An experimental investigation of bund wall overtopping and dynamic pressures on the bund wall following catastrophic failure of a storage vessel

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An experimental investigation of bund wall overtopping and dynamic pressures on the bund wall following catastrophic failure of a storage vessel

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The Methodology and Standards Development Unit of the Health and Safety Executive (HSE) has commissioned Liverpool John Moores University (LJMU) to construct a laboratory facility and to conduct a series of tests simulating the sudden failure of a tank such as is used industrially for the storage of hazardous liquids. Such failures are rare. However, history has shown that when they do occur a large proportion of the liquid is likely to escape over the surrounding bund wall or embankment, even if the force of the wave impact does not damage the retaining structures. This report describes the background to the LJMU Project, describes the new test facility and records the results of the investigation. The results will be of value to HSE in the performance of its statutory duties, and may be of value to tank storage operators in their consideration of the extent and severity of foreseeable major accidents, in their risk assessments and in their consideration of reasonably practicable measures to reduce those risks.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.
Executive Summary

Tanks used for bulk storage of hazardous liquids are often completely surrounded by a wall or earth embankment with the aim of providing secondary containment for any spillage from the tank. If the walls of the bunded area have been designed, built and maintained in line with current standards then they will provide full containment of the more likely spills. But they will not contain the surge of liquid that would follow a catastrophic failure of the tank; even if the surge does not destroy the bund wall, the flood wave is likely to overtop it. Whilst catastrophic failure of bulk storage tanks is rare, the consequences for site personnel, any local community and the environment can be severe. Such accidents have occurred in the USA, in Greece and in Lithuania, for example.

Liverpool John Moores University (LJMU) has been commissioned by the Health and Safety Executive (HSE) to build a laboratory facility to perform simulations of catastrophic failure of a storage tank, covering a comprehensive range of tank and bund arrangements, and to measure both the dynamic pressures that are exerted on the bund wall and the quantity of liquid that overtops it. Charts or correlating functions were to be derived, allowing interpolation to other tank and bund arrangements.

Such data are foreseen to be of value both to HSE in the performance of its statutory duties and to the operators of tank storage facilities in their consideration of the extent and severity of foreseeable major accidents, in their risk assessments and in their investigation of reasonably practicable measures for reducing the risks.

This report describes the test facility and presents the results of around 100 catastrophic tank failure simulations.

On completion of the work for HSE, ownership of the test facility will pass to LJMU who plan to make the facility available, via suitable contractual arrangements, to third parties for study of general or specific problems.
1 INTRODUCTION

1.1 Background

The bunds or earth banks that commonly surround tanks used for storing hazardous liquids are often designed with a capacity equal to 110% of the capacity of the largest storage tank within the bund, the excess height being claimed in part to prevent liquid surging over the top of the bund following sudden failure of a tank. In reality, whilst a 110% capacity bund will contain the release for less extreme modes of failure, it is unlikely to do so for more extreme modes. A series of experiments reported in HSE Contract Research Report 405/2002, in which the contents of a model storage tank were released gently into a 110% bund over a period of 30 seconds, showed that the bund was overtopped in almost every case.

More severe modes of release would clearly give more overtopping. Fortunately, catastrophic failure of tanks used for storing hazardous liquids is rare. However, the consequences for site personnel, any local community and the environment can be severe. Such failures have occurred in the USA, in Greece and in Lithuania, for example. Specific examples are:

- Floreffe, January 1988 – failure of a 4 million gallon tank of fuel oil at Ashland Oil released a wave of oil that surged through the bunded area damaging another tank and overtopping the bund.
- Iowa, March 1997 – failure of a 1 million gallon tank of ammonium phosphate.
- Michigan, July 1999 – a 1 million gallon tank of ammonium polyphosphate ruptured and damaged three other tanks.
- Ohio, August 2000 – a 1 million gallon tank of liquid fertilizer ruptured and damaged nearby tanks. The resulting wave of liquid broke through a concrete bund and hit five tractor-trailer rigs, pushing them into the Ohio River.
- Ohio, August 2000 – later that month a 1.5 million gallon tank of ammonium phosphate ruptured at the same storage facility. It damaged three other tanks causing them to leak, with liquid overflowing the bund. A total of 450,000 gallons of contaminated water was reclaimed from the sewers and the public drinking water system was feared contaminated, resulting in the widespread use of bottled water as reported by the United States Environmental Protection Agency (2001).

An extract from the official report of the Pennsylvania State authorities and a photograph taken following the Ashland Oil tank failure are shown below.

<table>
<thead>
<tr>
<th>Storage Tank Collapse Sends 500,000 Gallons Of Diesel Fuel into Monongahela River</th>
</tr>
</thead>
<tbody>
<tr>
<td>On January 2 1988 a large aboveground fuel storage tank located in Floreffe Pennsylvania suddenly and without warning collapsed as its shell rent completely from base to roof. The tank collapse unleashed a tsunami of petroleum product as almost 3.9 million gallons of diesel fuel surged out of the failed structure. The crest of this wave washed over nearby earthen dikes, whose intended design for containing a gradual release of petroleum products left them pitifully inadequate to confront the force of this catastrophe. Another tank, almost one hundred feet distant, was crumpled and dented at the point of impact of the surging fuel, as if a low-flying airplane had struck it.</td>
</tr>
<tr>
<td>Source: <a href="http://www.dep.state.pa.us/dep/pa">http://www.dep.state.pa.us/dep/pa</a>_ env-her/ashland.htm</td>
</tr>
</tbody>
</table>
Ashland Oil Floreffe Pennsylvania*

On the basis of the historical record and other considerations, the Health and Safety Executive (HSE) uses a catastrophic failure probability of a few $10^{-6}$ per storage tank per year in its risk assessments. At this level of likelihood the possibility of catastrophic failure has to be considered.

With these matters in mind HSE commissioned Liverpool John Moores University (LJMU) to build a laboratory facility to perform simulations of catastrophic failure of a storage tank and to obtain appropriate data for a range of tank and bund configurations. This report describes the Project and presents its results.

1.2 HSE’s statutory duties

HSE has a statutory duty to advise local planning authorities on the location of new hazardous installations and on suitable uses of land in the vicinity of existing hazardous installations. To do this HSE often needs to estimate the effectiveness of the bunds around storage tanks holding large quantities of hazardous liquids. Prior to this Project overtopping data for catastrophic failure were available to HSE only from small-scale facilities, making them of doubtful value, and dynamic pressure data had not been obtained at all in any systematic way. It was foreseen that data from this Project would strengthen the technical basis of HSE’s judgements, and may allow less pessimistic assumptions to be made.

