailabilities, probability of failure once running, cost and time to test. The unavailabilities
are tabulated in Table 11.3, these are again dependent on the inspection interval which
may be 3, 6 or 12 months. The longer the time between the inspections the higher the
unavailability is, however the time spent in testing and the cost incurred in doing so is
reduced as seen in Table 11.4.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>Deluge system</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unavailability (3 month inspection)</td>
<td>0.021</td>
<td>0.025</td>
<td>0.031</td>
<td>0.05</td>
</tr>
<tr>
<td>Unavailability (6 month inspection)</td>
<td>0.04</td>
<td>0.05</td>
<td>0.06</td>
<td>0.1</td>
</tr>
<tr>
<td>Unavailability (12 month inspection)</td>
<td>0.08</td>
<td>0.099</td>
<td>0.12</td>
<td>0.2</td>
</tr>
<tr>
<td>Cost (per module)</td>
<td>2400</td>
<td>2200</td>
<td>2100</td>
<td>2000</td>
</tr>
</tbody>
</table>

Table 11.3: Data for the deluge system.

<table>
<thead>
<tr>
<th>Inspection interval (months)</th>
<th>3</th>
<th>6</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to test system 1 (hours)</td>
<td>576</td>
<td>288</td>
<td>144</td>
</tr>
<tr>
<td>Time to test system 2 (hours)</td>
<td>432</td>
<td>216</td>
<td>108</td>
</tr>
<tr>
<td>Time to test system 3 (hours)</td>
<td>576</td>
<td>288</td>
<td>144</td>
</tr>
<tr>
<td>Time to test system 4 (hours)</td>
<td>288</td>
<td>144</td>
<td>72</td>
</tr>
</tbody>
</table>

Table 11.4: Data for the deluge system inspection.

It can be seen that the lower the unavailability is does not necessarily mean that a higher cost is incurred. Taking deluge system type 2 and inspecting this every 3 months yields an unavailability of 0.025 (Table 11.3) with a cost of 432 units (Table 11.4). Upgrading the deluge system to type 1 reduces the unavailability and increases the cost, as expected. Moving to a system of type 3 would be classed as downgrading since the unavailability is increased, 0.031, however such a downgrading incurs a higher cost, 576. Therefore in the optimisation a deluge system of type 3 will not be selected. This demonstrates that there is not necessarily any relationship between the components unavailability and its cost to install and maintain. Each component has a discrete unavailability and cost unconnected with any alternative component.

The detection systems within each module are assumed to be the same type. There are five detection systems to chose from which differ in their failure rates, repair times and cost. The unavailabilities are shown in Table 11.5, these are again dependent on the inspection interval which may be 3, 6 or 12 months.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>Detection system</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unavailability (3 month inspection)</td>
<td>0.00119</td>
<td>0.01143</td>
<td>0.05715</td>
<td>0.1119</td>
<td>0.2238</td>
</tr>
<tr>
<td>Unavailability (6 month inspection)</td>
<td>0.002214</td>
<td>0.02238</td>
<td>0.1119</td>
<td>0.2214</td>
<td>0.4428</td>
</tr>
<tr>
<td>Unavailability (12 month inspection)</td>
<td>0.004404</td>
<td>0.04428</td>
<td>0.2214</td>
<td>0.4404</td>
<td>0.8808</td>
</tr>
<tr>
<td>Cost (per module)</td>
<td>14000</td>
<td>12000</td>
<td>11000</td>
<td>10000</td>
<td>9000</td>
</tr>
</tbody>
</table>

Table 11.5: Data for the detection system.

<table>
<thead>
<tr>
<th>Inspection interval (months)</th>
<th>3</th>
<th>6</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to test system 1 (hours)</td>
<td>576</td>
<td>288</td>
<td>144</td>
</tr>
<tr>
<td>Time to test system 2 (hours)</td>
<td>576</td>
<td>288</td>
<td>144</td>
</tr>
<tr>
<td>Time to test system 3 (hours)</td>
<td>288</td>
<td>144</td>
<td>72</td>
</tr>
<tr>
<td>Time to test system 4 (hours)</td>
<td>288</td>
<td>144</td>
<td>72</td>
</tr>
<tr>
<td>Time to test system 5 (hours)</td>
<td>288</td>
<td>144</td>
<td>72</td>
</tr>
</tbody>
</table>

Table 11.6: Data for the detection system inspection.

Twelve of the fourteen isolation valves were in fixed positions between process vessels, therefore only two could be allowed any movement. Both these valves were connecting to section 4, valves 35XV104 and 34XV001. Allowable movement of valve 35XV104 decreases the inventory of section 4 whilst increasing the inventory of section 5. Moving valve 34XV001 again decreases the inventory of section 4 whilst increasing that on section 1. Any further movement of the valves, including moving both valves simultaneously, would result in eliminating a valve hence reducing the reliability of the isolation system. These valves may be seen in the schematic diagrams in Appendix A.

The design vector is therefore comprised of nine parameters which must take on integer values.

- $x_1$ is the type of isolation valve which may take values of 1, 2 or 3.
- $x_2$ is the type of blowdown valve which may take values of 1, 2 or 3.
- $x_3$ is the type of deluge system which may be 1, 2, 3 or 4.
- $x_4$ is the type of detection system which may be 1, 2, 3, 4 or 5.
Approaches to optimise the configuration of the safety systems.

- \( x_5 \) is the inspection interval of the isolation valves which may take values of 1 or 2, 1 representing 6 months and 2 representing 12 months.

- \( x_6 \) is the inspection interval of the blowdown valves which may take values of 1 or 2, 1 representing 6 months and 2 representing 12 months.

- \( x_7 \) is the inspection interval of the deluge system which may take values of 1, 2 or 3, 1 representing 3 months, 2 representing 6 months and 3 representing 12 months.

- \( x_8 \) is the inspection interval of the detection system which may take values of 1, 2 or 3, 1 representing 3 months, 2 representing 6 months and 3 representing 12 months.

- \( x_9 \) is the position of the isolation valves, position 2 represents the original location, moving 35XV104 is position 1 and moving 34XV001 is position 3.

The components in each parameter set have been ordered according to their unavailability with component 1 having the lowest unavailability.

The design vector consists of one element from each of the nine component sets.

11.4 Applicable optimisation techniques.

Explicit enumeration of the problem is an infeasible option as there are 19440 \((3 \times 3 \times 4 \times 5 \times 2 \times 2 \times 3 \times 3 \times 3)\) alternative solutions. The frequency of the overpressure exceeding 3 bar is determined via a cpu intensive computer program, it is therefore infeasible to opt for an optimisation scheme which requires many system evaluations. A scheme is required to optimise the safety systems using as few system evaluations as possible.

The literature survey in Chapter 5 demonstrated that there are no specific optimisation methods applicable to this type of problem. The variables must take on integer values and the objective function may be determined as a 'black box' process. As each variable must feature within the model once, the closest description to this problem is that of an integer multiple choice problem. However standard solution schemes require a linear objective function, otherwise they involve many system evaluations. This chapter introduces three schemes for optimising the problem. The first scheme is described as a stepping process, this uses the idea that the problem may be linear within the locality of the point and allows movement
to neighbouring points only. The second scheme advances on this and assumes that a linear function may be derived from local information to describe movement to anywhere within the feasible design space. The third scheme is heuristic and considers the contributions of each of the safety systems to the frequency of exceeding 3 bar. Each of these schemes are iterative and require some constraints to provide a feasible framework.

11.5 Limits and bounds.

If the best components, in terms of lowest unavailability, are considered then the data set is

\[ \{x_1 = 1, x_2 = 1, x_3 = 1, x_4 = 1, x_5 = 1, x_6 = 1, x_7 = 1, x_8 = 1, x_9 = 1\} \]

The valve positioning, variable \( x_9 \), could not be ordered in terms of unavailability. However from an observational level it appeared that the lowest frequencies of exceeding 3 bar were generated whilst the valves were in position 1. This system has the maximum cost at 255200 units and maximum time to inspect of 1308 hours and generates a frequency of exceeding overpressures of 3 bar of \( 3.73 \times 10^{-7} \) per year. The worst components in terms of unavailability were also considered, these are

\[ \{x_1 = 3, x_2 = 3, x_3 = 4, x_4 = 5, x_5 = 2, x_6 = 2, x_7 = 3, x_8 = 3, x_9 = 3\} \]

Such a system had the minimum cost of 111800 units and a time to inspect of 222 hours. The frequency of exceeding 3 bar is \( 6.55 \times 10^{-6} \) per year.

If a relationship between the costs and the frequency of exceeding 3 bar existed then it may be feasible to say that the best components produce the lowest frequency of exceeding 3 bar and the worst components produce the highest. This would set upper and lower bounds on the frequency of exceeding 3 bar possible. Without a relationship, the values obtained may be used as a guide to obtaining convergence of a method.

When optimising there needs to be some constraints placed on the amount that the engineer is prepared to pay for a lower frequency of exceeding 3 bar and the time spent in the inspection process. Possible costs range between 111800 and 255200 units and the times spent in testing the system between 222 and 1308 hours. For the design optimisation presented the maximum feasible values were assumed to be

\[ \text{cost} \leq 183500 \text{units} \]
Approaches to optimise the configuration of the safety systems.

time to inspect $\leq 765$ hours

Out of a total of 19440 combinations only 12783 were feasible according to these constraints.

11.6 The stepping process.

This method is based on the assumption that the variables may step to values within a neighbourhood of the current values. For example movement may be made from a detection system of type 3, forward stepping to type 2 or backward stepping to type 4, however from a system of type 3, types 1 and 5 may not be reached.

Consider a point in the feasible design space, $x$, this is determined by nine variables which represent the components of the safety system. This point is the initial case which evaluates to a frequency of exceeding 3 bar of $f_0(x)$. Depending on the location of the point within the design space, the variables, except $x_9$ may be stepped up to a component of reduced unavailability or down to a component of increased unavailability. The valve positioning, $x_9$, is not described in terms of unavailability, instead movement is made in terms of the ordering given previously. As there are only two choices for the inspection interval of the isolation and blowdown valves these variables may only step in one direction. The feasible design space can not be left.

Allowing multiple stepping either up or down to neighbouring components leads to a possible 6858 combinations. This is a significant reduction on the possible 12783 feasible combinations, however it remains impractical to evaluate them all. This method proposes that it is possible to estimate the values of the frequency of exceeding 3 bar in all 6858 neighbouring locations from knowledge of the values at 16 points. This is achieved by considering the points where only one of the variables has been stepped. In certain locations seven of the nine variables may be stepped up or stepped down, giving 14 possible combinations. The remaining two variables may only step in one direction. There is no relationship between the change in unavailability and the change in cost of a component when stepping, therefore platform evaluations are carried out for each possible movement, i.e. up and down, which will lead to a maximum of 16.

If $x$ represents an initial point then $x + \delta x_i$ is used to represent the variable $x_i$ being stepped
upwards whilst the remaining variables retain their current values. Stepping $x_i$ downwards is represented as $x - \delta x_i$. The corresponding platform evaluations with these data sets yields the frequency of exceeding 3 bar of $f_0(x + \delta x_i)$ and $f_0(x - \delta x_i)$.

From the 16 platform evaluations, gained by stepping one variable at a time, it is possible to generate all the neighbouring nodes by considering the upward and downward differentials (superscripted $u$ and $d$ respectively).

\[
\frac{\partial f_0^u}{\partial x_i} = \frac{f_0(x + \delta x_i) - f_0(x)}{\delta x_i} \quad (11.2)
\]

\[
\frac{\partial f_0^d}{\partial x_i} = \frac{f_0(x - \delta x_i) - f_0(x)}{\delta x_i} \quad (11.3)
\]

The stepping occurs from one discrete value to another therefore $\delta x_i = 1$. For the node which steps $n$ variables, $x_k$, upwards and $m$ variables, $x_j$, downwards where $n + m \leq 9$ and $k, j \in \{0, 1, ..., 9\}$, $k \neq j$ the frequency of exceeding 3 bar for this point is given by the following equation

\[
f_0 \left( x + \sum_{k \in U} \delta x_k - \sum_{j \in D} \delta x_j \right) = f_0(x) + \sum_{k \in U} \frac{\partial f_0^u}{\partial x_k} \delta x_k + \sum_{j \in D} \frac{\partial f_0^d}{\partial x_j} \delta x_j \quad (11.4)
\]

The combinations of variables stepped relating to the neighbouring nodes are determined. The possible combinations of variable steps are placed in a set, $S$. Each subset of $S$ is a combination of stepped variables relating to a neighbouring node, these subsets include $N$ elements, $N \leq 9$, where $N = n + m$ with $n$ being the number of upward steps and $m$ is the number of downward steps. The set $U$ includes the identification numbers of the variables stepped upwards and set $D$ includes those which step downwards. Using the appropriate upward and downward differentials each frequency of exceeding 3 bar may be estimated. For all the combinations which satisfy the financial cost and inspection time period restrictions comparisons are made to identify the lowest frequency.

