Report

Fire Hydrant Equipment Testing with Manly Hydraulics Laboratory – 2017

Document ID: D19/56801
Revision: 1.1
Issued: 12 March 2020

Fire Safety Policy Unit
Community Safety Directorate

Executive Summary

Table 2.2 of AS 2419.1-2005 *Fire Hydrant Installations* specifies the minimum required unassisted residual pressure at a feed fire hydrant. For NSW this is currently set at 150 kPa for each hydrant required to flow at not less than 10 L/s. In all other states and territories this value is 200 kPa.

The historical reasoning behind the 150 kPa in NSW is unknown. Therefore, Fire and Rescue NSW (FRNSW) commissioned Manly Hydraulics Laboratory (MHL) to undertake quantifiable testing of various configurations of its hydrants, standpipes, fire hoses and firefighting pumping appliances to assess FRNSW's operational needs against the AS 2419.1 nominated minimum residual pressure values.

An independent and appropriately qualified body was selected to undertake the testing to ensure that any results obtained were creditable and unbiased. FRNSW engaged MHL as they are a National Association of Testing Authorities (NATA) accredited testing laboratory. However, it is noted that the hydraulic testing conducted by MHL for FRNSW was not conducted to NATA standards.

MHL produced a written report titled, "*FIRE AND RESCUE NSW FIRE HYDRANT TESTING 2017 – Report MHL2534 February 2018*", quantifying the laboratory-derived hydraulic resistance constants for various firefighting components.

To facilitate a better understanding of the MHL report, this report provides further description and some sample calculations for the determination of the hydraulic resistant constants for the various firefighting components tested. This report also outlines further considerations necessary in any application of these values, such as including appropriate factors of safety.

Some observations of interest from the testing undertaken include:

- The minimum collector pressure prior to hose collapse was 0 kPa.
- There are two mechanisms that can potentially cause pump cavitation when water is being supplied to a firefighting pumping appliance via a fire hydrant and canvas hose:
    - If the residual pressure at the pump inlet is reduced to -70 kPa (as read on the compound gauge), cavitation will occur.
    - If the residual pressure in the lay-flat feed hose (as it enters the pump collector) drops to 0 kPa the hose will collapse, and pump cavitation will occur.

A summary of some of the hydraulic resistant constants due to flow resistance for various individual firefighting components is presented in Table 1 below. Please note that these constants are for the pressure drop due to flow resistance only, and do not account for any other losses, differences in elevation head, etc.

Component Description	Corresponding MHL test description	Pressure Drop "ΔP" (kPa) due to flow resistance vs Flow Rate "Q" (L/s)
FRNSW spring valve hydrant / standpipe combination	MHL Test results C1	**$\Delta P = 0.23 \times Q^2$ Note 1**
FRNSW 1-into-2 breeching (both outlets open)	MHL Test results C2	**$\Delta P = 0.02 \times Q^2$**
FRNSW 1-into-2 breeching (one outlet open)	MHL Test results C2	**$\Delta P = 0.07 \times Q^2$**
FRNSW Ø70mm x 30m canvas lay-flat hose on flat ground	MHL Test results C3	**$\Delta P = 0.38 \times Q^2$**
RFS Ø64mm x 30m canvas lay-flat hose on flat ground	MHL Test results C4	**$\Delta P = 0.43 \times Q^2$**
FRNSW screw valve hydrant / double delivery combination	MHL Test results C5	**$\Delta P = 0.14 \times Q^2$ Note 1**

Table 1: Summary of expected pressure drop due to flow resistance versus flow equations for individual firefighting components

Note 1: The difference in elevation head between the main and equipment being tested was not calculated during the MHL testing and therefore is not included in these derivations. The pressure drop from this equation is due to flow resistance only.

It is noted, however, that the results provided from this testing are from measurements in a test environment that may not include all considerations necessary on a real fire ground, e.g. actual hose lay, mains pressure fluctuations, elevation differences, variations in equipment due to deterioration, repair processes or manufacturing tolerances, etc. Therefore, factors of safety should be considered when using the test results.

Any use or application of the results in the MHL Report or this report should be discussed with the Fire Safety Policy Unit in FRNSW to ensure that the appropriate considerations are being made.