* Photograph source: http://www.epa.gov/superfund/programs/er/resource/d1_07.htm
HSE also has a statutory duty alongside the Environment Agencies as Competent Authority under the COMAH Regulations. As a part of this duty HSE must assess predictive aspects of COMAH safety reports. A failing of some such reports is the belief of their authors that because bunds satisfy current standards they do provide full secondary containment for all foreseeable failure modes; it follows that the estimates of the extent and severity of accidents in the reports may be seriously optimistic. It was foreseen that data from this Project would greatly strengthen the technical basis of HSE’s assessments. Moreover, data from the Project, when published, would provide tank storage operators with a means of assessing the current performance of their bunds, of assessing the extent and severity of accidents, and of considering the reasonable practicability of measures to reduce the risks.

Finally HSE is procuring computer programs to calculate liquid spreading and liquid/bund interaction using computational fluid dynamics. It was foreseen that data from this Project would guide the development of that software and be used in its validation.
2 CONSIDERATIONS INFLUENCING THE TEST FACILITY AND PROGRAMME

2.1 Representing tank failure in the laboratory

The failure mode in the event of a real tank rupture may be highly complex and involve the interaction between fracture propagation and the flow of a fluid with a free surface. For the purpose of the laboratory modelling described here the assumptions are made that the cracks propagate at a much higher velocity than that of the fluid motion, and that they propagate at the same time in the vertical and in the circumferential directions. Thus, the tank loses its integrity instantaneously and hence is considered to have disappeared as far as any containment is concerned. The condition at time zero of a cylindrical column of liquid free to collapse under gravity is clearly hypothetical, but it is a reasonable condition to assume as a bounding case for real events. It is an axisymmetric mode of failure, and it is an axisymmetric mode of failure that the tests described in this report represent.

An alternative mode of failure could be considered based upon the idea that the crack may propagate much faster in the vertical than in the circumferential direction, giving rise to a vertical section of the tank being removed and the liquid flowing directionally through the gap created. An asymmetric failure mode such as this would be expected to give an increased hydrodynamic loading on the bund in the vicinity of the break. However, this possibility has not been studied in this test programme. Data from earlier work suggest that overtopping fractions will be of similar order, but that dynamic pressures may be higher.

2.2 Characteristics of the new test facility

Over the years HSE has undertaken a number of experimental studies of bund overtopping, principally in its Health and Safety Laboratory (HSL) in Buxton. In 1997 an HSL report entitled ‘A Review of Data and Models Available for Estimating the Extent of Bund Overtopping’ by Thyer and Jagger examined the totality of the work, alongside known work performed outside HSE, and concluded that whilst much had been done the work was generally piecemeal and was in some cases not well recorded; in consequence it did not form the coherent and comprehensive picture that HSE required. It was this conclusion that led to the evolution of the new LJMU test facility.

An outcome of the 1997 review was a focussing on a particular set of overtopping experiments undertaken by Greenspan and Johansson at MIT in 1981. Greenspan and Johansson performed some fifty- laboratory simulations of a catastrophic failure of a storage tank located centrally within a circular surrounding bund. Their work has since formed the basis of derived overtopping correlations, described in more detail below. However, their model tank had a diameter of only about 8 inches, leading to a suspicion that their results would be influenced by frictional effects to an extent that made them not applicable to full-scale tanks. A requirement of the LJMU facility was that it should be sufficiently large that there should be no concern over scaling to full size.
Based on these considerations the new facility was to have:

- A suitably large scale to reduce friction and losses associated with smaller models.
- A tank and bund quadrant representing a quarter of an axisymmetrical release.
- A system to lift the tank very rapidly leaving a column of unsupported liquid able to slump freely under gravity.
- A set of dynamic pressure transducers fixed to the bund wall at various heights to record the dynamic pressures acting on the bund due to the liquid impact.
- Systems for measuring the quantity of overtopped liquid.

To meet these requirements it was decided that the tank bursts would be modelled using a single quadrant of space in the corner of a square spill table with sides 2 m long. The effects of any friction against the smooth acrylic sheets that would form the sides of the spill table were to be regarded as negligible for the geometry applied in the analysis of the results, when considering a complete tank and bund arrangement. The quadrant-tank would have a radius of 300 mm.

All tests were to be conducted using water at recorded ambient temperature and would consider only vertical inner-faced bunds. Most of the simulations would be with the bund plan forming a quarter-circle concentric with the quarter-tank. A few tests would be run for bunds of square or rectangular plan. Up to 100 different tank/bund combinations would be investigated.

Removal of the tank wall was to be as swift as possible in a vertical direction using a repeatable method of operation. The target time to clear the bottom half of the model tank height, thus clearing the expected depth of the escaping wave was set at 0.1 seconds. The effects of drag on the water were to be assessed and minimised as far as possible, by application of a suitable coating to the inner tank wall if necessary.

The overtopping fractions were to be determined using measurements of mass, both the mass retained within the bund and the mass overtopping the bund. A series of trials were to be run to investigate the repeatability of the test method employed and to determine the number of test runs required to produce reliable data. A number of dynamic pressure measurements were to be taken at various bund heights to determine peak values and to study isochrones for the pressure distribution over the height of the bund. A statistical analysis of the results was required to determine the distribution of the values obtained for the variables measured (Agreement No. D4501, 2002).
2.3 Characteristics of the test programme

During the conceptual phase of development of the new test facility HSE undertook a survey of the storage tanks and bunding arrangements at sites where it may be required to give land-use advice or to assess operator’s safety reports. With the results of this survey in mind the test programme was designed to embrace:

- Radius of model tank, R: single radius of 300 mm
- Height of water in tank, H: three ratios of (R/H): 0.5, 1.0, and 2.5
- Height of bund wall, h: to cover (h/H) ranges from 0.05 to 0.4 and 1.0 to 1.2
- Radius of bund wall, r: to cover the range of total bunded volumes from 110% to 200% of the volume of water in the tank.

The nomenclature used for describing a ‘circular’ bund configuration is shown below, and the agreed test matrix for ‘circular’ bunds is reproduced in Appendix 1.

![Figure 2.1 Tank and bund nomenclature for circular geometry](image)

For the bunds with ‘rectangular’ geometries the key question to be addressed is whether a non-circular bund is systematically better or worse than a circular bund of the same area and height. The basis for testing was to use the 110% bund capacity results from the circular configurations and identify the bund arrangement that gave the closest to 50% overtopping for each tank type.

The tests were then to be repeated with the bund plan changed from circular to square, keeping the bund capacity at 110%. Using symmetry in the quadrant of space there are two possibilities, one where the bund forms a 45° diagonal and one the bund consists of two equal walls parallel to the walls of the rig. Assuming no edge effects in the rig, then the two geometries should give similar values in overtopping. A rectangular bund with length/breadth = 2 was the final arrangement to be considered, again using the criteria as in the case of the square bund. In the case of the square and rectangular bunds small radii, $r_c = 12$ mm were used at the corners for fabrication purposes and to better introduce the threaded needle connectors of the dynamic pressure transducers.
In the case of the triangular bunds the dynamic pressure transducers were placed at mid-span, with the square and rectangular bunds having the sensors located at the corners.