The point with the lowest estimated frequency of exceeding 3 bar becomes the intermediate solution. The platform is then evaluated to give the SAROS model frequency of exceeding 3 bar. All possible variable steps are determined about this intermediate solution and the procedure repeats until convergence is obtained.

### 11.6.1 A two variable example.

Such a scheme may be represented geometrically in the two variable case, Figure 11.1.
Approaches to optimise the configuration of the safety systems.

Figure 11.1: Geometric interpretation of the linear optimisation procedure

The initial point \( x \) is chosen as \((x_1, x_2)\). Using the stepping process the variable \( x_1 \) may be stepped upwards to \( x_1 + \delta x_1 \) whilst \( x_2 \) remains constant giving \((x_1 + \delta x_1, x_2)\) and \( x_1 \) may be stepped downwards to give \((x_1 - \delta x_1, x_2)\). The variable \( x_2 \) may be stepped both upwards and downwards whilst keeping \( x_1 \) constant giving \((x_1, x_2 + \delta x_2)\) and \((x_1, x_2 - \delta x_2)\). These four points are indicated by \( \bigcirc \) on the diagram. Platform evaluations are carried out for these points, allowing the upward and downward differentials to be calculated. The stepping process allows movement to the neighbouring nodes, the combinations of the steps are placed in set \( S \), where

\[
S = \{ \{ \delta x_1 \}, \{-\delta x_1 \}, \{ \delta x_2 \}, \{-\delta x_2 \}, \{ \delta x_1, \delta x_2 \}, \{-\delta x_1, \delta x_2 \}, \{ \delta x_1, -\delta x_2 \}, \{-\delta x_1, -\delta x_2 \} \}.
\]

This set has eight elements four of which have been evaluated, the remaining four points, indicated by \( \bigtriangleup \) on the diagram, are calculated by Equation 11.4. For example the final element has \( N = 2 \) subelements, these are stepping the two variables downwards therefore \( n = 0 \) and \( m = 2 \). The set \( U \) is an empty set, \( U = \{ \} \) as no variable is stepped up. The set \( D \) has two elements \( D = \{1, 2\} \). Using Equation 11.4 the frequency of exceeding 3 bar is estimated for this point by

\[
f_o(x - \delta x_1 - \delta x_2) = f_o(x) + \frac{\partial f_o}{\partial x_1} + \frac{\partial f_o}{\partial x_2}
\]
11.6.2 The stepping algorithm.

The algorithm for the stepping process may be summarised as follows.

1. Take a point in the design space, $x$.

2. Run a platform evaluation on this point to give $f_0(x)$.

3. Determine the possible movements from this point by stepping one variable either up or down as the others remain constant. (maximum of 16 movements)

4. Run these platform evaluations to give $f_0(x + \delta x_i)$ & $f_0(x - \delta x_i)$.

5. Calculate the upward and downward differentials, as in Equations 11.2 & 11.3.

6. Create the set $S$ of all possible stepping combinations about $x$. (maximum of 6858)

7. Estimate the frequency of exceeding 3 bar using Equation 11.4 for each neighbouring node (i.e. each subset in $S$).

8. Compare to find the lowest estimated frequency of exceeding 3 bar which is within the specified constraints.

9. Accept the point corresponding to the lowest estimation as the intermediate solution.

10. Perform a platform evaluation, if this is an improvement on the previous value then repeat the process from step 3 otherwise stop.

Creating a set which may involve up to 6858 subsets is a tedious task. Therefore the steps from 6 to 8 in the algorithm have been automated in the form of a MAPLE procedure into which the user must input the upward and downward differentials and the possible one variable movements.

11.6.3 Results from the stepping process with a mid case initiator.

In order to use the stepping process a point must be chosen from the feasible design space. To get the maximum possible steps a central point was taken to be the initial case. This point consisted of the components shown in Table 11.7.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
</tr>
</tbody>
</table>

Table 11.7: The system components used in the first stepping procedure from a mid range initiator.

A platform evaluation using these components led to a frequency of exceeding 3 bar of $f_0(x) = 5.994 \times 10^{-7}$ per year. Such a combination has a cost of 175800 units and involves an inspection time of 660 hours. There are a possible sixteen steps that may be taken from this point, these are illustrated in Table 11.8.

<table>
<thead>
<tr>
<th>Component</th>
<th>$x$</th>
<th>Possible steps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>upward steps</td>
</tr>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
<td>2 1 2 2 2 2 2 2 2 3 2 2 2 2 2 2 2 2 2 2</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
<td>2 2 1 2 2 2 2 2 2 2 3 2 2 2 2 2 2 2 2 2</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
<td>2 2 2 1 2 2 2 2 2 2 2 3 2 2 2 2 2 2 2 2</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
<td>2 2 2 1 2 2 2 2 2 2 2 2 3 2 2 2 2 2 2 2</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1 2 1 1 1 1 1</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1 2 1 1 1 1 1</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
<td>2 2 2 1 2 2 2 2 2 2 3 2 2 2 2 2 2 2</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
<td>2 2 2 2 2 1 2 2 2 2 2 2 2 3 2 3 2 2</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
<td>2 2 2 2 2 2 1 2 2 2 2 2 2 2 2 2 2 2</td>
</tr>
</tbody>
</table>

Table 11.8: The steps that may be taken during the first stepping procedure from a mid range initiator.
Approaches to optimise the configuration of the safety systems.

For each of these cases the platform evaluations were performed giving

\[
fo(x + \delta x_i) \quad i \in U
\]

\[
fo(x - \delta x_i) \quad i \in D
\]

where \( U \) is the set of the variables which could move upwards, \( U = \{1, 2, 3, 4, 7, 8, 9\} \) and \( D \) is the set of the variables which could move downwards, \( D = \{1, 2, 3, 4, 5, 6, 7, 8, 9\} \). This then allowed the calculation of the upward and downward differentials. Using the MAPLE procedure, to create the estimated function value for the cases within the constraints, the lowest frequency of exceeding 3 bar was estimated to be \( 4.148 \times 10^{-7} \) per year. This has a cost of 182000 units and has an inspection time of 696 hours. Table 11.9 illustrates the case chosen.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>( x_1 )</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>( x_2 )</td>
</tr>
<tr>
<td>Deluge system</td>
<td>( x_3 )</td>
</tr>
<tr>
<td>Detection system</td>
<td>( x_4 )</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>( x_5 )</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>( x_6 )</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>( x_7 )</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>( x_8 )</td>
</tr>
<tr>
<td>Valve position</td>
<td>( x_9 )</td>
</tr>
</tbody>
</table>

Table 11.9: The system components used in the second stepping procedure from a mid range initiator.

Comparing Table 11.9 with 11.7 it can be seen that the types of isolation and blowdown valves selected improved, whilst the inspection interval for the isolation valves remained the same and it was decided to inspect the blowdown valves less often. The deluge and detection systems remained at type 2. The deluge system is to be inspected more often but the detection system is to be inspected less often. The isolation valve 35XV104 is to be moved so that the inventory of section 4 is decreased with that of section 5 increasing.

Performing a platform evaluation using this data set yielded a frequency of exceeding 3 bar of \( 4.18 \times 10^{-7} \) per year which is very close to the estimated value using the stepping process.
Approaches to optimise the configuration of the safety systems.

In order to repeat the process the possible steps must be identified. These are as shown in Table 11.10. In this case there are only eleven movements possible as four components which could move both ways in the last run have been selected as their highest type and therefore can no longer move upwards and one component can not move downwards.

<table>
<thead>
<tr>
<th>Component</th>
<th>$x$</th>
<th>Possible steps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>upward steps</td>
</tr>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
<td>1 1 1 1 1 2</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
<td>1 1 1 1 1 2</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
<td>2 1 2 2 2 2</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
<td>2 2 1 2 2 2</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
<td>1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
<td>2 2 2 1 2 2</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
<td>1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
<td>3 3 3 3 3 3</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
<td>1 1 1 1 1 1 1</td>
</tr>
</tbody>
</table>

Table 11.10: The steps that may be taken during the second stepping procedure from a mid range initiator.

In this case there are four variables that may move upwards, the identifications for these variables are placed in set $U = \{3, 4, 6, 8\}$. Seven variables can move downwards these are $D = \{1, 2, 3, 4, 5, 7, 9\}$. Repeating the stepping procedure yields an estimated frequency of exceeding 3 bar of $4.18 \times 10^{-7}$ per year at a cost of 182000 units and a time to test of 696 hours. This data set is identical to the previous iteration. The nature of this process will mean that further iterations will result in a repetition of this solution. Hence this stepping process has converged in a relatively short period of time. Table 11.11 shows the iterations needed to gain convergence. The optimal configuration for the safety systems using the stepping process is as shown in Table 11.12. This configuration was found by performing 29 platform evaluations.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 11.11: The intermediate solutions generated with the stepping process with a mid range initiator.

Table 11.12: The system components used in the optimal configuration with the stepping process, initiated from a mid range case.
Approaches to optimise the configuration of the safety systems.

This method has a large limitation in its movement capabilities. Due to the nature of the method and the quick convergence obtained, many combinations were not considered as options.

11.6.4 The results from the stepping process with a worst case initiator.

As a test of its robustness this process was performed on an initiating data set which used the ‘worst’ components, apart from the valve positioning. The initiating case was therefore as shown in Table 11.13.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
</tr>
</tbody>
</table>

Table 11.13: The system components used in the first stepping procedure from a worst case initiator.

This point had a platform evaluation yielding a frequency of exceeding 3 bar, $f_0(x)$, of $4.96 \times 10^{-6}$ per year which cost 111800 units and took 222 hours to inspect. The possible movements in this case totalled nine, eight of which were upward steps and the valve positioning was a downward step. The set $D$ comprised of $D = \{9\}$ and the set $U = \{1, 2, 3, 4, 5, 6, 7, 8\}$. The movements are shown in Table 11.14.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>Component</th>
<th>( x )</th>
<th>possible steps</th>
<th>upward steps</th>
<th>downward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>( x_1 )</td>
<td>3</td>
<td>2 3 3 3 3 3 3 3 3</td>
<td>3</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>( x_2 )</td>
<td>3</td>
<td>3 3 3 3 3 3 3 3 3</td>
<td>3</td>
</tr>
<tr>
<td>Deluge system</td>
<td>( x_3 )</td>
<td>4</td>
<td>4 4 3 4 4 4 4 4 4</td>
<td>4</td>
</tr>
<tr>
<td>Detection system</td>
<td>( x_4 )</td>
<td>5</td>
<td>5 5 5 4 5 5 5 5 5</td>
<td>5</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>( x_5 )</td>
<td>2</td>
<td>2 2 2 2 2 1 2 2 2</td>
<td>2</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>( x_6 )</td>
<td>2</td>
<td>2 2 2 2 2 1 2 2 2</td>
<td>2</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>( x_7 )</td>
<td>3</td>
<td>3 3 3 3 3 3 2 3 3</td>
<td>3</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>( x_8 )</td>
<td>3</td>
<td>3 3 3 3 3 3 3 2 3</td>
<td>3</td>
</tr>
<tr>
<td>Valve position</td>
<td>( x_9 )</td>
<td>1</td>
<td>1 1 1 1 1 1 1 1 1</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 11.14: The steps that may be taken during the first stepping procedure from a worst case initiator.

Platform evaluations were done for each of the above cases, then the upward and downward differentials were calculated. Using the stepping procedure the estimated frequency of exceeding 3 bar is \(-1.963 \times 10^{-6}\) per year with a cost of 159600 and a time to test of 588 hours. This estimated frequency is unrealistic as frequencies can not take negative values. The upward steps made such an improvement that the upward differentials used had such a large negative magnitude causing the estimation to be so far out. Even though the estimated frequency is clearly incorrect, this data set is taken as the intermediate solution. The components are shown in Table 11.15. The platform evaluation yielded a frequency of exceeding 3 bar of \(8.78 \times 10^{-7}\) per year. It can be seen that each of the components was upgraded in its type and the inspection interval. The possible steps that could be taken from this point increased to 15 as movement can now be made in either direction, these are shown in Table 11.16.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve $x_1$</td>
<td>2</td>
</tr>
<tr>
<td>Blowdown valve $x_2$</td>
<td>2</td>
</tr>
<tr>
<td>Deluge system $x_3$</td>
<td>3</td>
</tr>
<tr>
<td>Detection system $x_4$</td>
<td>4</td>
</tr>
<tr>
<td>Isolation inspection $x_5$</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown inspection $x_6$</td>
<td>1</td>
</tr>
<tr>
<td>Deluge inspection $x_7$</td>
<td>2</td>
</tr>
<tr>
<td>Detection inspection $x_8$</td>
<td>2</td>
</tr>
<tr>
<td>Valve position $x_9$</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 11.15: The system components used in the second stepping procedure from a worst case initiator.