Contents

1 Introduction

Following a request from FRNSW to undertake testing, MHL produced a written report titled, "*FIRE AND RESCUE NSW FIRE HYDRANT TESTING 2017 – Report MHL2534 February 2018*", quantifying the laboratory-derived hydraulic resistance constants for various firefighting components.

To facilitate a better understanding of the MHL report, this report provides further description and some sample calculations for the determination of the hydraulic resistant constants for the various firefighting components tested and also outlines further considerations necessary in any application of these values, such as including appropriate factors of safety.

The main focus of this report is on the "Type C tests" (*head-loss testing of components*), as described in the MHL report, as neither the Type A nor Type B test results were employed in the calculation of the hydraulic resistant constants of the firefighting components.

However, some observations of interest from other tests are noted in this report. A more detailed description of all the test scenarios can be found in Section 2.4 of the MHL report.

2 Background

Table 2.2 of AS 2419.1-2005 *Fire Hydrant Installations* specifies the minimum required unassisted residual pressure at a feed fire hydrant. For NSW this is currently set at 150 kPa for each hydrant required to flow at not less than 10 L/s. In all other states and territories this value is 200 kPa.

The historical reasoning behind the 150 kPa in NSW is unknown. Therefore, Fire and Rescue NSW (FRNSW) commissioned Manly Hydraulics Laboratory (MHL) to undertake quantifiable testing of various configurations of its hydrants, standpipes, fire hoses and firefighting pumping appliances to allow an assessment of the operational needs of FRNSW for comparison against the AS2419.1-2005 nominated minimum residual pressure values.

3 Methodology

An independent and appropriately qualified body was selected to undertake the testing to ensure that any results obtained were creditable and unbiased. FRNSW engaged MHL as they are a National Association of Testing Authorities (NATA) accredited testing laboratory. However, it must be noted that the hydraulic testing conducted for FRNSW was not conducted to NATA standards.

Numerous tests were performed by MHL. A brief description of only the test scenarios relevant to this report are presented. A more detailed description of all the test scenarios can be found in Section 2.4 of the MHL report.

The main focus of this report is on the "Type C tests" (*head-loss testing of components*). In order to facilitate further understanding of the Type C test results, two methods of calculation were employed to assess the MHL test data. The first of these was the Bernoulli Energy equation, with the second method being termed the "simple pressure drop equation".

Using these two calculations, an equation is developed to predict the pressure drop (in kPa) due to flow resistance for a given fire flow (in L/s) for each of the systems / components tested.

A check is then made of the two developed equations against the discrete measured values by way of plotting them on a graph for comparison.

4 Analysis

4.1 Observations from Type A Tests

MHL tests A5 and A6 were designed to determine the minimum pressure required at the feed hydrant and collector to prevent cavitation of the fire brigade appliance pump and/or hose collapse. Figure 1 shows the test configuration for Tests A5 and A6. The mains pressure was incrementally reduced until hose collapse or pump cavitation occurred.

While a standpipe was used, the results obtained in this test are applicable to any feed hydrant, whether it be a street hydrant or part of a booster assembly.