The agreed test matrix for ‘rectangular’ bunds is also shown in Appendix 1.
3 THE TEST RIG AND EXPERIMENTAL PROCEDURES

3.1 Scope

A water table was constructed together with a working model of a tank quadrant to simulate a catastrophic tank failure. The scale of the model used was to be large enough to overcome problems of excessive frictional effects, which could be detrimental to the results in terms of underestimating the level of overtopping. The type of tank failure modelled was to simulate a quadrant (90°) of a cylindrical column of liquid collapsing under gravity within the secondary containment and can be considered to represent an axisymmetric mode of failure once transposed to 360° geometry. The tank quadrant was removed by accelerating it upwards using a power spring at an initial rate of 250 m/s² based upon a 440 mm extension with a stored force of 800 N accelerating a mass of 3.2 kg, allowing water to rapidly escape. Using the average force in the power spring of 560 N at half the extension over the total distance travelled a mean upwards velocity of 12.41 m/s is obtained using Newton’s Laws of Motion. The velocity of the gate was measured using a magnetic pick-up connected to an oscilloscope, giving a peak to peak time of 8x10⁻³ sec for a screw pitch of 1 mm, leading to a mean upwards velocity of 12.5 m/s. The initial fluid height in the tank and the wave height at the bund were recorded by capacitance data. The overtopping fraction and volume of fluid retained in the bund were determined using as well as written to file for further processing in other software packages. Statistical analysis of the data was undertaken and dimensionless ratios were used to construct charts and correlating functions for the determination of overtopping fractions. The data from the dynamic pressure sensors was used to calculate the dynamic pressure profiles on the bund walls themselves and compare them to the hydrostatic profiles used for current design purposes. Additional data from the wave probes was used to help interpret the action of the overtopping waves in relation to the maximum dynamic pressures.

A series of model bund walls of various heights and placements and incorporating dynamic pressure sensors were fixed to the spill table with a second capacitance probe used to record the overtopping wave height. An investigation into the repeatability of the tank bursts and levels of overtopping was carried out to determine a suitable operating procedure for obtaining consistent data. The overtopping fraction and volume of fluid retained in the bund were determined using mass balances after collecting the fluid through a drainage point in the tank and using an industrial ‘aqua vac’ for the fluid overtopping the bund. The data collected was input into a computer via RS-232 interfaces and entered into a PDA for immediate statistical analysis.

Raw data for the dynamic pressures and the wave profiles was collected via a computer controlled National Instruments SCXI data logger used in conjunction with Labview virtual instrumentation software. The graphical programme written as part of this research enabled ‘real time’ visual data to be displayed on a computer screen as well as written to file for further processing in other software packages. Statistical analysis of the data was undertaken and dimensionless ratios were used to construct charts and correlating functions for the determination of overtopping fractions. The data from the dynamic pressure sensors was used to calculate the dynamic pressure profiles on the bund walls themselves and compare them to the hydrostatic profiles used for current design purposes. Additional data from the wave probes was used to help interpret the action of the overtopping waves in relation to the maximum dynamic pressures.

3.2 Materials used in construction

The model tank wall, support frame, bearing rails and fittings for the swinging compression latching bar mechanism were all constructed from stainless steel, with the swinging arms made from lightweight aluminium tube. The power spring, effectively a giant rubber band was supplied by a manufacturer specialising in multi strand elastomeric material capable of delivering a high load to extension relationship with good repeatability and sustained durability.
The main tank and spill table were manufactured using mild steel for the structural frame, with marine ply for the base of the spill table and two of the sides. The other two remaining sides were produced using laminated safety glass to enable video footage to be filmed through the main tank. One of the ply sides and one of the glass sides were then lined with Perspex to allow setscrews to be used for the bund wall fixings. The model bund walls were produced from polycarbonate to allow for the degree of bending required to form the smaller radii and to resist the impact loading produced by the rapidly released fluid.

3.3 Design considerations

The final design details were chosen for speed and ease of construction with as much as possible of the work performed in-house. Where equipment and tooling limitations existed, as in the manufacture of the tank quadrant and the frame incorporating the linear bearing rails, work was subcontracted to local specialist engineering companies. The resulting test rig design could thus be easily maintained in house with parts likely to be subject to wear and tear reproduced and installed relatively quickly, keeping any project delays to a minimum.

A number of design considerations led to the development of a basic model concept with three different methods of powering and triggering the rapid removal of the tank quadrant. Firstly a double acting arrangement of elastomeric power springs was considered using a twin catch release mechanism operated by a cam arrangement.

* Photograph source: LJMU
This also incorporated a spring loaded latching system to prevent the tank quadrant from returning back down the bearing runners at high speed. Secondly, the same power spring arrangement was designed to be used in conjunction with a dual catching mechanism operated by a lever system. In the second case the non-return catching system was to be constructed using a ‘butterfly’ type spring opening mechanism designed to latch through a hole in the tank quadrant-loading beam.

The final design, which was the one eventually constructed, used only a single power spring to accelerate the tank quadrant and a ‘bungee’ cord to decelerate it before contracting a pair of safety compression spring buffers. The single power spring was extended using a mechanical bed winch once the tank quadrant had been locked and securely held in place by a swinging compression-latching bar. The ‘firing’ mechanism was designed to operate via a bicycle hand brake lever pulling down a spring-loaded stainless steel release pin running through a plain bronze bearing. The movement of the release pin allowed the swinging arm to move back, thus jumping off the roller bearing retaining bar on the tank quadrant, hence leading to the required rapid release of the contained liquid.

The resulting design gave rise to the required rapid removal of the tank quadrant and the standing head of liquid specified in the initial brief. Video footage was taken to show the tank side removal in an upward direction and to see the liquid released fall under gravity.

* Photograph source: LJMU
3.4 Instrumentation

The brief required the determination of the dynamic pressure profiles on each of the bunds under test and in order to facilitate this, piezotronic type pressure transducers were incorporated at predetermined percentage heights for each bund. Kistler type 211B5 pressure transducers were selected, powered by a type 5134A power supply/coupler.

Model 211B5 series piezotron pressure transducers are miniature, acceleration compensated instruments, which produce a high level, low impedance signal that is the voltage analogue of dynamic pressure input. Resolution is in the order of one part per 20,000 of full-scale range, in other words plus or minus 34.5 Pa for a 0 to 100 psi transducer. These transducers incorporate sensing elements of crystalline quartz and contain a solid-state impedance converter with sensitivity expressed in millivolts per unit of pressure. The acceleration compensation is required as the mass of the diaphragm and sensing element produces an inherent acceleration sensitivity, which is eliminated by the embodiment of a quartz accelerometer whose output polarity is opposite to that of the pressure-sensing element. Thus, the accelerometer output nominally cancels or nulls what would otherwise be a component of the sensing element output attributed to the acceleration (Kistler Universal Pressure Transducer Manual).

*Photograph source: LJMU*
The wave monitoring equipment was supplied by Churchill Controls and comprises two probes and a wave monitor module. One probe was placed inside the tank quadrant to record the level as the tank emptied, the other being positioned adjacent to the inner face of the bund wall to monitor the wave height at the bund.