The upward steps may be taken on the 6 variables in set $U = \{1, 2, 3, 4, 7, 8\}$, the downward steps are $D = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$. The upward and downward differentials were created for these variable sets, following the platform evaluations. The MAPLE procedure is then utilised to find the possible steps to the neighbouring nodes and the estimated frequency of exceeding 3 bar for each node within the constraints.

<table>
<thead>
<tr>
<th>Component</th>
<th>Possible steps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>upward steps</td>
</tr>
<tr>
<td>Isolation valve $x_1$</td>
<td>2 2 2 2 2 2 2 2</td>
</tr>
<tr>
<td>Blowdown valve $x_2$</td>
<td>2 2 1 2 2 2 2 2</td>
</tr>
<tr>
<td>Deluge system $x_3$</td>
<td>3 3 3 2 3 3 3 3</td>
</tr>
<tr>
<td>Detection system $x_4$</td>
<td>4 4 4 4 3 4 4 4</td>
</tr>
<tr>
<td>Isolation inspection $x_5$</td>
<td>1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>Blowdown inspection $x_6$</td>
<td>1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>Deluge inspection $x_7$</td>
<td>2 2 2 2 2 1 2 2</td>
</tr>
<tr>
<td>Detection inspection $x_8$</td>
<td>2 2 2 2 2 2 2 2</td>
</tr>
<tr>
<td>Valve position $x_9$</td>
<td>1 1 1 1 1 1 1 1</td>
</tr>
</tbody>
</table>

Table 11.16: The steps that may be taken during the second stepping procedure from a worst case initiator.
Approaches to optimise the configuration of the safety systems.

The best position was found to have an estimated frequency of exceeding 3 bar of $3.16 \times 10^{-7}$ per year with a cost of 182,600 units and a time to test of 732 hours. This data set is shown in Table 11.17. Following a platform evaluation the frequency of exceeding 3 bar from the SAROS model was found to be $4.5 \times 10^{-7}$ per year.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
</tr>
</tbody>
</table>

Table 11.17: The system components used in the third stepping procedure from a worst case initiator.

The possible steps that may be taken from this data set involve three upward steps and nine downward steps, $U = \{3, 4, 8\}$ and $D = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$. These steps are shown in Table 11.18. After creating the upward and downward differentials from the results of the platform evaluations for these 12 cases, the best point chosen was identical to the previous iteration.

The optimum configuration was achieved after 40 platform evaluations had been carried out. The steps leading to the optimum configuration from a worst case initiator are as shown in Table 11.19. A summary of the optimal configuration gained from a worst case initiator is shown in Table 11.20.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>Component</th>
<th>Possible steps</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>upward</td>
<td>downward</td>
<td>steps</td>
<td>steps</td>
<td>steps</td>
<td>steps</td>
<td>steps</td>
<td>steps</td>
<td>steps</td>
<td>steps</td>
<td>steps</td>
<td>steps</td>
<td>steps</td>
</tr>
<tr>
<td>Isolation valve x₁</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown valve x₂</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Deluge system x₃</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Detection system x₄</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Isolation inspection x₅</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown inspection x₆</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Deluge inspection x₇</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Detection inspection x₈</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Valve position x₉</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 11.18: The steps that may be taken during the third stepping procedure from a worst case initiator.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve x₁</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown valve x₂</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Deluge system x₃</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Detection system x₄</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Isolation inspection x₅</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown inspection x₆</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Deluge inspection x₇</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Detection inspection x₈</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Valve position x₉</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

| Estimated frequency of exceeding 3 bar | -1.96 × 10⁻⁶ | 3.16 × 10⁻⁷ |
| SAROS frequency of exceeding 3 bar    | 4.96 × 10⁻⁶  | 8.78 × 10⁻⁷  | 4.5 × 10⁻⁷ |

Table 11.19: The intermediate solutions generated with the stepping process with a worst case initiator.
Table 11.20: The system components used in the optimal configuration with the stepping process, initiated from a worst case.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of exceeding 3 bar</td>
<td>$4.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>Frequency of explosion</td>
<td>$4.47 \times 10^{-5}$</td>
</tr>
<tr>
<td>System cost</td>
<td>182600</td>
</tr>
<tr>
<td>Inspection time</td>
<td>732</td>
</tr>
</tbody>
</table>

11.6.5 An evaluation of the stepping process.

The stepping process was initiated from a mid range base case so that it had the opportunity of moving in all directions. After only two iterations and 29 platform iterations the method had converged. This meant that very few combinations had been available as options since stepping was only permitted to neighbouring nodes. As a test of this method a worst case was selected as an initiator, this meant that during the first iteration only improved components could be selected unless the component did not alter. By doing this it was hoped that more combinations would be considered as an option. From this initiator the method converged in three iterations and 40 platform evaluations. Unfortunately the two initiating cases did not converge to the same solution. Table 11.21 shows the two solutions gained.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mid case</th>
<th>Worst case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Deluge system</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Detection system</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Valve position</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of exceeding 3 bar</td>
<td>4.2 \times 10^{-7}</td>
<td>4.5 \times 10^{-7}</td>
</tr>
<tr>
<td>Frequency of explosion</td>
<td>3.74 \times 10^{-5}</td>
<td>4.4736 \times 10^{-5}</td>
</tr>
<tr>
<td>System cost</td>
<td>182000</td>
<td>182600</td>
</tr>
<tr>
<td>Inspection time</td>
<td>696</td>
<td>732</td>
</tr>
</tbody>
</table>

Table 11.21: A comparison of the system components used in the optimal configuration with the stepping process.

The solutions gained differ in their detection type and inspection and the inspection of the blowdown valves. It is clear that the solution gained from the mid case initiator is better than that gained from the worst case.

The components that differ between the two cases may be stepped to in one iteration. It is therefore interesting to consider why the solution from the worst case initiator did not step further to reach the solution from the mid case. The estimating function for the frequency of exceeding 3 bar is

\[
of\left(x + \sum_{k \in U} \delta x_k - \sum_{j \in D} \delta x_j\right) = f_0(x) + \sum_{k \in U} \frac{\partial f_0^u}{\partial x_k} + \sum_{j \in D} \frac{\partial f_0^d}{\partial x_j}
\]

For the worst case solution to reach that of the mid case solution \( x_4 \) must upgrade and \( x_6 \) \& \( x_8 \) must downgrade whilst the other components remain constant. The subset of \( S \) referring to this case is \( \{ \delta x_4, -\delta x_6, -\delta x_8 \} \), \( U = \{4\} \) and \( D = \{6, 8\} \). This means that the estimating function for the movement required is

\[
of(x + \delta x_4 - \delta x_6 - \delta x_8) = f_0(x) + \frac{\partial f_0^u}{\partial x_4} + \frac{\partial f_0^d}{\partial x_6} + \frac{\partial f_0^d}{\partial x_8}
\]
Approaches to optimise the configuration of the safety systems.

This function requires the upward differential for \( x_4 \) and the downward differentials for \( x_6 \) and \( x_8 \). These are obtained from the platform evaluations obtained when stepping one variable at a time.

\[
\frac{\partial f_0^u}{\partial x_4} = -4.35 \times 10^{-8} \\
\frac{\partial f_0^d}{\partial x_6} = 4.09 \times 10^{-10} \\
\frac{\partial f_0^d}{\partial x_8} = 5.32 \times 10^{-8}
\]

Substituting these upward and downward differentials into the estimating function yields the following result.

\[
f_0 (x + \delta x_4 - \delta x_6 - \delta x_8) = 4.5 \times 10^{-7} - 4.35 \times 10^{-8} + 4.09 \times 10^{-10} + 5.32 \times 10^{-8} \\
= 4.6 \times 10^{-7}
\]

This value is higher than the current \( f_0(x) \) and so it was not selected as a possible minimum even though the true platform evaluation for this case gives a lower frequency of exceeding 3 bar. This demonstration shows why the worst case initiated solution did not evolve to that of the mid case initiated solution. The reasons for this lie in the calculation of the differentials and the specification of the design parameters.

\( f_0(x) \) was calculated with a detection system of type 3 which was inspected type 2. This combination led to an unavailability for the detection system of 0.1119, taken from Table 11.5. The stepping procedure calculates differentials based on only one component changing whilst the rest remain constant. Therefore changing the detection type involved the detection system being of type 2 whilst the inspection remained at type 2. This combination had an unavailability of 0.02238 which improved the reliability of the platform and led to a differential of \(-4.35 \times 10^{-8}\). Changing the inspection interval of the detection system to type 3 whilst the detection system remains at type 3 leads to a combination for the detection which has an unavailability of 0.2214. This reduction in the reliability is shown in the differential calculation which gave a value of \(5.32 \times 10^{-8}\). The combination of these differentials led to a positive contribution for the estimated frequency of exceeding 3 bar which is not an improvement. However the combination that was required was to have the detection system at type 2, inspected type 3, if these could have been changed together then the unavailability for the detection system would have been 0.04428 which is an improvement on the current status.
This highlights deficiencies in the definitions of the parameters. An alternative approach would be to consider the safety system and its inspection interval as one variable and reorder these according to unavailability.

11.7 The linearisation process.

This method assumes that the change in the frequency of exceeding 3 bar may be represented as a linear function. This is based on successive linear optimisation where linearisation takes place about a point to determine a better point whereby linearisation occurs again.

Consider a point in the design space, \( x \), which yields a frequency of exceeding 3 bar \( f_o(x) \). Assuming a linear relationship in the locality of \( x \), a Taylor series expansion of first order accuracy gives the frequency of exceeding 3 bar at any point within the design space as

\[
f_o(x + dx) = f_o(x) + \sum_i \delta x_i \frac{\partial f_o}{\partial x_i}
\]

where \( \delta x_i \) is the step made by variable \( x_i \), this may be forwards or backwards to any possible value of \( x_i \). \( \frac{\partial f_o}{\partial x_i} \) is the first order differential for the change in \( f_o(x) \) with respect to a change in \( x_i \). This differential may be approximated by forward, central or backward differences. Whenever possible central differences were used for greater accuracy. These take the form

\[
\frac{\partial f_o}{\partial x_i} = \frac{f_o(x + \delta x_i) - f_o(x - \delta x_i)}{2\delta x_i}
\]

For each variable describing \( x \) it was determined whether this could move forwards or backwards. If a component was capable of moving both ways, the data sets were created by moving the component either way whilst keeping the rest constant. The two platform evaluations were carried out to give the terms for the central difference equation. If a component could only move downwards, backwards differencing was used as in the following equation.

\[
\frac{\partial f_o}{\partial x_i} = \frac{f_o(x) - f_o(x - \delta x_i)}{\delta x_i}
\]

Otherwise forward differencing was used.

\[
\frac{\partial f_o}{\partial x_i} = \frac{f_o(x + \delta x_i) - f_o(x)}{\delta x_i}
\]

Every movement within the feasible design space is considered using Equation 11.6 to determine the lowest estimation of the frequency of exceeding 3 bar. Once the point representing this frequency value is identified this is classed as the intermediate solution the linearisation process is then employed about this point until convergence is obtained.
11.7.1 The linearisation algorithm.

The algorithm for the linearisation process may be summarised by the following steps.

1. Take a point in the design space, \( x \).
2. Run a platform evaluation on this point to give \( f_0(x) \).
3. Determine the possible movements from this point by stepping one variable either up or down as the others remain constant.
4. Run these platform evaluations to give \( f_0(x + \delta x_i) \) \& \( f_0(x - \delta x_i) \).
5. Create the central, forward or backward differences.
6. Create the linear function as in Equation 11.6.
7. Run this function through all combinations of variables.
8. Select the combination which gives the lowest frequency of exceeding 3 bar whilst remaining within the constraints.
9. Run a platform evaluation on this point, if it is an improvement on the previous case then relinearise about this point by repeating the process from step 3 otherwise stop.