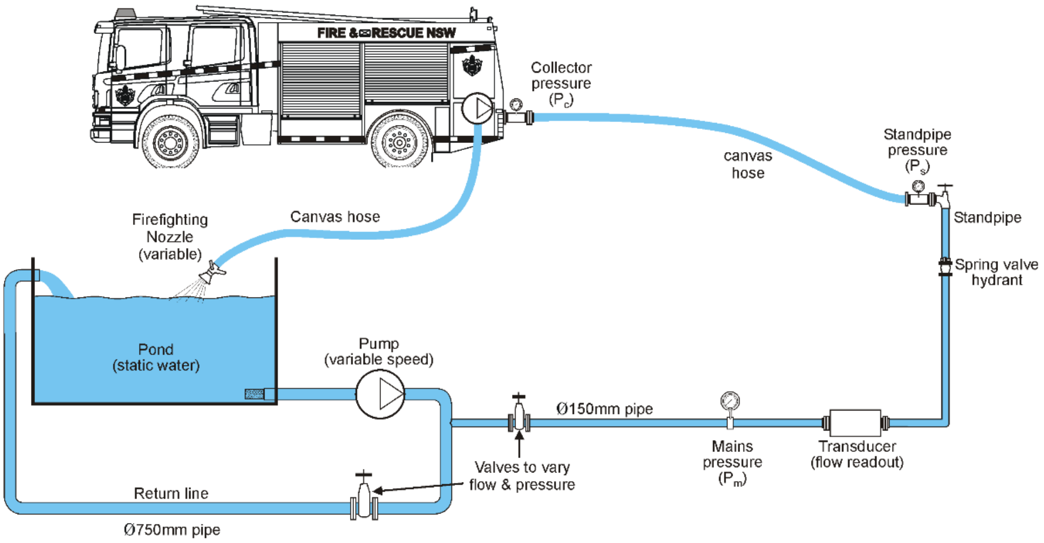

Figure 1: MHL Figure 2-7 : Tests A5 and A6 configuration

Observations of interest from the testing undertaken include:

- The minimum collector pressure prior to hose collapse was 0 kPa.
- There are two mechanisms that can potentially cause pump cavitation when water is being supplied to a firefighting pumping appliance via a fire hydrant and canvas hose.
  - If the residual pressure at the pump inlet is reduced to -70 kPa (as read on the compound gauge) cavitation will occur.
  - If the residual pressure in the lay-flat feed hose (as it enters the pump collector) drops to 0 kPa the hose will collapse, and pump cavitation will occur.

4.2 MHL Test results C1 (spring valve hydrant and standpipe)

The aim of this test was to develop equations that could be used to predict the pressure drop due to flow resistance for a given fire flow across a spring valve hydrant / standpipe combination.

This test considers the pressure drop from the hydrant connection in the town main, through the spring valve hydrant / standpipe combination, through to the outlet of a FRNSW standpipe. Refer to Figure 2 below for the test rig arrangement.

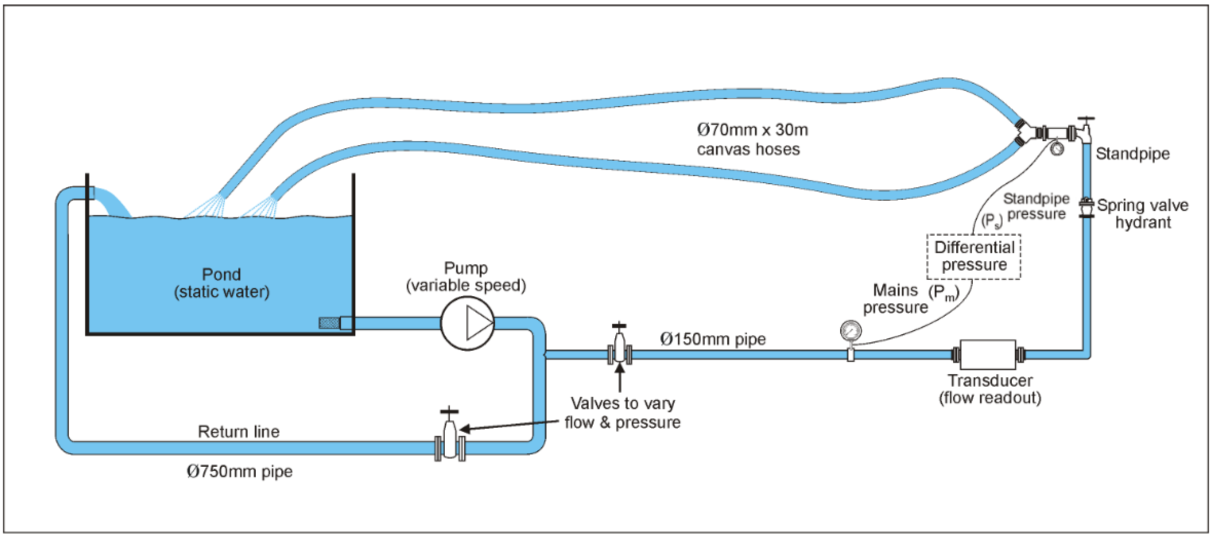

Figure 2: MHL Figure 2-9: Test C1 (and Test C5) set-up, spring valve hydrant / standpipe

4.2.1 MHL Test Results

Table 2 below shows the results for Test C1 and has been taken from MHL Table 3-8: Test C1 results (spring valve hydrant and standpipe). It is noted that some slight modifications have been made to the table, such as additional descriptions included, to provide further clarification.