The system works on the principle of measuring the current flowing in a probe, which consists of a pair of stainless steel wires. The probe is energised with a high frequency square wave voltage to avoid polarisation effects at the wire surface. The wires dip into the water and the current that flows between them is proportional to the depth of immersion. The current is sensed by an electronic circuit, which provides an output voltage proportional to the instantaneous depth of immersion, or wave height, which can be used as input to a high-speed data logger (Churchill Controls Wave Monitor Manual).

The mass of the fluid overtopping the bund and the mass of the fluid retained by the bund were measured using Adam Equipment RFC/L series platform scales, one for each side of the bund. The capacity of each scale is 100 kg with readability of 10 g, the output received over the RS-232 interface. The balance data was then logged using A&D software and saved to file for later use in an Excel spreadsheet.

The speed of operation of the tank quadrant was determined using a fixed magnetic pick-up and a length of mild steel threaded studding of known pitch moving along with the tank quadrant. The device responds to the movement of ferrous parts past the pole-piece on the end of the unit. The passive nature of the device requires no external power and yields an output voltage in response to variations in a self induced magnetic field caused by proximity to moving ferrous metal parts. The output from this device was input into an oscilloscope and the time based used to determine the time between successive peaks on the 1mm pitch threaded studding.

* Photograph source: LJMU
The data logger used for data collection from the pressure transducers and the wave monitoring probes was a National Instruments SCXI 1000 chassis with an SCXI 1200, 12 bit A to D converter with SCXI 1121 amplifier modules and SCXI 1321 terminal blocks. The data logger was then in turn connected to a computer and controlled through the use of Labview virtual instrumentation software, which is user programmable via a graphical programming language.

The resolution of the signals from the dynamic pressure transducers and the wave monitoring probes depends upon the gain used on the SCXI 1121 amplifier modules. For a chosen amplifier gain of 10 the resolution is 29 Pa/bit, for a gain of 100 this changes to 2.9 Pa/bit and for a gain of 200 this becomes 1.45 Pa/bit. A gain of 1 was used throughout for wave monitoring probes, with the probe length changing from 950 mm with a resolution of 0.29 mm/bit to 475 mm with a resolution of 0.145 mm/bit, depending upon the height of bund under test (see appendix 1).

Video footage was recorded for each of the bund configurations under test; the footage was then transferred to computer using video editing software. The video recordings were then used to monitor the movement of the tank quadrant and the subsequent motion of the fluid under the action of gravity as it approached and overtopped the bund.

### 3.5 Trials

A number of trials were undertaken to check the repeatability of the test rig operation and ensure each test run could be repeated giving a reasonable spread of data for each configuration. One of the bund configurations was chosen for the trials and the experiment was repeated 30 times to analyse the spread of data in terms of the mass of the fluid overtopping the bund and the mass of the fluid retained within the bund (see appendix 2).

Checks were also made with respect to the maximum dynamic pressure measured upon impact with the bund. By calculating the mean values and plotting the spread of the retained and overtopping data it was decided that the results gave rise to a normal distribution with very little spread. This is clearly indicated by the sample standard deviation. Hence it was decided to limit the test runs to five per configuration, as most of the results were close to the mean. Variation in the level of fill for the tank quadrant was also monitored with measured values falling below the theoretical values by approximately 3% in the worst case.

The main component where variation in operational repeatability was most likely was the power spring. The high number of operations made it susceptible to wear and tear and its performance would have to be checked on a regular basis. Two methods were employed for this: -

1). For quick checks, a load cell could be incorporated into the system to check the load extension characteristics.

2). For calibration purposes, a dead loading rig was used to plot the load extension curve for the power spring and comparisons made to previous tests. The performance of the power spring was most satisfactory, even though some minor damage to the outer sheath became visible with repeated operations.
4 RESULTS

4.1 Data processing

The data collected from each test run were imported into a Microsoft Excel spreadsheet for statistical analysis. For each configuration examined the maximum, minimum, mean and sample standard deviation for the masses overtopping the bund and retained by the bund in each of the five test runs were calculated to check the spread of the data about the mean. The spread was found to be small, usually within 1% of the mean. The maximum value of the overtopping fraction, Q, over the five test runs was taken forward as the overtopping fraction for the configuration.

Dynamic pressures and fluid heights were plotted against time to allow comparison of results and permit the evaluation of values such as the average speed of the approaching wave. The dynamic pressure profiles were plotted and the maximum dynamic pressure at the base was estimated using linear extrapolation of the signals from the two sensors nearest to the base. The majority of tests had these sensors at 10% and 30% of the bund height, but the physical size of the sensors meant that for bund heights of 36 mm and below different heights had to be used. The extrapolation is therefore less reliable for the lower bunds (and indeed is not available for the 6 mm bund as only one sensor could be used in that case). The sensor positions are recorded in Table 1.3. The extrapolated pressure could then be compared to the wave height measured at the bund in the vicinity of the transducers.

Full results for the ‘circular’ configurations are given in Appendix 3. For each of the 84 configurations studied the Appendix shows a Table of measured parameters in each of the five test runs and their statistical analysis, followed by a Table showing extrapolation of the worst-case dynamic pressures and their analysis alongside wave heights, followed finally by Excel Charts showing variation of pressures and fluid depths against time, and of best-fit curves to the pressure data.

Similar tables are shown in Appendix 4 for each of the 9 ‘rectangular’ configurations.

A summary of all the results is given in Table 4.0, with additional detail in Tables 4.1 to 4.7. Tables 4.1 to 4.6 also contain the predictions of a number of theoretical overtopping correlations, with which comparisons are later made.

4.2 Overtopping

A comparison between the total overtopping and the overtopping due to the first wave impact was also considered and an experimental procedure developed to investigate the relationship. By repeating the same tests, only this time suddenly opening the tank drain before any reflected wave could overtop the bund, a series of first wave overtopping results were obtained. The values were compared and it was found that a reduced overtopping fraction resulted, indicating that 94 to 95% of the total overtopping takes place with the impact of the first wave (see appendix 2).
4.3 Dynamic pressures

An estimate of the maximum dynamic pressure at the base of the bund was obtained by extrapolating the pressure profiles, and comparisons were then made with the pressures that would apply if the bund were just full of static water. For the non high-collar bunds, it was found that the actual pressure experienced in the event of a catastrophic failure was higher than that normally employed for design purposes. For high-collar bunds the dynamic pressures were lower than the static pressure.

Further comparisons between the fluid levels and the maximum dynamic pressures led to the investigation of the crossover points (that is, the moment in time when the fluid level in the tank and that at the bund are equal) and the instantaneous pressure heads corresponding to the positions of local maxima. The wave-monitoring probe was repositioned to be as close as possible to the dynamic pressure transducers in order to obtain more accurate correlations.