11.7.2 Results from the linearisation process with a mid case initiator.

As a comparison between the linearisation process and the stepping process, the linearisation process was initiated with the same mid range base case. This is shown in Table 11.22.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
</tr>
</tbody>
</table>

Table 11.22: The system components used in the first linearisation procedure from a mid range initiator.

In order to create a linear function the differentials for the change in each variable were required. To determine whether these were to be central, forward or backward differences the possible steps were identified. These are shown in Table 11.23.

<table>
<thead>
<tr>
<th>Component</th>
<th>Possible steps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>upward steps</td>
</tr>
<tr>
<td>Isolation valve $x_1$</td>
<td>2 1 2 2 2 2 2 2 2 3 2 2 2 2 2 2 2</td>
</tr>
<tr>
<td>Blowdown valve $x_2$</td>
<td>2 2 1 2 2 2 2 2 2 3 2 2 2 2 2 2 2</td>
</tr>
<tr>
<td>Deluge system $x_3$</td>
<td>2 2 2 1 2 2 2 2 2 2 3 2 2 2 2 2 2</td>
</tr>
<tr>
<td>Detection system $x_4$</td>
<td>2 2 2 2 1 2 2 2 2 2 2 3 2 2 2 2 2</td>
</tr>
<tr>
<td>Isolation inspection $x_5$</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>Blowdown inspection $x_6$</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>Deluge inspection $x_7$</td>
<td>2 2 2 2 1 2 2 2 2 2 2 3 2 2 2 2 2</td>
</tr>
<tr>
<td>Detection inspection $x_8$</td>
<td>2 2 2 2 2 1 2 2 2 2 2 2 3 2 2 2 2</td>
</tr>
<tr>
<td>Valve position $x_9$</td>
<td>2 2 2 2 2 2 2 2 1 2 2 2 2 2 2 2 3</td>
</tr>
</tbody>
</table>

Table 11.23: The steps that may be taken during the first linearisation procedure from a mid range initiator.

As in the stepping process the sets $U$ and $D$ can be created to identify those variables that
Approaches to optimise the configuration of the safety systems.

are able to move upwards and those that move downwards. \( U = \{1, 2, 3, 4, 7, 8, 9\} \) and \( D = \{1, 2, 3, 4, 5, 6, 7, 8, 9\} \). Variables present in both sets may be used for central differencing, variables in \( U \) only for forward differencing and those in \( D \) only for backward differencing.

Running platform evaluations on the data sets in Table 11.23 provides \( f_0(x + \delta x_i) \ i \in U \) and \( f_0(x - \delta x_i) \ i \in D \). The base case evaluates to \( f_0(x) = 5.99 \times 10^{-7} \) per year. This leads to the linear function about \( x \) being

\[
f_0(x + \delta x) = 5.99 \times 10^{-7} - 1.085 \times 10^{-7}x_1 - 4 \times 10^{-9}x_2 - 5.25 \times 10^{-7}x_3 \\
-6.1 \times 10^{-8}x_4 - 9.56 \times 10^{-8}x_5 - 3.78 \times 10^{-9}x_6 \\
-1.96 \times 10^{-7}x_7 - 1.85 \times 10^{-8}x_8 - 2.09 \times 10^{-9}x_9
\]

When using this function the types of components must be renumbered, with the current type being 0, moving backwards being negative and forwards positive.

This function was evaluated at all nodes in the feasible design space. The optimum, estimated, value was found to be \( 3.1 \times 10^{-7} \) per year with the data set shown in Table 11.24. The true frequency of exceeding 3 bar was evaluated by SAROS as \( 4.18 \times 10^{-7} \) per year.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>( x_1 )</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>( x_2 )</td>
</tr>
<tr>
<td>Deluge system</td>
<td>( x_3 )</td>
</tr>
<tr>
<td>Detection system</td>
<td>( x_4 )</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>( x_5 )</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>( x_6 )</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>( x_7 )</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>( x_8 )</td>
</tr>
<tr>
<td>Valve position</td>
<td>( x_9 )</td>
</tr>
</tbody>
</table>

Table 11.24: The system components used in the second linearisation procedure from a mid range initiator.

The linearisation procedure must now take place around this point. To do this the movements must again be identified to determine whether central, forward or backward differencing should be used. These movements are shown in Table 11.25.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>Component</th>
<th>$x$</th>
<th>Possible steps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>upward steps</td>
</tr>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
<td>1 1 1 1 1</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
<td>1 1 1 1 1</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
<td>2 1 2 2 2</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
<td>2 2 1 2 2</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
<td>1 1 1 1 1</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
<td>2 2 2 1 2</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
<td>1 1 1 1 1</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
<td>3 3 3 3 2</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
<td>1 1 1 1 1</td>
</tr>
</tbody>
</table>

Table 11.25: The steps that may be taken during the second linearisation procedure from a mid range initiator.

The set $U$ comprises of $\{3,4,6,8\}$ and the set $D$ has elements $\{1,2,3,4,5,7,9\}$. Central differencing may only be performed for $x_3$ and $x_4$, the other elements of $U$ and $D$ must be used for forward and backward differencing respectively. Following the platform evaluations and the creation of the differentials the linear function is determined to be

$$f_o(x + \delta x) = 4.18 \times 10^{-7} - 5.47 \times 10^{-8}x_1 - 2.49 \times 10^{-9}x_2 - 2.45 \times 10^{-8}x_3$$

$$-5.3 \times 10^{-8}x_4 - 1.85 \times 10^{-8}x_5 - 4.4 \times 10^{-10}x_6$$

$$-1.23 \times 10^{-7}x_7 - 1.06 \times 10^{-8}x_8 - 5.99 \times 10^{-9}x_9$$

The point with the best estimated frequency of exceeding 3 bar from this linear function is shown in Table 11.26. The estimated frequency of exceeding 3 bar was $3.86 \times 10^{-7}$ per year, a platform evaluation on this data set gives an actual value of $4.2 \times 10^{-7}$. Since this frequency of exceeding 3 bar is higher than the current intermediate solution, the process is halted.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
</tr>
</tbody>
</table>

Table 11.26: The system components used in the third linearisation procedure from a mid range initiator.

This method has now converged. Table 11.27 shows the results of each linearisation up to convergence being obtained.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

**Estimated frequency of exceeding 3 bar**

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated frequency of exceeding 3 bar</td>
<td>$3.1 \times 10^{-7}$</td>
<td>$3.86 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>SAROS frequency of exceeding 3 bar</td>
<td>$5.99 \times 10^{-7}$</td>
<td>$4.18 \times 10^{-7}$</td>
<td>$4.2 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Table 11.27: The intermediate solutions generated with the linearisation process with a mid case initiator.

The algorithm defined for this linearisation process states that iteration 2 should be selected.
as the optimal solution as the frequency of exceeding 3 bar gained from the SAROS program was lower than for iteration 3. Iteration 2 had a lower financial cost although a longer period of time was spent inspecting it. The optimal solution is shown in Table 11.28. This optimal was reached after performing 30 platform evaluations and creating 2 linear functions. The deciding criteria between the final two intermediate solutions was based on the magnitude of the frequency of exceeding 3 bar, however the two solutions had very similar results. It may be appropriate to say that the linearisation method generated two alternative solutions. This linearisation method generated the case that was chosen as the optimum with the stepping process but continued to iterate to an alternative solution. As with the stepping process the linearisation method was carried out with a worst case initiator as a comparison of the methods.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
</tr>
<tr>
<td>Frequency of exceeding 3 bar</td>
<td>$4.18 \times 10^{-7}$</td>
</tr>
<tr>
<td>Frequency of explosion</td>
<td>$3.74 \times 10^{-5}$</td>
</tr>
<tr>
<td>System cost</td>
<td></td>
</tr>
<tr>
<td>Inspection time</td>
<td></td>
</tr>
</tbody>
</table>

Table 11.28: The system components used in the optimal configuration with the linearisation process, initiated from a mid range case.
11.7.3 The results of the linearisation process from a worst case initiator.

The linearisation process was initiated from the worst case described for the stepping process, this has components shown in Table 11.29.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
</tr>
</tbody>
</table>

Table 11.29: The system components used in the first linearisation procedure from a worst case initiator.

As for the stepping process the possible movements were determined which are shown in Table 11.14. In this case central differencing could not be used as there were no components that could move both ways. Forward differencing was required on the variables in set $U$, $U = \{1, 2, 3, 4, 5, 6, 7, 8\}$ and backward differencing was used for the valve positioning, $D = \{9\}$. The linear function generated was

$$f_0(x + \delta x) = 4.96 \times 10^{-6} - 9.27 \times 10^{-8} x_1 - 1.83 \times 10^{-8} x_2 - 1.87 \times 10^{-6} x_3$$

$$-1.26 \times 10^{-6} x_4 - 7.65 \times 10^{-8} x_5 - 1.55 \times 10^{-8} x_6$$

$$-1.25 \times 10^{-6} x_7 - 2.34 \times 10^{-6} x_8 - 1.59 \times 10^{-6} x_9$$

Running this function through all possible nodes in the feasible design space led to an intermediate solution of $-9.36 \times 10^{-6}$ per year. As in the case of the stepping process this solution is infeasible because a frequency can not be negative. The data set relating to this frequency, Table 11.30, was taken to be the intermediate solution and performing a system evaluation yielded a frequency of exceeding 3 bar of $5.14 \times 10^{-7}$ per year. As this frequency
Approaches to optimise the configuration of the safety systems.

of exceeding 3 bar was lower than the previous case \((4.96 \times 10^{-6} \text{ per year})\) the linearisation process continued from here.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve (x_1)</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown valve (x_2)</td>
<td>3</td>
</tr>
<tr>
<td>Deluge system (x_3)</td>
<td>1</td>
</tr>
<tr>
<td>Detection system (x_4)</td>
<td>3</td>
</tr>
<tr>
<td>Isolation inspection (x_5)</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown inspection (x_6)</td>
<td>2</td>
</tr>
<tr>
<td>Deluge inspection (x_7)</td>
<td>2</td>
</tr>
<tr>
<td>Detection inspection (x_8)</td>
<td>1</td>
</tr>
<tr>
<td>Valve position (x_9)</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 11.30: The system components used in the second linearisation procedure from a worst case initiator.

The possible steps from this point were determined, these are shown in Table 11.31.

<table>
<thead>
<tr>
<th>Component</th>
<th>(x)</th>
<th>Possible steps</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>upward steps</td>
<td>downward steps</td>
</tr>
<tr>
<td>Isolation valve (x_1)</td>
<td>1</td>
<td>1 1 1 1 1 2 1 1 1 1 1 1</td>
<td></td>
</tr>
<tr>
<td>Blowdown valve (x_2)</td>
<td>3</td>
<td>3 3 3 3 3 3 3 3 3 3 3 3 3</td>
<td></td>
</tr>
<tr>
<td>Deluge system (x_3)</td>
<td>1</td>
<td>1 1 1 1 1 1 2 1 1 1 1 1 1</td>
<td></td>
</tr>
<tr>
<td>Detection system (x_4)</td>
<td>3</td>
<td>3 3 2 3 3 3 3 4 3 3 3 3 3 3</td>
<td></td>
</tr>
<tr>
<td>Isolation inspection (x_5)</td>
<td>1</td>
<td>1 1 1 1 1 1 1 1 1 2 1 1 1</td>
<td></td>
</tr>
<tr>
<td>Blowdown inspection (x_6)</td>
<td>2</td>
<td>2 2 2 1 2 2 2 2 2 2 2 2 2 2</td>
<td></td>
</tr>
<tr>
<td>Deluge inspection (x_7)</td>
<td>2</td>
<td>2 2 2 2 1 2 2 2 2 2 3 2 2 2</td>
<td></td>
</tr>
<tr>
<td>Detection inspection (x_8)</td>
<td>1</td>
<td>1 1 1 1 1 1 1 1 1 1 1 2 1</td>
<td></td>
</tr>
<tr>
<td>Valve position (x_9)</td>
<td>1</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1 1 2</td>
<td></td>
</tr>
</tbody>
</table>

Table 11.31: The steps that may be taken during the second linearisation procedure from a worst range initiator.