1	Flow Q	L/s	2.5	5	7.5	10	12.5	14.8	18.3	19.9	22.5	25	26.7	27.4	Measured
2	Differential Pressure	kPa	1.5	6	12	23	36	48	74	87	113	140	160	170	Measured ~ P_{DIFF}
3	Differential Head	m	0.153	0.612	1.225	2.348	3.675	4.899	7.553	8.880	11.534	14.290	16.332	17.352	$P_{DIFF}/(\rho g)$
4	Velocity Mains	m/s	0.141	0.283	0.424	0.566	0.707	0.838	1.036	1.126	1.273	1.415	1.511	1.551	V_M = Q/A - Based on Ø150mm
5	Velocity Head mains	m	0.001	0.004	0.009	0.016	0.026	0.036	0.055	0.065	0.083	0.102	0.117	0.123	$V_M^2/(2g)$
6	Velocity Standpipe	m/s	0.753	1.507	2.260	3.014	3.767	4.460	5.515	5.997	6.781	7.534	8.046	8.257	V_S = Q/A - Based on Ø65mm
7	Velocity Head standpipe	m	0.029	0.116	0.261	0.463	0.724	1.015	1.552	1.835	2.346	2.897	3.304	3.480	$V_S^2/(2g)$
8	k* (individual)		4.32	4.32	3.73	4.10	4.11	3.86	3.90	3.87	3.95	3.97	3.98	4.02	$\left[\frac{P_{Diff}}{\rho g}+\frac{V_M^2}{2g}-\frac{V_S^2}{2g}\right]/\frac{V_S^2}{2g}$
9	k* (average)		4.0												
10	k_Q (individual)	[kPa], [L/s]	0.24	0.24	0.21	0.23	0.23	0.22	0.22	0.22	0.22	0.22	0.22	0.23	$k = P_{DIFF}/Q^2$
11	k_Q (average)	[kPa], [L/s]	0.23												

** k is based on the Ø65mm ID of the standpipe outlet*

Table 2: MHL Table 3-8: Test C1 results (spring valve hydrant and standpipe)

4.2.2 Determination of Equation A using the Bernoulli Energy equation

Starting with the Bernoulli Energy equation:

$$\underbrace{\frac{P_M}{\rho g} + \frac{V_M^2}{2g}}_{\text{Energy in Mains}} = \underbrace{\frac{P_S}{\rho g} + \frac{V_S^2}{2g}}_{\text{Energy at Standpipe}} + \underbrace{hl}_{\text{Energy lost}}$$

Where: P_M = Pressure in the Mains adjacent to the hydrant in [Pa]

P_S = Pressure at the outlet of the Standpipe in [Pa]

Diameter of the water Main = ø150mm

Diameter of pipe at the Standpipe pressure gauge = ø65mm

V_M = Velocity in the Mains in [m/s]

V_S = Velocity at the Standpipe outlet in [m/s]

ρ = water density of 1000 [kg/m^3]

g = acceleration due to gravity [m/s^2]

$hl = k\frac{V_S^2}{2g}$ = the Energy lost from town Main to the exit of the Standpipe [m].

Note 1: Convention requires that the hydraulic resistance constant “k” above should be based on the smaller of the internal diameters; i.e. that of the standpipe at Ø65mm.

Note 2: As a differential pressure gauge was used during testing, the difference in elevation head between the main (Z_M) and standpipe (Z_S), was not calculated during the MHL testing, and therefore not included within the MHL report. For consistency, it has also not been included in the above Bernoulli Energy equation. However, the difference in elevation heads for Z_M and Z_S would need to be considered in any application of the hydraulic resistance constants. For example, if 1.2 m is the height from the main up to the outlet of a typical standard FRNSW standpipe, a 1.2 m difference in elevation would need to be accounted for, i.e. 12 kPa.