As work progressed it was consistently apparent that the maximum wave height did not correspond to the timings or magnitudes of the maximum dynamic pressures. Video footage allowed an upward and forward momentum to be identified along with the formation of a separation layer, which having a higher energy level, starts to rapidly rise upwards and forwards to leave the main body of fluid.

High-speed camera footage was used to further confirm the behaviour of the fluid at the point of contact with the bund. The same characteristics were observed with the separation layer further forming droplets flying through the air. It is therefore concluded that the full wave height, including the separation layer does not fully contribute to the maximum dynamic pressure at the base of the bund wall.

The ratios of maximum dynamic pressures to hydrostatic pressure obtained in this work are mostly in keeping with the results reported by Trbojevic and Slater (1989), where a ratio of 2.5 is quoted for a typical liquefied fuel gas and a ratio of 3.5 for Diesel fuel. The LJMU work has, however, shown much higher values in some cases, generally for the lower bunds. The values for lower bunds may have been exaggerated by the need to extrapolate data from sensors whose placement was not ideal, and it has to be noted that the dynamic pressures obtained in nominally identical tests showed a substantial variability. Other workers have stated higher values than did Trbojevic and Slater, for example Cuperus (1980) quoted a ratio of 6, but the pedigree of the Cuperus data is unknown. The ratios obtained by LJMU are shown in the “Summary of Results” Tables, in the column headed “Dyn/Stat$_{base}$”.

Impact velocities shown in Appendix 3 for circular bunds and in Appendix 4 for rectangular bunds are calculated from Newton’s Laws of Motion considering the fluid to be accelerated uniformly from rest over a known distance in known time. There are inherent inaccuracies in the calculation of velocities, as the horizontal acceleration is not uniform as the standing head of fluid falls and spreads over the bunded area and friction acts to slow the motion, especially over the larger distances travelled. The transit times are also shown and these are more reliable as they are inferred directly from the recorded data.
4.4 Comparison with published overtopping correlations

Earlier studies, principally those of Greenspan and Young (1978) and Greenspan and Johansson (1981), led to a conclusion that simple formulae to estimate the overtopping fraction could probably be based on dimensionless combinations of parameters:

\[
Q = Q\left(\frac{h}{H}, \frac{r}{H}, \frac{R}{H}, \theta\right)
\]

with h/H as the main variable and r/H, R/H and the angle of inclination of the bund, \(\theta\), as subsidiary parameters.
Recently, two sets of workers have proposed such functions based on the small-scale test data of Greenspan and Johansson.

Clark (2001) put forward the following relationship to predict the overtopping fraction, $Q_C$:

$$Q_C = \exp\left[-p \times \left(\frac{h}{H}\right)\right]$$  \hspace{1cm} (4.1)

where $p = 3.89$ when $\theta = 90^\circ$. Generally, it was found that the overtopping fraction $Q_C$ and the relationship with $h/H$ held true over the range $0.33 \leq (r - R) / R \leq 4$.

Independently, Hirst (in Thyer et al, 2002) derived formulae fitted to the same test data to predict the overtopping fraction, $Q_H$:

$$Q_H = A + B \times \ln\left(\frac{h}{H}\right) + C \times \ln\left(\frac{r}{H}\right)$$  \hspace{1cm} (4.2)

where $A = 0.044$, $B = -0.264$ & $C = -0.116$ for $\theta = 90^\circ$.

Both the Clark correlation and the Hirst correlation gave good fits to the data of Greenspan and Johansson on which they were based. However, as the test data did not include high collar bunds, neither Clark nor Hirst claimed that their functions could be used for such cases. Moreover, the Greenspan and Johansson tests were performed at very small scale so may systematically underestimate the overtopping fraction. The performance of both equations (4.1) and (4.2) are tested in this research against the newly obtained test data. Failure to perform well would indicate a systematic difference between the small-scale test data and the new LJMU data.

The LJMU results are separated into three groups corresponding to different levels of tank fill and called “squat”, “medium” and “tall”. To allow comparisons a number of common, important, non-dimensionalised variable were adopted. For each group a plot of overtopping fraction against $h/H$ was produced and comparisons made with the Clark and Hirst overtopping correlations (Charts 4.3, 4.6 and 4.9).

Considering the plot of overtopping fraction against $h/H$ for squat tanks, the Clark correlation seems to be in keeping with most of the LJMU test results, however, at lower ratios of $h/H$ and higher bund containment ratios, the Hirst correlation is better.

For medium tanks, both correlations show general agreement with the test results.

For tall tanks, the Clark correlation most closely fits the test results, with both Clark and Hirst correlations approaching the test results at smaller values of $h/H$. 
4.5 Multivariate curve fitting

New correlations have been derived by LJMU to fit the LJMU test results. The functions

\[ Q = A \times \exp[-B \times (h/H)], \]

with \( A \) and \( B \) taking the values shown below, are recommended. This is of the same form as the Clark correlation. The range of validity is \( 0.66 \leq (r - R)/R \leq 5.32 \). It should be noted that high-collar bunds are excluded from the range of validity, as the overtopping fraction is negligible, usually less than 5%. Omitting the high-collar bunds improves the quality of fit for the smaller bunds at greater radii, where frictional forces start to affect the result.

<table>
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<th>Bund capacity (%)</th>
<th>A</th>
<th>B</th>
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<td>150</td>
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<tr>
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<td>200</td>
<td>0.1824</td>
<td>0.4972</td>
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<td>Middle</td>
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<td>Tall</td>
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<td>200</td>
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<td>3.5240</td>
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Plots are shown in Charts 4.1, 4.2, 4.4, 4.5, 4.7 and 4.8.

4.6 Presentation of overtopping results

In the “Summary of Results” Tables below the column headed “\( Q \)” shows the measured overtopping fractions, those headed \( Q_h, Q_C, \) and \( Q_H \) show the overtopping fractions predicted using the correlations of LJMU, Clark and Hirst respectively.

Graphical comparisons are made in Charts 4.1 to 4.9.
## Table 4.0 Short summary of all results

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<th>R = 300 mm</th>
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<td>h(mm)</td>
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19
Table 4.1 Summary of results for squat tank releases (110% and 120% nominal bund capacity)

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<tr>
<th>h (Θ=90°)</th>
<th>h/H (mm)</th>
<th>r/H (mm)</th>
<th>r/R (mm)</th>
<th>L (mm)</th>
<th>V_cap (m^3)</th>
<th>V_cap/V_rel</th>
<th>V_bund (m^3)</th>
<th>V_slosh (m^3)</th>
<th>V_bund + V_slosh (m^3)</th>
<th>Q (Pa)</th>
<th>Q_f (Pa)</th>
<th>Q_c (Pa)</th>
<th>Q_H (Pa)</th>
<th>Dyn_base (Pa)</th>
<th>Stat_base (Pa)</th>
<th>Dyn/Stat_base</th>
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<table>
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<tr>
<th>h (Θ=90°)</th>
<th>h/H (mm)</th>
<th>r/H (mm)</th>
<th>r/R (mm)</th>
<th>L (mm)</th>
<th>V_cap (m^3)</th>
<th>V_cap/V_rel</th>
<th>V_bund (m^3)</th>
<th>V_slosh (m^3)</th>
<th>V_bund + V_slosh (m^3)</th>
<th>Q (Pa)</th>
<th>Q_f (Pa)</th>
<th>Q_c (Pa)</th>
<th>Q_H (Pa)</th>
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<th>Stat_base (Pa)</th>
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<td>$Q_C$</td>
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Table 4.2 Summary of results for squat tank releases (150% and 200% nominal bund capacity)
Chart 4.1 Test results and LJMU correlations for overtopping for squat tank releases