From this table \(U = \{2, 4, 6, 7\}\) and \(D = \{1, 3, 4, 5, 7, 8, 9\}\). Central differencing could only
be performed on $x_4$ and $x_7$, forward and backward differencing was required for the other variables. The linear function generated was

$$f_0(x + \delta x) = 5.14 \times 10^{-7} - 7.06 \times 10^{-8}x_1 - 8.13 \times 10^{-9}x_2 - 5.44 \times 10^{-8}x_3 - 4 \times 10^{-8}x_4 - 2.38 \times 10^{-8}x_5 - 6.84 \times 10^{-9}x_6 - 1.61 \times 10^{-7}x_7 - 4.35 \times 10^{-8}x_8 - 7.27 \times 10^{-9}x_9$$

This linear function generated the intermediate solution shown in Table 11.32 which is the same case as that found to be the solution for the stepping process from a worst case initiator. The linear function estimates the frequency of exceeding 3 bar to be $4.27 \times 10^{-7}$ per year but the platform evaluation of this case yields $4.5 \times 10^{-7}$ per year.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>$x_1$</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>$x_2$</td>
</tr>
<tr>
<td>Deluge system</td>
<td>$x_3$</td>
</tr>
<tr>
<td>Detection system</td>
<td>$x_4$</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>$x_5$</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>$x_6$</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>$x_7$</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>$x_8$</td>
</tr>
<tr>
<td>Valve position</td>
<td>$x_9$</td>
</tr>
</tbody>
</table>

Table 11.32: The system components used in the third linearisation procedure from a worst case initiator.

The possible steps are shown in Table 11.18 where $U = \{3, 4, 8\}$ and $D = \{1, 2, 3, 5, 6, 7, 8, 9\}$. The linear function generated was

$$f_0(x + \delta x) = 4.5 \times 10^{-7} - 5.07 \times 10^{-8}x_1 - 1.17 \times 10^{-9}x_2 - 3.15 \times 10^{-8}x_3 - 9.6 \times 10^{-8}x_4 - 1.72 \times 10^{-8}x_5 - 4.09 \times 10^{-10}x_6 - 1.59 \times 10^{-7}x_7 - 3.95 \times 10^{-8}x_8 - 1.15 \times 10^{-8}x_9$$

This function yielded a data set identical to iteration 3 from the mid case initiator. As this case has been reached the process will now follow the same pattern as that generated for the mid case initiator. The intermediate solutions are as demonstrated in Table 11.33.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation valve</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown valve</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Deluge system</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Detection system</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Isolation inspection</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Blowdown inspection</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Deluge inspection</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Detection inspection</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Valve position</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

|                |                |                |                |                |                |
|----------------|----------------|----------------|----------------|----------------|
| Estimated frequency of exceeding 3 bar | $-9.36 \times 10^{-6}$ | $4.27 \times 10^{-7}$ | $3.16 \times 10^{-7}$ | $4.14 \times 10^{-7}$ |
| SAROS frequency of exceeding 3 bar | $4.96 \times 10^{-6}$ | $5.14 \times 10^{-7}$ | $4.5 \times 10^{-7}$ | $4.2 \times 10^{-7}$ | $4.18 \times 10^{-7}$ |

Table 11.33: The intermediate solutions generated with the linearisation process with a worst case initiator.

As with the mid case initiator iteration 5 provides the optimum solution.

11.7.4 **An evaluation of the linearisation process.**

The linearisation process was initiated from a mid case and a worst case to observe any differences in the selection of the optimum. Both cases iterated to the same solution, with the worst case initiated process requiring two more iterations. During the linearisation process both cases generated with the stepping process were encountered. Due to the linearisation process having the capability to move to any point in the design space movement was made from these points.

The linear function was not very accurate in estimating the frequency of exceeding 3 bar. However its accuracy improved as the optimum was approached.
11.8 A heuristic approach.

This section describes a heuristic approach to finding the optimum configuration of the safety systems on an offshore platform. Heuristic methods do not follow any strict mathematical criteria, however to aim for a good heuristic model some guidelines should be followed. These state that the solution should be yielded in a reasonable amount of computer time and should be close to the optimum most of the time.

To develop the heuristic scheme the aim, rules and strategy should be defined.

Aim: To obtain the combination of the safety system components which generate the lowest frequency of exceeding 3 bar.

Rules: Two rules must be strictly adhered to.

1. the cost must be less than 183500 units.
2. the time taken to inspect must be less than 765 hours.

The basis of this scheme is the contribution supplied by each of the safety systems to the frequency of exceeding 3 bar. The SAROS code has been adapted to provide these percentage contributions for the isolation system, blowdown system, deluge system and detection system.

A platform evaluation has been used to describe running the SAROS code for the three modules on the platform, extracting the frequencies of overpressure exceedence, interpolating to obtain values for exceeding 3 bar and then summing these results to give the frequency of exceeding 3 bar for the platform. For the heuristic approach the term platform evaluation shall not be referred to, as the process differs, the term contribution evaluation shall be used instead. A contribution evaluation involves running the modified SAROS code for the three modules on the platform. This modified code produces a data file for each module detailing the contributions to the frequency of exceeding 3 bar from each of the safety systems. The contributions provide the percentage of the frequency of exceeding 3 bar due to the failure of the safety systems. A short program then processes these data files to give the overall contributions for the platform.
11.8.1 The design vector.

Because the contributions to the frequency of exceeding 3 bar are determined for the safety systems and not for the type and the inspection intervals individually, the variables in the design vector need to be redefined. The design vector, \( x \), is made up of \( x_1 \), the isolation system, \( x_2 \), the blowdown system, \( x_3 \), the deluge system and \( x_4 \), the detection system. Each of these variables must take on an integer value identifying the type of system in use.

The isolation system is one variable which combines the type of the isolation valves and their inspection intervals. These combinations are ordered according to the unavailability as seen in Table 11.34. It can be seen that there is no relationship between the unavailability and the time it takes to inspect the system or the cost involved. The new ordering for the blowdown system, deluge system and detection system are shown in Tables 11.35, 11.36 and 11.37 respectively.

<table>
<thead>
<tr>
<th>System</th>
<th>type</th>
<th>inspection</th>
<th>unavailability</th>
<th>cost</th>
<th>time to test</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
<td>0.01</td>
<td>14000</td>
<td>84</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>2</td>
<td>0.02</td>
<td>9800</td>
<td>42</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>1</td>
<td>0.04</td>
<td>12600</td>
<td>84</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>2</td>
<td>0.08</td>
<td>8400</td>
<td>42</td>
</tr>
<tr>
<td>E</td>
<td>3</td>
<td>1</td>
<td>0.1</td>
<td>9800</td>
<td>84</td>
</tr>
<tr>
<td>F</td>
<td>3</td>
<td>2</td>
<td>0.2</td>
<td>5600</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 11.34: The isolation systems in terms of the type and inspection interval ordered according to the unavailability.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>System</th>
<th>type</th>
<th>inspection</th>
<th>unavailability</th>
<th>cost</th>
<th>time to test</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
<td>0.01</td>
<td>1000</td>
<td>72</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>2</td>
<td>0.02</td>
<td>8400</td>
<td>36</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>1</td>
<td>0.04</td>
<td>10800</td>
<td>72</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>2</td>
<td>0.08</td>
<td>7200</td>
<td>36</td>
</tr>
<tr>
<td>E</td>
<td>3</td>
<td>1</td>
<td>0.1</td>
<td>8400</td>
<td>72</td>
</tr>
<tr>
<td>F</td>
<td>3</td>
<td>2</td>
<td>0.2</td>
<td>4800</td>
<td>36</td>
</tr>
</tbody>
</table>

Table 11.35: The blowdown systems in terms of the type and inspection interval ordered according to the unavailability.

<table>
<thead>
<tr>
<th>System</th>
<th>type</th>
<th>inspection</th>
<th>unavailability</th>
<th>cost</th>
<th>time to test</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
<td>0.021</td>
<td>129600</td>
<td>576</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>1</td>
<td>0.025</td>
<td>109200</td>
<td>432</td>
</tr>
<tr>
<td>C</td>
<td>3</td>
<td>1</td>
<td>0.031</td>
<td>120600</td>
<td>576</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>2</td>
<td>0.04</td>
<td>100800</td>
<td>288</td>
</tr>
<tr>
<td>E</td>
<td>2</td>
<td>2</td>
<td>0.05</td>
<td>87600</td>
<td>216</td>
</tr>
<tr>
<td>F</td>
<td>4</td>
<td>1</td>
<td>0.05</td>
<td>88800</td>
<td>288</td>
</tr>
<tr>
<td>G</td>
<td>3</td>
<td>2</td>
<td>0.06</td>
<td>91800</td>
<td>288</td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>3</td>
<td>0.08</td>
<td>86400</td>
<td>144</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>3</td>
<td>0.099</td>
<td>76800</td>
<td>108</td>
</tr>
<tr>
<td>J</td>
<td>4</td>
<td>2</td>
<td>0.1</td>
<td>74400</td>
<td>144</td>
</tr>
<tr>
<td>K</td>
<td>3</td>
<td>3</td>
<td>0.12</td>
<td>77400</td>
<td>144</td>
</tr>
<tr>
<td>L</td>
<td>4</td>
<td>3</td>
<td>0.2</td>
<td>67200</td>
<td>72</td>
</tr>
</tbody>
</table>

Table 11.36: The deluge systems in terms of the type and inspection interval ordered according to the unavailability.

The design vector is therefore

- \( x_1 \) is the isolation system which may take values from 1 to 6.
- \( x_2 \) is the blowdown system which may take values from 1 to 6.
- \( x_3 \) is the deluge system which may take values from 1 to 12.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>System</th>
<th>type</th>
<th>inspection</th>
<th>unavailability</th>
<th>cost</th>
<th>time to test</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
<td>0.00119</td>
<td>99600</td>
<td>576</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>2</td>
<td>0.002214</td>
<td>70800</td>
<td>288</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>3</td>
<td>0.004404</td>
<td>56400</td>
<td>144</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>1</td>
<td>0.01143</td>
<td>93600</td>
<td>576</td>
</tr>
<tr>
<td>E</td>
<td>2</td>
<td>2</td>
<td>0.02238</td>
<td>64800</td>
<td>288</td>
</tr>
<tr>
<td>F</td>
<td>2</td>
<td>3</td>
<td>0.04428</td>
<td>50400</td>
<td>144</td>
</tr>
<tr>
<td>G</td>
<td>3</td>
<td>1</td>
<td>0.05715</td>
<td>61800</td>
<td>288</td>
</tr>
<tr>
<td>H</td>
<td>3</td>
<td>2</td>
<td>0.1119</td>
<td>47400</td>
<td>144</td>
</tr>
<tr>
<td>I</td>
<td>4</td>
<td>1</td>
<td>0.1119</td>
<td>58800</td>
<td>288</td>
</tr>
<tr>
<td>J</td>
<td>3</td>
<td>3</td>
<td>0.2214</td>
<td>40200</td>
<td>72</td>
</tr>
<tr>
<td>K</td>
<td>4</td>
<td>2</td>
<td>0.2214</td>
<td>44400</td>
<td>144</td>
</tr>
<tr>
<td>L</td>
<td>5</td>
<td>1</td>
<td>0.2238</td>
<td>55800</td>
<td>288</td>
</tr>
<tr>
<td>M</td>
<td>4</td>
<td>3</td>
<td>0.4404</td>
<td>37200</td>
<td>72</td>
</tr>
<tr>
<td>N</td>
<td>5</td>
<td>2</td>
<td>0.4428</td>
<td>41400</td>
<td>144</td>
</tr>
<tr>
<td>O</td>
<td>5</td>
<td>3</td>
<td>0.8808</td>
<td>34200</td>
<td>72</td>
</tr>
</tbody>
</table>

Table 11.37: The detection systems in terms of the type and inspection interval ordered according to the unavailability.

- $x_4$ is the detection system which may take values from 1 to 15.

From the results of the stepping and linearisation processes valve position 1 appears to be the optimum position, therefore this is taken as standard with no changes optional throughout the process.

11.8.2 The strategy.

An initiating strategy for finding the optimum configuration has been developed. Although, due to the nature of heuristic models this may not always be strictly adhered to and may be modified at any time if results warrant it. The strategy is to consider the safety system which yields the greatest contribution to the frequency of exceeding 3 bar and then attempt to improve this in terms of unavailability. If improvements require more resources than are available then the lowest contributor is identified and resources are taken from this.
In some cases resources may be saved when improving the unavailability of a component. For example, improving the isolation system from type C to type B will save 2800 units financially and 42 hours inspection time. Hence all systems should be considered to check that they are as good as possible whilst saving as many resources as possible.

The algorithm for this procedure is as follows.