Inputting $hl = k\frac{V_S^2}{2g}$, $P_{IN} - P_{OUT} = P_{DIFF}$ (refer to row 2 of Table 2 above) into the above Bernoulli Energy equation and making “k” the subject provides:

$$k = \left[\frac{P_{Diff}}{\rho g} + \frac{V_M^2}{2g} - \frac{V_S^2}{2g}\right] / \frac{V_S^2}{2g} \sim \text{Equation A}$$

Equation A above was then used to calculate the “k (individual)” values in Table 2 above, refer to row 8. From which the “k (average)” value of “4.0” was calculated, refer to row 9 in the above table.

4.2.3 Determination of Equation 1 using the Bernoulli Energy equation

Inputting $hl = k\frac{V_S^2}{2g}$ into the Bernoulli Energy equation and making $P_M - P_S$ the subject of the equation provides:

$$P_M - P_S = \rho g\left[\frac{V_S^2}{2g} - \frac{V_M^2}{2g} + k\left(\frac{V_S^2}{2g}\right)\right] \sim [\text{Pa}]$$

Converting the units from [Pa] to [kPa] by dividing by 1000 (thus cancelling out ρ) provides:

$$P_M - P_S = \frac{\cancel{\rho}\cancel{g}}{\cancel{1000}}\left[(k+1)\left(\frac{V_S^2}{2\cancel{g}}\right) - \frac{V_M^2}{2\cancel{g}}\right] \sim [\text{kPa}]$$

Inputting the value for “k (average)” of “4.0” from row 9 of Table 2 above provides:

$$P_M - P_S = \frac{(5.0)V_S^2 - V_M^2}{2} \; [\text{kPa}] \sim \text{Equation B}$$

Next, to define $(P_M - P_S)$ in terms of flow Q in units of [L/s] consider the following:

If Q = AV; therefore $V^2 = \frac{Q^2}{A^2}$

And $V_S^2 = \frac{Q^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2}$ & $V_M^2 = \frac{Q^2/1000^2}{\left[\frac{\pi(0.15^2)}{4}\right]^2}$ ~ (Q in L/s)

Equation B above becomes: $P_M - P_S = \frac{(5.0)\frac{Q^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2} - \frac{Q^2/1000^2}{\left[\frac{\pi(0.15^2)}{4}\right]^2}}{2}$ [kPa]

Which reduces to: $P_M - P_S = 0.23 * Q^2$ [kPa]

Or, $\mathbf{\Delta P = 0.23 * Q^2}$ **[kPa] ~ Equation 1**

Equation 1 can be used to predict the pressure drop due to flow resistance in units of kPa for a given fire flow in units of L/s when considering the system from the hydrant connection in the town main, through the spring valve hydrant / standpipe combination, through to the outlet of a FRNSW standpipe.

4.2.4 Determination of Equation 2 using the simple pressure-drop equation

Starting with the *simple pressure-drop equation* below:

$$\Delta P = kq \times Q^2$$

Where: ΔP = Recorded *Differential Pressure* drop from Mains to Standpipe in [kPa]

kq = the hydraulic resistance constant for the particular component

Q = Recorded flow rate in [L/s]

Re-arranging the *simple pressure-drop equation* to provide for kq:

$$kq = \frac{\Delta P}{Q^2} \text{ [kPa, L/s]} \sim \text{Equation C}$$

Equation C above was then used to calculate the “kq (individual)” values in Table 2 above, refer to row 10. From which the “kq (average)” value of “0.23“ was calculated, refer to row 11 of the Table.

Inputting the “kq (average)” value of “0.23” from row 11 of Table 2 above into the *simple pressure-drop equation* above provides:

$$\mathbf{\Delta P = 0.23 * Q^2 \text{ [kPa]}} \sim \text{Equation 2}$$

Equation 2 can also be used to predict the pressure drop in units of kPa due to flow resistance for a given fire flow in units of L/s when considering the system from the hydrant connection in the water main, through the spring valve hydrant / standpipe combination, to the outlet of a FRNSW standpipe.

4.2.5 Results

Note that both the Bernoulli Energy equation (Equation 1) and the simple pressure-drop equation (Equation 2) provided the same results, implying that the Bernoulli Energy equation reduces to the *simple pressure-drop equation.*

To demonstrate the close correlation between the discrete measured values and the two developed equations, these values were entered in Figure 3 below.