Plot of Experimental Q against h/H for R/H = 2.5

- $y = 0.5789e^{-2.0818x}$, $R^2 = 0.9495$
- $y = 0.5193e^{1.9671x}$, $R^2 = 0.9484$
- $y = 0.3978e^{-2.0051x}$, $R^2 = 0.8824$
- $y = 0.1824e^{-0.4972x}$, $R^2 = 0.1262$
Chart 4.2 Performance of LJMU correlations for squat tank releases

Plot of fitted $Q_f$ against experimental $Q$ for $R/H = 2.5$
Chart 4.3 Test results versus Clark and Hirst correlations for squat tank releases

Plot of Predicted $Q_C$ & $Q_H$ against $h/H$
for $R/H = 2.5$
### Table 4.3 Summary of results for middle tank releases (110% and 120% nominal bund capacity)

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<tr>
<th>r (mm)</th>
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<th>V slosh (m$^3$)</th>
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<th>Q f</th>
<th>Q C</th>
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### Table 4.4 Summary of results for middle tank releases (150% and 200% nominal bund capacity)

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<th>r/R</th>
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<th>V(<em>{\text{cap}/V</em>{\text{rel}}})</th>
<th>V(_{\text{band}}) (m(^3))</th>
<th>V(<em>{\text{band}+V</em>{\text{slosh}}}) (m(^3))</th>
<th>Q (m(^3)/s)</th>
<th>Q(_f) (m(^3)/s)</th>
<th>Q(_C) (m(^3)/s)</th>
<th>Q(_H) (m(^3)/s)</th>
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<th>r/R</th>
<th>L (mm)</th>
<th>V(_{\text{cap}}) (m(^3))</th>
<th>V(<em>{\text{cap}/V</em>{\text{rel}}})</th>
<th>V(_{\text{band}}) (m(^3))</th>
<th>V(<em>{\text{band}+V</em>{\text{slosh}}}) (m(^3))</th>
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<th>Q(_f) (m(^3)/s)</th>
<th>Q(_C) (m(^3)/s)</th>
<th>Q(_H) (m(^3)/s)</th>
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Chart 4.4 Test results and LJMU correlations for overtopping for middle tank releases

Plot of experimental Q against h/H for R/H=1.0

- $y = 0.7588e^{-2.3529x}$; $R^2 = 0.959$
- $y = 0.7306e^{-2.3834x}$; $R^2 = 0.9488$
- $y = 0.6359e^{-2.4451x}$; $R^2 = 0.9307$
- $y = 0.4814e^{-2.1866x}$; $R^2 = 0.9091$

Legend:
- ▲ 110%
- + 120%
- - 150%
- □ 200%
- Expon. (110%)
- Expon. (120%)
- Expon. (150%)
- Expon. (200%)
Chart 4.5 Performance of LJMU correlations for middle tank releases

Plot of fitted $Q_f$ against experimental $Q$
for $R/H = 1.0$
Chart 4.6 Test results versus Clark and Hirst correlations for middle tank releases

Plot of predicted $Q_C$ & $Q_H$ against $h/H$ for $R/H=1.0$
Table 4.5 Summary of results for tall tank releases (110% and 120% nominal bund capacity)

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<th>Q&lt;sub&gt;c&lt;/sub&gt;</th>
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Table 4.6 Summary of results for tall tank releases (150% and 200% nominal bund capacity)

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$h (\Theta=90^\circ)$ | $h/H$ | $r$ | $r/H$ | $r/R$ | $L$ | $V_{cap}$ | $V_{band}$ | $V_{slosh}$ | $V_{slosh}+V_{band}$ | $Q_f$ | $Q_C$ | $Q_H$ | $Dyn_{base}$ | $Stat_{base}$ | $Dyn/Stat_{base}$ |
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$h (\Theta=90^\circ)$ | $h/H$ | $r$ | $r/H$ | $r/R$ | $L$ | $V_{cap}$ | $V_{band}$ | $V_{slosh}$ | $V_{slosh}+V_{band}$ | $Q_f$ | $Q_C$ | $Q_H$ | $Dyn_{base}$ | $Stat_{base}$ | $Dyn/Stat_{base}$ |
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Chart 4.7 Test results and LJMU correlations for overtopping for tall tank releases

Plot of Experimental Q against h/H for R/H=0.5

\[ y = 0.8873e^{-3.1682x} \quad R^2 = 0.984 \]
\[ y = 0.8942e^{-3.4692x} \quad R^2 = 0.9799 \]
\[ y = 0.8244e^{-3.4712x} \quad R^2 = 0.9794 \]
\[ y = 0.7369e^{-3.524x} \quad R^2 = 0.9703 \]
Chart 4.8 Performance of LJMU correlations for tall tank releases

Plot of fitted $Q_f$ against experimental $Q$
for $R/H = 0.5$
Chart 4.9 Test results versus Clark and Hirst correlations for tall tank releases

Plot of Predicted $Q_C$ & $Q_H$ against $h/H$
for $R/H=0.5$
### Table 4.7 Summary of results for all tank releases for rectangular geometry bunds (110% nominal bund capacity)

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<th>V_cap/Vrel</th>
<th>V_bund (m³)</th>
<th>V_bund/Vrel</th>
<th>V_slosh (m³)</th>
<th>V_bund+V_slosh (m³)</th>
<th>Q (Pa)</th>
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<th>y/H (mm)</th>
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<th>V_cap/Vrel</th>
<th>V_bund (m³)</th>
<th>V_bund/Vrel</th>
<th>V_slosh (m³)</th>
<th>V_bund+V_slosh (m³)</th>
<th>Q (Pa)</th>
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5 DISCUSSION

5.1 Overtopping

The results from the overtopping measurements are consistent for each test configuration and indicate a serious problem if full secondary containment is to be relied upon in the event of a catastrophic tank failure. This is in direct agreement with similar results found by other researchers, where large overtopping fractions have been found both experimentally and by computational methods.

A conclusion from earlier work, supported by the new work, is that the fraction that escapes the confines of the bund is mainly a function of $h/H$ and generally increases if $h/H$ is reduced and the bund moved further away from the tank to maintain the same bund volume. However, a feature seen in the new work is that beyond a certain point the overtopping fraction begins to decrease. This is believed to be because surface friction begins to affect the results at larger spreading distances.