1. Select a feasible point in the design space, x.
2. Perform a contribution evaluation.
3. Determine the system that contributes the most to the frequency of exceeding 3 bar.
4. Ensure that each system is the best possible for the resources allocated to it.
5. Identify all improvements that may be made to the major contributor in terms of unavailability.
6. If any of these improvements can be made whilst remaining within the constraints, select this as the next feasible design point and continue from step 2.
7. If this cannot be done then determine the system with the lowest contribution to the frequency of exceeding 3 bar.
8. Identify all situations where resources can be reduced for the lowest contributor.
9. Bearing in mind the potential resource savings choose which improvement will be made to the major contributor.
10. Select the cost reduction for the lowest contributor whilst keeping the system as good as possible.
11. If the chosen case is within the constraints then select this as the next feasible point and continue from step 2.
12. If the chosen case is outside the bounds then resources must be reallocated, if it is not practical to take any more from the lowest contributor then consider the second lowest contributor. When a feasible case is decided upon begin from step 2.
13. The process terminates when the controller decides that there are no more viable resource allocations available to try.
11.8.3 The heuristic method in practice.

A guideline for a heuristic method is to keep close to the optimum if possible. As the stepping and linearisation processes both found an optimum in very few iterations from a mid case initiator, it was decided to begin the heuristic approach from the same initiator. In terms of the new variable definitions this case is defined as shown in Table 11.38.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Financial cost</th>
<th>Inspection time(hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>C</td>
<td>12600</td>
<td>84</td>
</tr>
<tr>
<td>blowdown</td>
<td>C</td>
<td>10800</td>
<td>72</td>
</tr>
<tr>
<td>deluge</td>
<td>E</td>
<td>87600</td>
<td>216</td>
</tr>
<tr>
<td>detection</td>
<td>E</td>
<td>64800</td>
<td>288</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>175800</td>
<td>660</td>
</tr>
</tbody>
</table>

Table 11.38: The combination of safety system types selected as the initiator.

The contribution evaluation gives a frequency of exceeding 3 bar for the platform of $5.99 \times 10^{-7}$ per year, this frequency is attributed to the separation, compression and wellhead modules as shown in Table 11.39. The compression module provides the greatest contribution accounting for 55% of the overpressures exceeding 3 bar. The separation module accounts for 41%. The wellhead module, accounting for 3%, rarely generates overpressures exceeding 3 bar in comparison with the other two modules. The contributions for the failure of the safety systems are also shown in Table 11.39.

<table>
<thead>
<tr>
<th>The system contributions</th>
<th>The module contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>separation</td>
</tr>
<tr>
<td>C</td>
<td>41.1%</td>
</tr>
<tr>
<td>blowdown</td>
<td>compression</td>
</tr>
<tr>
<td>C</td>
<td>55.6%</td>
</tr>
<tr>
<td>deluge</td>
<td>wellhead</td>
</tr>
<tr>
<td>E</td>
<td>3.3%</td>
</tr>
<tr>
<td>detection</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>5.8%</td>
</tr>
</tbody>
</table>

Table 11.39: The contributions to the frequency of exceeding 3 bar of the safety systems selected as the initiator.

The deluge failure is involved in 100% of the overpressures exceeding 3 bar, hence when the deluge system is operational the overpressures generated do not reach this level. Improving
Approaches to optimise the configuration of the safety systems.

the deluge system would lead to less situations involving deluge failure and therefore a lower frequency of exceeding 3 bar. Isolation valve failures are involved in 32.5% of the overpressures exceeding 3 bar. 14% are due to blowdown failure and 5.8% due to detection failure. These percentage values do not sum to 100% as the events could occur simultaneously and overpressures may exceed 3 bar when the isolation, blowdown and detection systems operate as designed.

Since the deluge system failure is critical for generating overpressures exceeding 3 bar this system must be improved. Possible improvements in the unavailability are shown in Table 11.40. This table gives details of the costs and times involved and the effect on the platform cost if everything else remains constant.

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>E</td>
<td>D</td>
</tr>
<tr>
<td>unavailability</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>financial cost</td>
<td>87600</td>
<td>100800</td>
</tr>
<tr>
<td>time to inspect</td>
<td>216</td>
<td>288</td>
</tr>
<tr>
<td>platform cost</td>
<td>175800</td>
<td>189000</td>
</tr>
<tr>
<td>total time</td>
<td>660</td>
<td>732</td>
</tr>
</tbody>
</table>

Table 11.40: Possible improvements to the deluge system from the initiating case.

It can be seen that all improvements take the cost out of bounds, therefore the lowest contributor must be identified so that resources can be reallocated. The lowest contributor is the detection system contributing 5.8%. However before resources are taken from the detection system the other two systems should be considered to see if any improvements could be made in unavailability whilst saving resources. It is found that improving both the isolation and blowdown systems will save resources. Improving the detection system will also save resources. The system is now that shown in Table 11.41.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Financial cost</th>
<th>Inspection time(hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>B</td>
<td>9800</td>
<td>42</td>
</tr>
<tr>
<td>blowdown</td>
<td>B</td>
<td>8400</td>
<td>36</td>
</tr>
<tr>
<td>deluge</td>
<td>C</td>
<td>56400</td>
<td>144</td>
</tr>
<tr>
<td>detection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>76400</td>
<td>222</td>
</tr>
</tbody>
</table>

Table 11.41: Iteration 1: intermediate step to find a feasible combination.

This gives 108900 units available to spend on a deluge system with 543 hours to inspect. From Table 11.40 it can be seen that the deluge system may be improved to type D. This has been accomplished by reducing the resources to the other three systems whilst also improving their unavailabilities. This system is shown in Table 11.42.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Financial cost</th>
<th>Inspection time(hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>B</td>
<td>9800</td>
<td>42</td>
</tr>
<tr>
<td>blowdown</td>
<td>B</td>
<td>8400</td>
<td>36</td>
</tr>
<tr>
<td>deluge</td>
<td>D</td>
<td>100800</td>
<td>288</td>
</tr>
<tr>
<td>detection</td>
<td>C</td>
<td>56400</td>
<td>144</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>175400</td>
<td>510</td>
</tr>
</tbody>
</table>

Table 11.42: The combination of safety system types selected from the first selection process.

A contribution evaluation was performed on this case, this gives a frequency of exceeding 3 bar for the platform of $4.83 \times 10^{-7}$ per year. Therefore improving all safety systems by reallocating resources has been beneficial. The percentage of overpressures exceeding 3 bar due to isolation failure has fallen to 19.5%, the percentage due to blowdown failure has fallen to 4.9% and due to detection failure has fallen to 1.07%. The percentage due to deluge failure remained at 100%. The module contributions have been reallocated. The compression module now contributes 62% and the separation module contributes 35%. These contributions are shown in Table 11.43.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>The system contributions</th>
<th>The module contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>B</td>
</tr>
<tr>
<td>blowdown</td>
<td>B</td>
</tr>
<tr>
<td>deluge</td>
<td>D</td>
</tr>
<tr>
<td>detection</td>
<td>C</td>
</tr>
<tr>
<td>separation</td>
<td></td>
</tr>
<tr>
<td>compression</td>
<td></td>
</tr>
<tr>
<td>wellhead</td>
<td></td>
</tr>
</tbody>
</table>

Table 11.43: The contributions to the frequency of exceeding 3 bar of the safety systems selected during the first iteration.

This system cost 8100 units below the limit set, rather than waste these resources they should be used to try and improve systems further. The deluge system is clearly the system that requires the most resources, however this amount of resources will not improve the system without taking further resources from another system. The detection system is the lowest contributor and should be the system to lose resources. To reduce the resources on this system would require a selection of type F which is a significant drop in availability. Since all safety systems rely on the detection system working, a break in the strategy is proposed. As an alternative these extra resources shall be spent on the second largest contributor, the isolation system. The isolation system may be improved to type A at an additional cost of 4200 and incurring an extra 42 hours in the inspection process. There are still an available 3900 units and 213 hours. The isolation system is at its highest type therefore these remaining resources will be used for the blowdown system. 3600 units and 36 hours are required to upgrade the blowdown system to its highest type, type A. The choice of systems is shown in Table 11.44.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Financial cost</th>
<th>Inspection time(hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>A</td>
<td>14000</td>
<td>84</td>
</tr>
<tr>
<td>blowdown</td>
<td>A</td>
<td>12000</td>
<td>72</td>
</tr>
<tr>
<td>deluge</td>
<td>D</td>
<td>100800</td>
<td>288</td>
</tr>
<tr>
<td>detection</td>
<td>C</td>
<td>56400</td>
<td>144</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>183200</td>
<td>588</td>
</tr>
</tbody>
</table>

Table 11.44: The combination of safety system types selected from the second selection process.
Approaches to optimise the configuration of the safety systems.

The contribution evaluation for this system yielded a frequency of exceeding 3 bar of $4.59 \times 10^{-7}$ per year. Table 11.45 shows the contributions of the safety systems. The contributions for the isolation and blowdown systems have fallen whilst the detection system has risen slightly to 1.13%. The deluge system is still the most critical system with its failure accounting for 100% of the overpressures exceeding 3 bar.

<table>
<thead>
<tr>
<th>The system contributions</th>
<th>The module contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>A</td>
</tr>
<tr>
<td>blowdown</td>
<td>A</td>
</tr>
<tr>
<td>deluge</td>
<td>D</td>
</tr>
<tr>
<td>detection</td>
<td>C</td>
</tr>
<tr>
<td>separation</td>
<td></td>
</tr>
<tr>
<td>compression</td>
<td></td>
</tr>
<tr>
<td>wellhead</td>
<td></td>
</tr>
</tbody>
</table>

Table 11.45: The contributions to the frequency of exceeding 3 bar of the safety systems selected during the second iteration.

As the deluge system is the major contributor, resources shall be reallocated to improve this system. Improvements to the deluge system are shown in Table 11.46. It is not worth improving the deluge system to type C as the resources requires are much higher then those required for type B.

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>D</td>
<td>C</td>
</tr>
<tr>
<td>unavailability</td>
<td>0.04</td>
<td>0.031</td>
</tr>
<tr>
<td>financial cost</td>
<td>100800</td>
<td>120600</td>
</tr>
<tr>
<td>time to inspect</td>
<td>288</td>
<td>576</td>
</tr>
</tbody>
</table>

Table 11.46: Possible improvements to the deluge system from the second iteration.

The additional resources necessary to change to type B are 8400 units and 144 hours. The hours required are available but the financial resources are not. Hence these shall be taken from the detection system, the lowest contributor. Table 11.47 shows the detection systems which use lower resources than the current type.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>type</th>
<th>Current</th>
<th>Cost reductions</th>
</tr>
</thead>
<tbody>
<tr>
<td>unavailability</td>
<td>C 0.004404</td>
<td>L 0.2238</td>
</tr>
<tr>
<td>financial cost</td>
<td>56400</td>
<td>55800</td>
</tr>
<tr>
<td>time to inspect</td>
<td>144</td>
<td>288</td>
</tr>
</tbody>
</table>

Table 11.47: Possible cost savings with the detection system from the second iteration.

It is clear that detection system type \( L \) will not be selected as there are other types which have a lower unavailability whilst costing less. In order to make the saving required the detection system would need to change from type \( C \) to type \( H \). This reduction does not seem reasonable for the system on which all other systems depend. Hence it is decided to reduce the detection system to type \( F \). The combination of safety systems chosen so far is shown in Table 11.48.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Financial cost</th>
<th>Inspection time(hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>A</td>
<td>14000</td>
<td>84</td>
</tr>
<tr>
<td>blowdown</td>
<td>A</td>
<td>12000</td>
<td>72</td>
</tr>
<tr>
<td>deluge</td>
<td>B</td>
<td>109200</td>
<td>432</td>
</tr>
<tr>
<td>detection</td>
<td>F</td>
<td>50400</td>
<td>144</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>185600</td>
<td>732</td>
</tr>
</tbody>
</table>

Table 11.48: Iteration 3: intermediate step to find a feasible solution.

This system is over budget by 2100 units, so resources must be lost from somewhere. The second lowest contributor to the frequency of exceeding 3 \( \text{bar} \) was the blowdown system, hence resources shall be saved by dropping this to type \( B \). The case decided on after the third iteration is shown in Table 11.49.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Financial cost</th>
<th>Inspection time(hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>A</td>
<td>14000</td>
<td>84</td>
</tr>
<tr>
<td>blowdown</td>
<td>B</td>
<td>8400</td>
<td>36</td>
</tr>
<tr>
<td>deluge</td>
<td>B</td>
<td>109200</td>
<td>432</td>
</tr>
<tr>
<td>detection</td>
<td>F</td>
<td>50400</td>
<td>144</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>182000</td>
<td>696</td>
</tr>
</tbody>
</table>

Table 11.49: The combination of safety system types selected from the third selection process.