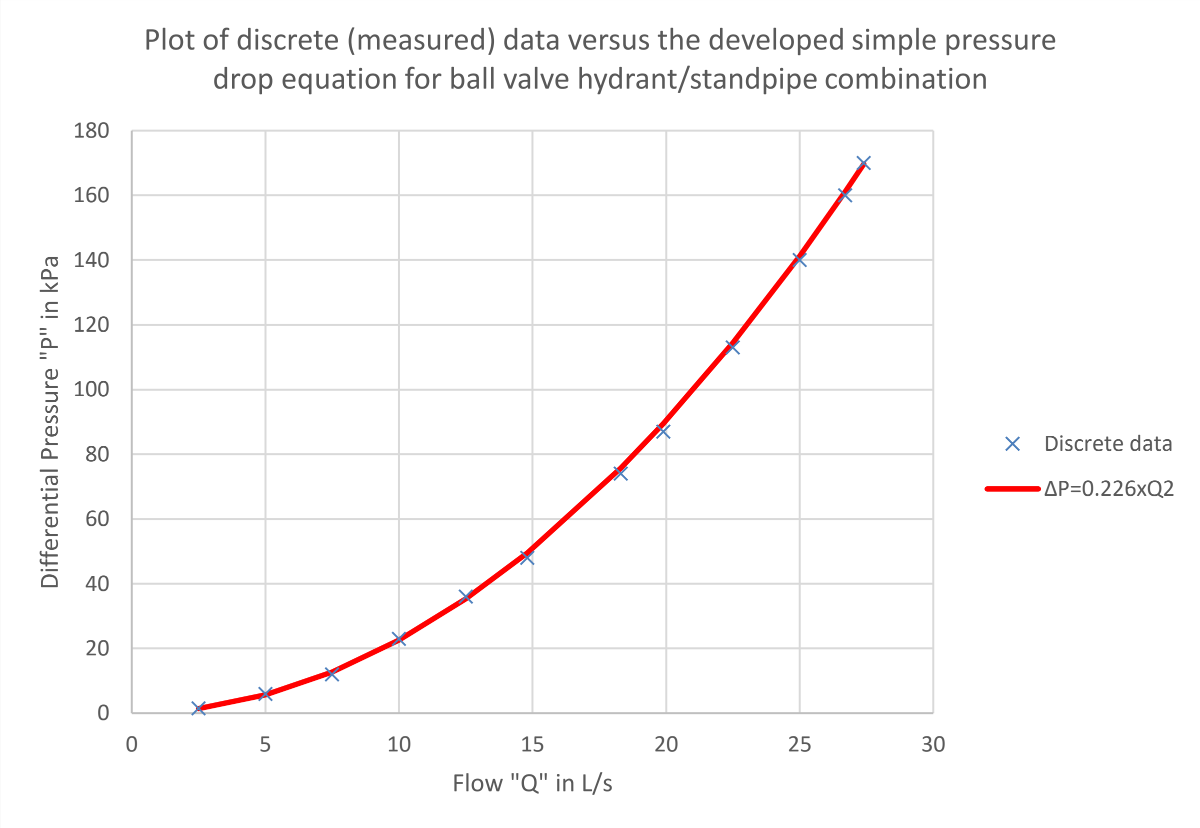

Figure 3 Plot of discrete (measured) data versus the developed simple pressure drop equation for ball valve hydrant/standpipe combination

4.3 MHL Test results C2 (FRNSW 1-into-2 breeching)

The aim of this test was to develop equations that can be used to predict the pressure drop due to flow resistance for a given fire flow across a FRNSW 1-into-2 breeching. Refer to Figure 4 for the test rig arrangement.

Testing was firstly conducted for flow through both outlets of the breeching; and secondly for flow through one outlet only of the breeching.