With regard to the height of the overtopping wave, the level to which the main body of fluid reaches is in some cases higher than the original tank level prior to release. A main feature of the breaking wave is the separation layer that develops giving rise to the flight of droplets from the leading edge or crest of the wave as indicated in the video capture photograph in section 4. The height these droplets can attain generally reaches a level at least three times the original tank level, with the smallest droplets travelling even higher, especially in the case of the high collar bunds. The vertical nature of the bund face contributes greatly to this effect, as the forward horizontal momentum of the fluid is violently interrupted and a sudden change in the direction of the fluid takes place as it rapidly accumulates behind the bund, eventually surging upwards and forwards over the bund.

Reflected waves contribute to the final overtopping fraction, however this has been shown to be minor with impacts after the first one accounting for only 5 to 6% of the total, as in the case of the initial trials configuration (see appendix 2). Greenspan and Young (1978) also found that 5% of the total overtopping was from sloshing after the initial impact. The action of these ‘sloshings’ becomes more significant when $(r – R)$ is small and $h$ is large as in the case of high collar bunds, however no attempt was made to quantify this.

Comparison between the smaller scale Greenspan and Johansson test data and test data obtained by JMU for overtopping suggests a good level of agreement with slightly more scatter associated with the squat tank results, particularly at greater separation distances. An improved level of agreement for overtopping is observed in the case of both middle and tall tank releases, again with some scatter occurring at larger separation distances in the case of the middle tank results. It therefore seems that the effects of scale are not overly apparent in terms of the overtopping results, which is interesting as the effects of friction at smaller scales should lead to slightly smaller overtopping fractions.

The ‘square’ and ‘rectangular’ bunds investigated had overtopping fractions very similar to those of ‘circular’ bunds with the same area and height, slightly greater (52-55% versus 49%) for a squat tank, slightly smaller (47-50% versus 52%) for a middle tank, and in good agreement (48-50% versus 49%) for a tall tank.
5.2 Dynamic pressures

It is clear from the results in this report and from work carried out by previous researchers that the current design for bunds is in question with respect to containment of spillage from a sudden catastrophic failure of the primary storage. The problem of overtopping is not the only issue and the actual mechanical integrity of the bund is also in question when the magnitudes of the dynamic pressures are considered. The dynamic pressure profiles obtained in the experimental results are very different than those used in the normal hydrostatic design, being of generally greater magnitude but shorter duration. Structural response calculations would be needed to determine the significance, but there is a prima facie possibility of the collapse of the bund leading to a total failure of the secondary containment to retain any of the fluid released.

The results from the dynamic pressure transducers take a little interpretation in terms of identifying true signals and those generated by the impact of the overtopping waves striking the sensor bodies and cables. Comparison with video footage using frame-by-frame analysis was used to confirm the timings of the wave impacts and identify the time periods to be used for sampling. Data logger gains were selected to ensure that sensible signals were within the ranges selected, thus avoiding any signal truncation due to excessive voltages. The largest dynamic/static pressure factors are found in the case of the smaller bund heights $h$, at the larger bund radii $r$, for each of the nominal bund capacities of 110%, 120%, 150% and 200%. These configurations also give rise to the largest overtopping fractions indicating the obvious relationship between the overtopping fraction and the associated dynamic pressures exerted on the bund. Upon examination of the local dynamic pressure maxima and static pressure profiles it can be seen that when the plot of dynamic pressure values falls below that of the static values, then overtopping fraction is reduced, the larger the difference the smaller the volume of fluid escaping the bund. Conversely, with dynamic values falling above the static pressure plot, the level of the overtopping fraction is increased, with large deviations leading to significant fluid loss over the bund. At the point where the difference in the envelope of bund pressure maxima is at a minimum i.e. the dynamic pressure profile is close to that of the static profile, then the overtopping fraction is at a minimum for non-high collar bunds. This corresponds to $h = 48$ mm for squat tank releases, $h = 120$ mm for middle tank releases and finally $h = 240$ mm for tall tank releases. This may be as expected in terms of overtopping, however a direct link between the overtopping fraction and the dynamic pressures is now clearly established. In the case of high collar bunds, the dynamic/static ratios are all less than 1 and hence have the smallest overtopping fractions, as would be expected.

The ‘rectangular’ bunds gave mixed results in terms of the dynamic pressures calculated at the base. In the case of the triangular configuration, the dynamic pressure was lower than that calculated for the circular equivalent for squat tanks but larger for middle and tall tank releases. The square configuration again gave a lower result than the circular for the squat tanks, but higher results for middle and tall tanks. Finally, the rectangular bund gave a lower result for the squat tank releases, but higher for middle and tall tanks when compared to their circular equivalents.
5.3 Wave heights

The wave monitoring probes have inherent problems with respect to establishing constant datum positions and hence were calibrated against initial tank fill levels for each test using Excel. These datum variations were due to temperature changes and the build up of contamination on the stainless steel probes. Other problems were experienced with the high collar bunds, as the reading from the probe located at the bunds tended to give wave heights in excess of the probe length. This was due to the large amounts of spray formed and the electrical connections at the probe being compromised. The results from the probes are useful in terms of determining the time between fluid release and initial impact with the bund, as the probe separation distance corresponds to the bund radius, \( r \), this enables the average velocity of the wave to be estimated. In the case of this investigation these velocities have been calculated in terms of impact velocities with the distance travelled calculated from the tank wall directly to a point at the bund. The probes were also useful in allowing the investigation of the point of intersection, where the falling tank contents level is equal to that accumulated at the inner face of the bund. An estimate of the maximum wave height at the bund was also possible giving a comparison with the dynamic pressure at the base of the bund.

Assuming the dynamic pressure consists of an instantaneous hydrostatic head and an associated velocity head an estimate can be made of the maximum instantaneous hydrostatic head using the maximum wave height at the bund. A number of areas of interest were highlighted by the results from the wave monitoring probes including the apparent relationship between the position of the point of intersection for equal tank and bund wave heights and the position of the maximum dynamic pressures with respect to time. This relationship is particularly true in the case of the non-high collar bunds, where the positions of the maximum wave heights at the bunds lag the positions of the maximum dynamic pressures.

Examination of the video footage in slow motion led to the observation that the hydrostatic element of the maximum dynamic pressure due to the instantaneous height of fluid occurred due to a mass of fluid building at the bund, prior to the formation of the separation layer as the surge moved upwards and forwards overtopping the bund. Hence the maximum wave height consists of an element of fluid, which has upwards and forwards momentum eventually forming the separation layer, leading to the expulsion of elongated fingers of fluid and finally the ejection of droplets. As is the case with the “crown” of liquid formed by a single droplet splashing onto a surface or into a liquid pool.

The nature of the wave impact means that the full height of the wave does not contribute to the instantaneous hydrostatic element of the maximum dynamic pressure, as only part of the height has a gravitational component at that instant in time. The part of the wave with the gravitational component corresponds to the point of intersection of the fluid height in the tank and the developing wave at the bund, where both levels are equal. This means that the potential energy due to the level in the tank is equal to that of the wave building at the bund just prior to the formation of the observed separation layer.