The contribution evaluation for this combination gives a frequency of exceeding 3 bar for the platform of $4.18 \times 10^{-7}$ per year. This is again a better combination. The contributions are as shown in Table 11.50. The major contributor remains as the deluge system and the lowest contributor stays as the detection system even though this contribution has increased to 8.7%. However the blowdown system and the isolation system have switched places, with the blowdown system increasing to 12.4% and the isolation system dropping to 9.9%.

<table>
<thead>
<tr>
<th>The system contributions</th>
<th>The module contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation A</td>
<td>9.9%</td>
</tr>
<tr>
<td>blowdown B</td>
<td>12.4%</td>
</tr>
<tr>
<td>deluge B</td>
<td>100%</td>
</tr>
<tr>
<td>detection F</td>
<td>8.7%</td>
</tr>
</tbody>
</table>

Table 11.50: The contributions to the frequency of exceeding 3 bar of the safety systems selected during the third iteration.

This system configuration is currently the ‘best’ in lowering the frequency of exceeding 3 bar. The deluge system can be improved one stage further to type A. This will have an additional financial cost of 20400 units and an additional time of 144 hours. The combination of resources is shown in Table 11.51.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Financial cost</th>
<th>Inspection time(hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>A</td>
<td>14000</td>
<td>84</td>
</tr>
<tr>
<td>blowdown</td>
<td>B</td>
<td>8400</td>
<td>36</td>
</tr>
<tr>
<td>deluge</td>
<td>A</td>
<td>129600</td>
<td>576</td>
</tr>
<tr>
<td>detection</td>
<td>F</td>
<td>50400</td>
<td>144</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>202400</td>
<td>840</td>
</tr>
</tbody>
</table>

Table 11.51: Iteration 4: intermediate step to find a feasible solution.

This case is over budget by 18900 units and 75 hours. Resources must be reallocated to cope with this. The isolation system and the detection system must lose resources. It is undesirable to take the detection system any lower as its contribution to the overpressure exceedence is rising as this happens, therefore an attempt will be made to take resources from the isolation system. The number of hours spent in the inspection process has now become important. Dropping the isolation system to types B, D or F will save only 42 hours leaving another 33 hours to be found. The blowdown system already has its minimum number of hours so savings must be made on the detection system. This requires the reduction of the detection system to one of the types in Table 11.52.

<table>
<thead>
<tr>
<th>type</th>
<th>Current</th>
<th>Time reductions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>J</td>
</tr>
<tr>
<td>unavailability</td>
<td>0.04428</td>
<td>0.2214</td>
</tr>
<tr>
<td>financial cost</td>
<td>50400</td>
<td>40200</td>
</tr>
<tr>
<td>time to inspect</td>
<td>144</td>
<td>72</td>
</tr>
</tbody>
</table>

Table 11.52: Possible time savings with the detection system from the third iteration.

If the isolation system is reduced to type B, 35700 units are available to spend on a detection system. The only detection system this will buy is type O. The combination is shown in Table 11.53.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Financial cost</th>
<th>Inspection time(hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>B</td>
<td>9800</td>
<td>42</td>
</tr>
<tr>
<td>blowdown</td>
<td>B</td>
<td>8400</td>
<td>36</td>
</tr>
<tr>
<td>deluge</td>
<td>A</td>
<td>129600</td>
<td>576</td>
</tr>
<tr>
<td>detection</td>
<td>O</td>
<td>34200</td>
<td>72</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>182000</td>
<td>726</td>
</tr>
</tbody>
</table>

Table 11.53: The combination of safety system types selected from the fourth selection process.

It is unlikely that this system will produce a lower frequency of exceeding 3 bar as the detection system is at its worst type and this determines the response of the other systems. This theory was confirmed when the contribution evaluation yielded a frequency of exceeding 3 bar of \(7.99 \times 10^{-7}\) per year. Improving the deluge system to type A was too expensive as substantial reductions in resources for other systems was required. Therefore this decision shall be ignored and the previous case returned to.

The compression module had the greatest contribution to the overpressures exceeding 3 bar. Within the compression module the blowdown system was the most critical system if deluge was neglected hence improvements shall be made to the blowdown system. Table 11.54 demonstrates the effect on the costs.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Financial cost</th>
<th>Inspection time(hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>A</td>
<td>14000</td>
<td>84</td>
</tr>
<tr>
<td>blowdown</td>
<td>A</td>
<td>12000</td>
<td>72</td>
</tr>
<tr>
<td>deluge</td>
<td>B</td>
<td>109200</td>
<td>432</td>
</tr>
<tr>
<td>detection</td>
<td>F</td>
<td>50400</td>
<td>144</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>185600</td>
<td>732</td>
</tr>
</tbody>
</table>

Table 11.54: Iteration 5: intermediate step to find a feasible solution.

This combination is too expensive. Since the detection system is the lowest contributor, resources should be taken from it. For sufficient resources to be gained the detection system must drop to type \(H\). This gives the case shown in Table 11.55.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Financial cost</th>
<th>Inspection time(hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>A</td>
<td>14000</td>
<td>84</td>
</tr>
<tr>
<td>blowdown</td>
<td>A</td>
<td>12000</td>
<td>72</td>
</tr>
<tr>
<td>deluge</td>
<td>B</td>
<td>109200</td>
<td>432</td>
</tr>
<tr>
<td>detection</td>
<td>H</td>
<td>47400</td>
<td>144</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>182600</td>
<td>732</td>
</tr>
</tbody>
</table>

Table 11.55: The combination of safety system types selected from the fifth selection process.

A contribution evaluation for this case gives the frequency of exceeding 3 bar as $4.5 \times 10^{-7}$ per year. Table 11.56 shows the distribution of the contributions. The compression module now has a smaller influence. The frequency of exceeding 3 bar has increased and therefore this allocation of resources is not an improvement. The blowdown contribution has increased even though the resources to it increased. This can be explained by the reduction in the detection system, the contribution for which has increased to 20.6%. Resources should be given back to the detection system, to do this they shall be taken from the isolation system as this was the lowest contributor in this case. This gives the case shown in Table 11.57.

<table>
<thead>
<tr>
<th>The system contributions</th>
<th>The module contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>A</td>
</tr>
<tr>
<td>blowdown</td>
<td>B</td>
</tr>
<tr>
<td>deluge</td>
<td>B</td>
</tr>
<tr>
<td>detection</td>
<td>H</td>
</tr>
<tr>
<td>separation</td>
<td></td>
</tr>
<tr>
<td>compression</td>
<td></td>
</tr>
<tr>
<td>wellhead</td>
<td></td>
</tr>
</tbody>
</table>

Table 11.56: The contributions to the frequency of exceeding 3 bar of the safety systems selected during the fifth iteration.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Financial cost</th>
<th>Inspection time(hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>B</td>
<td>9800</td>
<td>42</td>
</tr>
<tr>
<td>blowdown</td>
<td>A</td>
<td>12000</td>
<td>72</td>
</tr>
<tr>
<td>deluge</td>
<td>B</td>
<td>109200</td>
<td>432</td>
</tr>
<tr>
<td>detection</td>
<td>F</td>
<td>50400</td>
<td>144</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>181400</td>
<td>690</td>
</tr>
</tbody>
</table>

Table 11.57: The combination of safety system types selected from the sixth selection process.

A contribution evaluation on this combination of systems gives a frequency of exceeding 3 bar of $4.36 \times 10^{-7}$ per year which is again a worse case. Table 11.58 shows the contributions the safety systems have on this frequency. The contribution due to the detection system failure has fallen back to 8.3%. The isolation contribution has risen whilst the blowdown contribution has fallen.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>The system contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>B</td>
<td>17.4%</td>
</tr>
<tr>
<td>blowdown</td>
<td>A</td>
<td>10.35%</td>
</tr>
<tr>
<td>deluge</td>
<td>B</td>
<td>100%</td>
</tr>
<tr>
<td>detection</td>
<td>F</td>
<td>8.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>The module contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>separation</td>
</tr>
<tr>
<td>compression</td>
</tr>
<tr>
<td>wellhead</td>
</tr>
</tbody>
</table>

Table 11.58: The contributions to the frequency of exceeding 3 bar of the safety systems selected during the sixth iteration.

At this point it is worth considering all the cases run so far. These are illustrated in Table 11.59.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th>System configurations</th>
<th>isolation</th>
<th>blowdown</th>
<th>deluge</th>
<th>detection</th>
<th>frequency of exceeding 3 bar ($\times 10^{-7}$) per year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>5.99</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>4.83</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>4.59</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>4.18</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>F</td>
<td>7.99</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>F</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>F</td>
<td>4.36</td>
</tr>
</tbody>
</table>

Table 11.59: All cases evaluated at present.

It can be seen from the above table that the lower frequencies of exceeding 3 bar were generated when the deluge system was type B. Therefore this shall remain as the deluge system type. The lowest contributions from the detection system are seen when it is type C, the isolation and blowdown systems also have low contributions when this is the case. Therefore the next case shall revert to the detection system being type C. The next case shall therefore have components as seen in Table 11.60.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Financial cost</th>
<th>Inspection time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>blowdown</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>deluge</td>
<td>B</td>
<td>109200</td>
<td>432</td>
</tr>
<tr>
<td>detection</td>
<td>C</td>
<td>56400</td>
<td>144</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>165600</td>
<td>576</td>
</tr>
</tbody>
</table>

Table 11.60: Iteration 7: intermediate step to find a feasible solution.

This combination of the deluge and the detection system leaves 17900 units to be split between the isolation and the blowdown systems. Comparing the fourth and the seventh cases in Table 11.59 it can be seen that they have identical deluge and detection systems whilst differing in whether the isolation or the blowdown takes the better type. The frequency of exceeding 3 bar is lower when the isolation is better than the blowdown system, therefore in this case the isolation system will have priority. If the isolation system is chosen to be type A at a cost of 14000 units then only 3900 units remain which is insufficient to purchase a blowdown system. If the isolation system is type B at a cost of 9800 units then 8100 units
Approaches to optimise the configuration of the safety systems.

remain which is sufficient to purchase a blowdown system of type $D$. The case to be used is therefore as shown in Table 11.61.

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Financial cost</th>
<th>Inspection time(hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>B</td>
<td>9800</td>
<td>42</td>
</tr>
<tr>
<td>blowdown</td>
<td>D</td>
<td>7200</td>
<td>36</td>
</tr>
<tr>
<td>deluge</td>
<td>B</td>
<td>109200</td>
<td>432</td>
</tr>
<tr>
<td>detection</td>
<td>C</td>
<td>56400</td>
<td>144</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>182600</td>
<td>654</td>
</tr>
</tbody>
</table>

Table 11.61: The combination of safety system types selected from the seventh selection process.

The contribution evaluation for this data set gives a frequency of exceeding 3 bar of $4.2 \times 10^{-7}$ per year. The contributions due to the safety systems are shown in Table 11.62. Improving the detection system has led to a low contribution for this system and consequently a low frequency of exceeding 3 bar. However having a lower type of detection system and improved isolation and blowdown system provided a lower frequency of exceeding 3 bar, as seen in the fourth case evaluated.

<table>
<thead>
<tr>
<th>The system contributions</th>
<th>The module contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolation</td>
<td>B</td>
</tr>
<tr>
<td>blowdown</td>
<td>D</td>
</tr>
<tr>
<td>deluge</td>
<td>B</td>
</tr>
<tr>
<td>detection</td>
<td>C</td>
</tr>
</tbody>
</table>

Table 11.62: The contributions to the frequency of exceeding 3 bar of the safety systems selected during the seventh iteration.

At this stage it appears that the optimum configuration has been determined. Table 11.63 shows the components used in this optimum and the second best configuration.
Approaches to optimise the configuration of the safety systems.

<table>
<thead>
<tr>
<th></th>
<th>Optimum configuration</th>
<th>Second best</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency of exceeding 3 bar</td>
<td>$4.18 \times 10^{-7}$</td>
<td>$4.2 \times 10^{-7}$</td>
</tr>
<tr>
<td>System</td>
<td></td>
<td></td>
</tr>
<tr>
<td>isolation</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>blowdown</td>
<td>B</td>
<td>D</td>
</tr>
<tr>
<td>deluge</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>detection</td>
<td>F</td>
<td>C</td>
</tr>
<tr>
<td>Resources</td>
<td></td>
<td></td>
</tr>
<tr>
<td>financial cost</td>
<td>182000</td>
<td>182600</td>
</tr>
<tr>
<td>inspection time</td>
<td>696</td>
<td>654</td>
</tr>
<tr>
<td>Module contributions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>separation</td>
<td>34.7%</td>
<td>35.2%</td>
</tr>
<tr>
<td>compression</td>
<td>62.3%</td>
<td>62.2%</td>
</tr>
<tr>
<td>wellhead</td>
<td>3%</td>
<td>2.6%</td>
</tr>
<tr>
<td>System contributions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>isolation</td>
<td>9.9%</td>
<td>18.8%</td>
</tr>
<tr>
<td>blowdown</td>
<td>12.4%</td>
<td>16.2%</td>
</tr>
<tr>
<td>deluge</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>detection</td>
<td>8.7%</td>
<td>0.8%</td>
</tr>
</tbody>
</table>

Table 11.63: The combination of safety system types selected for the optimum configuration.