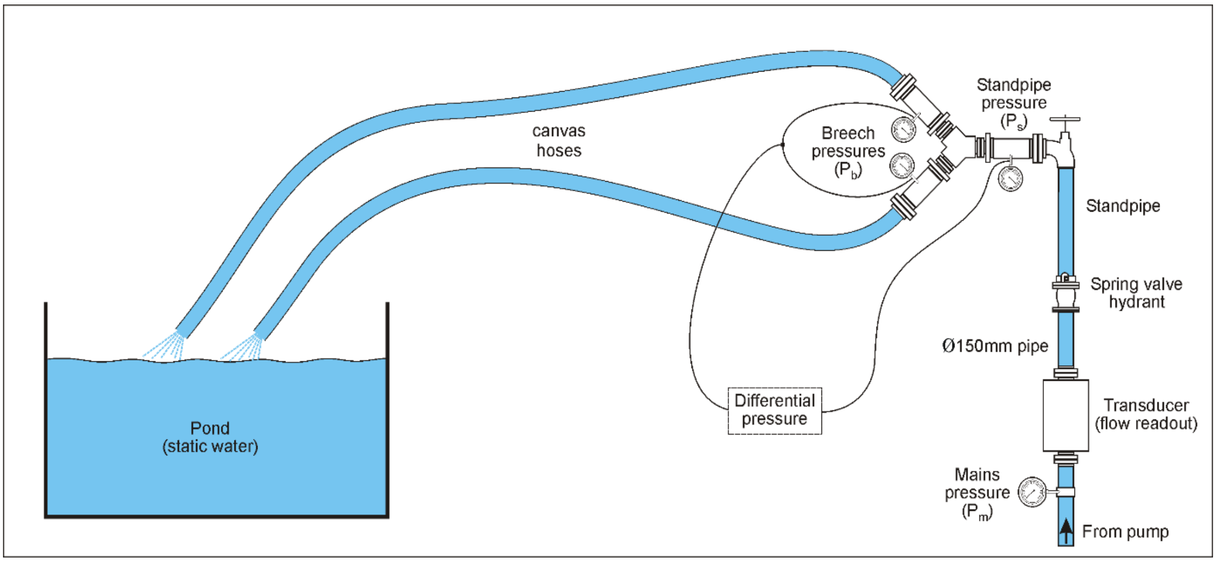

Figure 4: MHL Figure 2-10 – Test C2 set-up for flow across a 1-into-2 breeching

4.3.1 MHL Test Results

Table 3 below shows the results for Test C2 for flow through both outlets of the breeching and has been reproduced from MHL Table 3-9 (BOTH): Test C2 results for flow through both outlets of the breeching. It is noted that some slight modifications have been made to the table, such as additional descriptions included, to provide further clarification.

1	Flow Q (Both sides)	L/s	2.5	5	7.5	10	12.5	15.1	17.5	19.8	Measured
2	Differential Pressure	kPa	0.20	0.25	0.60	1.21	2.22	3.30	4.60	5.88	Measured ~ P_{DIFF}
3	Differential Head	m	0.02	0.03	0.06	0.12	0.23	0.34	0.47	0.60	$P_{DIFF}/(\rho g)$
4	Velocity IN	m/s	0.8	1.5	2.3	3.0	3.8	4.6	5.3	6.0	V_{IN} = Q/A - Based on ⌀65mm
5	Velocity Head IN	m	0.03	0.12	0.26	0.46	0.72	1.06	1.42	1.82	$V_{IN}^2/(2g)$
6	Velocity OUT	m/s	0.38	0.75	1.13	1.51	1.88	2.28	2.64	2.98	V_{OUT} = Q/A - Based on 2 x ⌀65mm
7	Velocity Head OUT	m	0.007	0.029	0.065	0.116	0.181	0.264	0.355	0.454	$V_{OUT}^2/(2g)$
8	k* (individual)		1.45	0.97	0.98	1.02	1.06	1.07	1.08	1.08	$\left[\frac{P_{DIFF}}{\rho g} + \frac{V_{IN}^2}{2g} - \frac{V_{OUT}^2}{2g}\right] / \left(\frac{V_{OUT}^2}{2g}\right)$
9	k* (average)		1.09								
10	kq (individual)	[kPa], [L/s]	0.03	0.01	0.01	0.01	0.01	0.01	0.02	0.01	$k = P_{DIFF}/Q^2$
11	kq (average)	[kPa], [L/s]	0.015								

** k is based on the ⌀65mm ID of the breeching Inlet*

Table 3: MHL Table 3-9 (BOTH): Test C2 results for flow through both outlets of the breeching

Table 4 below shows the results for Test C2 results for flow through one outlet only of the breeching and has been reproduced from MHL Table 3-9 (ONE): Test C2 results for flow through one outlet only of the breeching. It is noted that some slight modifications have been made to the table, such as additional descriptions included, to provide further clarification.