With respect to high collar bunds, this is not always the case and for the larger bund heights, the intersections occur after the positions of maximum dynamic pressures. Conversely, in the case of the smaller bunds at the larger radii, the points of intersection occur before the positions of the maximum dynamic pressures. This illustrates the interplay of the hydrostatic and velocity heads, which form the dynamic pressures, with the smaller bund heights unable to oppose the full heights of the approaching surge profiles, thus significant dynamic pressures and overtopping result, even with reduced instantaneous wave heights. This situation changes for the largest bund radii considered due to friction with the base of the spill table, where velocities are reduced enough to actually cause a slight reduction in the overtopping fraction.
When considering the ‘rectangular’ bunds, in the case of squat and middle tanks, all the configurations gave intercept and maximum wave heights lower than those found for the equivalent circular configuration. The tall tank releases gave mixed results with the triangular configuration having a greater intercept height and smaller maximum height. The square configuration gave a smaller intercept height and a greater maximum height and finally, the rectangular configuration having lower intercept and maximum heights.
6 CONCLUSIONS

6.1 Overtopping

The overtopping fractions possible in the event of a catastrophic failure of the primary containment have been established and their magnitudes give cause for concern to any operators who are relying on the bunds to provide full secondary containment in such circumstances. For high-collar bunds the overtopping fraction is only a few % but for non-high collar bunds the overtopping fractions vary from 14 to 28% at best, depending upon the initial tank fill levels and considering the larger height bunds at the closer bund radii, at the various bund capacities. For bunds of 110% nominal capacity overtopping fractions up to 70% were obtained. This represents a considerable loss of fluid over the secondary containment with the possibility of formidable environmental impact on the area surrounding the bund, and human impact if that area is populated.

It has thus been demonstrated that the present bund design criteria produce structures that are unable to contain the spills resulting from catastrophic tank failures, the amount of spillage depending upon the individual configurations used, even if those structures are not damaged by the impact.

6.2 Dynamic pressures

The dynamic pressures on the bunds have also been established. They have been linked to the overtopping fractions and in some cases are of significant magnitudes when compared to the hydrostatic pressures at the base of the bunds. The pressures on the bunds can be much greater than those normally employed for design purposes and were found to be mostly up to as high as 6 times the hydrostatic pressure at the base. Normally, bund design only considers the hydrostatic pressures, however the dynamic pressure distributions are very different to the hydrostatic pressure profiles, with variations of local dynamic pressure maxima. In the case of the smaller bunds, large variations in the dynamic/static pressure ratios were calculated, in one case the ratio was indicated to be as high as 16.45. However, such values are subject to interpretation due to the method of extrapolation and the positions of the sensors used to compute the dynamic pressures at the base.

The mechanical integrity of current bund design has to be questioned if the bunds are relied upon to provide secondary containment in the event of a sudden catastrophic failure of the primary containment. A catastrophic breach in the secondary containment due to the impact of a surge would be disastrous in terms of the total loss of any containment leading to a major incident of possible overwhelming environmental and human proportions.

6.3 Wave heights

The waves generated by a catastrophic tank failure can be considerable in terms of their height, and may reach heights greater than that of the original level of tank fill, with the potential to cause damage to adjoining tanks and equipment. The resulting tsunami can be far reaching with the separation layer and eventual droplet formation throwing fluid over vast distances.
7  RECOMMENDATIONS

7.1  Overtopping

A directional release of fluid from the primary storage may lead to increased levels of overtopping due to the localised nature of the failure and the occurrence of jetting near the base of the storage tank. The effect of ground conditions will obviously cause variations in the speed of the wave approaching the bund, especially with porous ground materials, where the volume released will decrease as fluid is absorbed. Further work could be undertaken:

- To investigate the effects of localised low level jetting on the overtopping fractions for similar geometries used in this research.
- To evaluate the overtopping fractions based on porous/roughened ground conditions again using similar test configurations used in this investigation.
- To investigate the use of remedial works to modify existing bunding arrangements using inward facing deflectors or profiles to redirect the vertical and forward motion of the wave backwards and reduce the overtopping fraction.

7.2  Dynamic pressures

Any directional release of fluid under the jetting scenario would lead to the likelihood of some form of mechanical failure of the bund itself due to the localised high impact. All bunds are susceptible to dynamic loading under primary storage catastrophic failure conditions, with higher dynamic/static pressure ratios occurring for smaller height bunds at larger radii. Further work could be undertaken:

- To undertake an experimental investigation of the directional nature of low level jetting and the determination of the magnitude of the localised dynamic pressures generated.
- To further investigate the dynamic pressures experienced by low-level bunds at larger radii, with careful consideration given to more accurate determination of the dynamic pressures at the base of the bunds, given the limitations of scale and the physical size of any sensors used.

7.3  Wave heights

The importance of the action of the resulting wave of fluid striking the bund has been established to some degree in this research, the nature of the overtopping wave in relation to the dynamic pressures being observed in some detail. Further work could be undertaken:

- To reproduce the experimental work undertaken with emphasis on more detailed measurements on the actions of the overtopping waves in direct relation to the dynamic pressures generated on the bunds.
7.4 Modification of the storage vessel

It is important to consider the function of the storage vessel in providing primary containment and any possible improvements in design that may reduce the damaged caused in the event of a catastrophic failure. A research programme has recently been approved by LJMU to investigate the feasibility of storage vessel modifications using a number of design options. It is planned to compare the performance of any feasible designs to the newly obtained test data. Further work could be undertaken:

- To investigate the possibility of modifications to the primary containment in order to substantially reduce the overtopping fraction and dynamic pressures without the need to modify existing bunding arrangements.

7.5 Site-specific modelling

The work undertaken has been limited to considering a single tank surrounded by a single bund wall. Further work could be undertaken, for example:

- To study the effect on the overtopping fraction of having other tanks within the same bund. The positions of adjacent tanks can act to reduce the overtopping fraction by providing a physical obstacle to the escaping wave of fluid. Previous incidents have shown that there is a possibility of close proximity tanks sustaining impact damage and further adding to the quantity of escaping fluid.

- To study the effects of buildings or natural features of the terrain outside the bund in diverting the overtopped fluid. The ground levels and other features of the site can act to concentrate or divert the flow of overtopped fluid with directed flow having sufficient energy to cause considerable damage to structures or plant in areas surrounding the bund.

- To study retention in an adjacent bund or bunds following a catastrophic failure. Considerable quantities of fluid can be collected by neighbouring bunds in the event of significant overtopping of the bund containing the original source of failure.

- To study the optimum design of an additional ‘tertiary’ bund or flow diverter. An additional bund surrounding the secondary containment area can limit the quantity of fluid escaping to the site in the event of overtopping of the main bund. The size and position of an additional bund could be identified using existing tank and bund parameters. The possible use of diverters to control the direction of any spills could be investigated, particularly where damage to items of important plant needs to be considered.