11.8.4 An evaluation of the heuristic method.

The heuristic method is very subjective in the choices made. A background knowledge of the system was required to understand why the system became poorer when the detection system was limited in its resources yet other components were improved.

The optimum chosen and the second best case were very similar and if the variables are transcribed into those used for the stepping and linearisation processes, it can be seen that the three methods have all converged to the same points. The optimum generated with the heuristic method was reached after only four contribution evaluations had been performed, with seven being completed in total. This method was therefore very economical on computer
Approaches to optimise the configuration of the safety systems.

processing time compared to the stepping and the linearisation processes.

The nature of the contribution evaluation allows the analyst to know what the systems contribute to the module frequency of exceeding 3 bar and the overall platform frequency of exceeding 3 bar. This then gives the opportunity to address the system contributing the most to the major module contributor even though this may not appear to be a critical component for the whole platform. For the optimisation processes, considered so far, the systems chosen for the platform were identical on each of the modules. With the stepping and linearisation processes there was no way to differentiate between the modules. However for the heuristic approach the modules may be treated differently. If, for example, the blowdown system failure was critical on the compression module but the detection system failure was critical on the wellhead module, then it would be possible to upgrade the blowdown system on the compression module and the detection system on the wellhead module and analyse the effects on the whole system.

11.9 Discussion.

In order to determine the optimum configuration of the safety systems on an offshore platform in terms of the frequency of exceeding 3 bar generated, three methods have been presented. The safety systems have been defined in terms of the types of systems and the inspection intervals for these systems. The combination of the type of system and the inspection interval defined the unavailability for the system. An assumption was made that each of the three modules on the platform would receive the same type of detection and deluge system and that each isolation valve would be of the same type and also each blowdown valve would be the same type.

The best possible components available would no doubt produce the optimum configuration for the platform. However there are no limitless supplies of resources available, therefore constraints were placed on the financial cost and the time spent in the inspection process.

The first two methods described relied on performing platform evaluations on a set point and some of the neighbouring nodes. The stepping process used these results to produce upward and downward differentials. These were then used to determine whether it was worth stepping up or down to a neighbouring component. Once a step had been decided
up, the platform evaluations were taken again and the process was repeated. This method was limited in the movement it could take since stepping was restricted to neighbouring components even though multi components could step at once. This method was relatively successful in finding an optimum configuration although the initial starting point played a major part in determining this.

The linearisation process used the platform evaluations of the neighbouring nodes to create central, forward or backward differences which were then used to create an estimating function for the frequency of exceeding 3 bar. This function was evaluated at all points within the feasible design space. Once a point had been selected as an improvement the next linear estimating function was created. This method was not limited to its movement within the design space, however it was using local differentials to determine whether points further away were preferable. At least with the stepping process the differentials calculated related to the movements that were carried out, whereas with the linearisation process a differential for moving upward by one component type did not necessarily relate to moving upwards by three component types. However this method was slightly more successful than the stepping process as the optimums found were not dependent on the initiating case.

The stepping and linearisation processes required many platform evaluations, using many hours of computer processing time. The third method proposed was the heuristic method. This method was based on performing one platform evaluation, processing the results through a short program to determine the contributions each system had on the frequency of exceeding 3 bar and then analysing to decide whether resources should be reallocated. Each iteration therefore required one platform evaluation compared to the 17 (maximum) for the other two methods. The method of reallocating resources is subjective but also minimises the risk that no erroneous cases are evaluated. This method also provides the chance for the systems to differ between modules should one module require resources spent on a system that the other modules did not require.

The three methods produced the same cases as the optimum configuration. This involved having the best type of isolation valves inspected twice yearly, the best type of blowdown valves although only inspected once per year, deluge system type 2 inspected every 3 months and detection system type 2 inspected once per year.
12. Summary and conclusions.

Within this thesis work is presented, the objective of which, is to minimise the risk posed to offshore platforms as a result of an explosion originating from an accidental release of gas.

The literature survey showed that there was a general consensus on the factors involved in modelling an explosion, however varying techniques have been employed as modelling tools. In order to estimate the overpressures generated it is not necessary to use CFD tools, empirical models enable mathematical techniques to be employed without necessarily being computer intensive. Modelling the dispersion of the gas cloud is complex due to the obstacles on the platform. The literature suggests that the most effective method of determining the concentration build up is by the use of CFD, however combining the complex geometries with the number of potential leak positions would make this impractical.

Chapter 6 of this thesis has presented SAROS, a methodology, developed by Andrews and Smith (1994)\cite{31}, to predict the frequencies of explosions occurring on an offshore platform and the magnitude of the overpressures generated. Predictions are required to be as accurate as possible to enable reliable risk estimations to be made. Simplifying assumptions were made in the original modelling calculations of SAROS. These assumptions have been investigated and addressed as described below.

Chapter 7 considered the release flow modelling from a leaking pipe or vessel into a semi enclosed module on an offshore platform. The original modelling assumed a gas, condensate and oil release occurring with changing temperature, implying negligible entropy changes. New modelling was introduced which assumed a constant temperature release. The methodology was adapted to deal with a gas and condensate release and a gas only release. From the results obtained it was concluded that a gas and condensate release was most appropriate. A suite of subroutines was added to the SAROS code as an alternative to BANG, the original release modelling subroutine. These subroutines assumed that the leak was occurring whilst the leaking section remained at constant temperature as evaporation of the condensate occurred. This model led to higher initial release rates and results demonstrated higher explosion frequencies and higher frequencies of the overpressures generated. In reality
there is likely to be heat transfer occurring within the system but not sufficient to retain the section at constant temperature. Hence the creation of this model has provided an upper and lower bound for the explosion frequencies. This bound was of small magnitude suggesting that either of the models could be used with confidence to predict the explosion frequencies.

Chapter 8 considered the explosion frequency calculations. The frequencies of explosions were assumed to be dependent only on the ignition source probability density function and the time periods that the concentration was within the flammable range. These calculations would provide an over estimation of the frequency as they did not account for previous ignitions. A previous ignition could have destroyed the platform or produced an escalation of the initial hazard to further releases and fires. The calculations were adapted to account for previous ignitions by assuming that if ignition had previously occurred it could not happen again. The results showed negligible differences in comparison with the original results. Hence concluding that the results produced with this simplifying assumption were both accurate and pessimistic.

Chapter 9 considered the dispersion of the gas cloud. The original modelling assumed immediate mixing of the gas and air within the specified volume, therefore giving uniform concentration throughout. Due to the presence of obstacles and the semi enclosed nature of the module, the concentration may not build up uniformly or immediately. To obtain correlations for the cloud volume enclosed between a specific concentration range the use of computational fluid dynamics is required. The aim being to produce an empirical formula. The applicable Navier Stokes equations required to model the concentration build up are presented in this chapter with background on the appropriate solution schemes. Due to computational resource restrictions correlations were not obtained. However a scheme is presented for calculating the frequencies of an explosion using such correlations. In these models the probability of ignition occurring at a specific concentration level is a function of the cloud size since this influences the chances of encountering an ignition source. The use of such a scheme will account for the position of the ignition source relative to the volume concentration.

Once the modelling assumptions had been addressed the next step was to consider the data used within the methodology. Chapter 10 presented a sensitivity analysis of some of the parameters in the model. The parameters were taken in turn and altered by varying percentages to assess the effects on the frequency due to their uncertainty. The results show
that some of the parameters have a linear effect, these were those associated calculating the frequency. Parameters associated with determining the gas concentration within the module tended to demonstrate non-linear effects.

As a means of reducing the risk posed should an explosion occur, the configuration of the safety systems on the platform was considered. Chapter 11 presented three approaches for finding an optimum configuration within the limitations set. To demonstrate the techniques hypothetical data was assumed for the variety of the safety components available for selection. The methods developed were applied assuming heavy constraints due to the platform already existing. This approach is more flexible if used at the design stage and is intended as a design tool. Each of the three proposed strategies for determining the optimum all converged on a configuration within a reasonable time scale. Without exhaustive enumeration it is not certain that these methods found the global optimum, however they were all successful in improving the system.

12.1 Conclusions.

This thesis has achieved the following objectives.

- Reviewed the literature concerning offshore hazards, particularly explosion and dispersion modelling. There is a great deal of information available on explosions and dispersion, the physics of which are not fully understood, therefore models applicable to offshore scenarios are generally crude approximations.

- Adapted SAROS to consider different constituents within its release flow modelling and compared the results. From this it is concluded that when modelling the frequency of the overpressure generated from an explosion, the gas and condensate release, which considers the leakage of oil as a factor in reducing the volume, is the most appropriate.

- An alternative release flow model is presented which assumes constant temperature whilst the leak occurs. This model and the original model, with the assumption of changing temperature, provide upper and lower bound for the explosion frequency. The negligible differences between the results from the two models infers that the less computer intensive model of the original changing temperature scenario is a valid
Summary and conclusions.

- The frequency calculations in SAROS have been adapted to account for the likelihood of previous ignitions. The modelling equations presented are more accurate in their calculations, however comparison of the results shows negligible differences between these and the original simplifications. Therefore concluding that the simplification incurred no loss of accuracy.

- A technique for integrating CFD generated dispersion correlations into the frequency calculations was developed. This accounts for the gas dispersion within the module compared with the ignition source location. Due to resource constraints when using the commercial CFD packages there were no correlations available to assess the accuracy of the new technique.

- A sensitivity study on the parameters which may have incurred errors in there collation was conducted, to assess the effects on the explosion frequency results. A linear relationship was demonstrated with alterations to five of the parameters. Two of the parameters, the leak hole size distribution and the ventilation rate, appeared to have non linear effects on the explosion frequency.

- In optimising the offshore platform in terms of the safety systems and the overpressures generated, an optimisation procedure which uses integer variables and does not rely on a defined objective function was required. A review of current optimisation techniques was performed to assess whether any were applicable.

- Three approaches for optimising the configuration of the safety systems were suggested and tested their effectiveness on a hypothetical platform. These three approaches all converged to the same optimum, although they may not have found the global optimum.

12.2 Extensions to this work.

Chapter 9 has presented a methodology for integrating dispersion correlations into the frequency calculations, however this has not been implemented due to correlations not having been determined. Such correlations may be obtainable with sufficient computer resources,
time and CFD expertise. If these could be found and the methodology implemented, the results would determine whether the initial assumption of immediate perfect mixing was valid.

This thesis has been concerned with the major hazard of explosions and the overpressure consequence. Another major hazard is that of fires and the thermal load imparted onto the structure. The factors controlling fires are similar to those presented in Chapter 3, as the influencing factors for explosions. The hydrocarbon release mechanisms are the same as those considered in the explosion model. The complex geometry offshore makes it difficult to model the length and speed of the flame due to distortion and the generation of turbulence. Although empirical models exist for determining the behaviour of flames, these work most effectively when the geometry is simple, the literature suggests that CFD is most effective when studying the effects of a fire. If correlations could be obtained for the flame movement and heat generated within the module then the SAROS code could be adapted to determine the frequency of a fire generating a specific thermal load occurring.
References


References


Appendix
A. Schematic diagrams of the sections on the platform.
Figure A.1: Section 1 - the atmospheric separator.
Schematic diagrams of the sections on the platform.

Figure A.2: Section 3 - the inlet separator.
Fig. 3: Section 4 - the low pressure scrubbers and compressors.
Schematic diagrams of the sections on the platform.

Figure A.4: Section 5 - the medium pressure scrubbers and compressors (stage 1).
Figure A.5: Section 6 - the medium pressure scrubbers and compressors (stage 2).
Figure A.6: Section 8 - the injection compressors.
Schematic diagrams of the sections on the platform.

Figure A.7: Section 9 - the wellhead and production header lines.
Schematic diagrams of the sections on the platform.

Figure A.8: Section 10 - the gas injection line.
Schematic diagrams of the sections on the platform.

Figure A.9: Section 11 - the gas lift line.