1	Flow Q (One side)	L/s	2.5	5.2	7.6	10	12.5	15	16.1	Measured
2	Differential Pressure	kPa	0.6	1.5	3.7	6.2	11.0	17.0	21.0	Measured ~ P_{DIFF}
3	Differential Head	m	0.06	0.15	0.38	0.63	1.12	1.74	2.14	$P_{DIFF}/(\rho g)$
4	Velocity IN = Velocity OUT	m/s	0.8	1.6	2.3	3.0	3.8	4.5	4.9	V_{IN} = Q/A - Based on Ø65mm
5	k* (individual)		2.11	1.22	1.41	1.37	1.55	1.66	1.78	$2(P_{DIFF}) / V_{IN}^2$
6	k* (average)		1.59							
7	kq (individual)	[kPa], [L/s]	0.096	0.055	0.064	0.062	0.070	0.076	0.081	$k = P_{DIFF}/Q^2$
8	kq (average)	[kPa], [L/s]	0.072							

** k is based on the Ø65mm ID of the breeching Inlet*

Table 4 MHL Table 3-9 (ONE): Test C2 results for flow through one outlet only of the breeching

4.3.2 Determination of Equation D for flow through both outlets of the breeching using the Bernoulli Energy equation

Starting with the Bernoulli Energy equation below.

$$\underbrace{\frac{P_{IN}}{\rho g} + \frac{V_{IN}^2}{2g}}_{\text{Energy IN}} = \underbrace{\frac{P_{OUT}}{\rho g} + \frac{V_{OUT}^2}{2g}}_{\text{Energy OUT}} + \underbrace{hl}_{\text{Energy lost}}$$

Where:
P_{IN} = Pressure in the Inlet in [Pa]
P_{OUT} = Pressure at the Outlet in [Pa]
Diameter of Inlet and both Outlets = Ø65mm
V_{IN} = Velocity at the Inlet in [m/s]
V_{OUT} = Velocity at the Outlet in [m/s]
ρ = water density of 1000 [kg/m^3]
g = acceleration due to gravity [m/s^2]
$hl = k\frac{V_{In}^2}{2g}$ = the Energy lost through the breeching in [m].

Note 1: As the elevation heads of Z_{IN} and Z_{OUT} above the datum are the same, they have been excluded from the Bernoulli Energy equation.

Note 2: The hydraulic resistance constant "k" above is based on the internal diameter of the Inlet i.e. Ø65mm.

Inputting $hl = k\frac{V_S^2}{2g}$ and $P_{IN} - P_{OUT} = P_{DIFF}$ (refer to row 2 of Table 3 above) into the above Bernoulli Energy equation and making "k" the subject of the equation provides:

$$k = \left[\frac{P_{DIFF}}{\rho g} + \frac{V_{IN}^2}{2g} - \frac{V_{OUT}^2}{2g}\right] / \left(\frac{V_{OUT}^2}{2g}\right) \quad \sim \text{Equation D}$$

Equation D above was then used to calculate the "k (individual)" values in Table 3 above, refer to row 8, from which the "k (average)" value of "1.09" was calculated, refer to row 9 of the Table.

4.3.3 Determination of Equation 3 for flow through both outlets of the breeching using the Bernoulli Energy equation

Inputting $hl = k\frac{V_S^2}{2g}$ into the above Bernoulli Energy equation, converting the units from [Pa] to [kPa] by dividing by 1000 (thus cancelling out ρ), and making $P_{IN} - P_{OUT}$ the subject of the equation provides:

$$P_{IN} - P_{OUT} = \frac{\rho g}{1000}\left[\frac{V_{OUT}^2}{2g} + (k-1)\frac{V_{IN}^2}{2g}\right] \text{ [kPa]}$$

Inputting the value for "k (average)" of "1.09" from row 9 of Table 3 above provides:

$$P_{IN} - P_{OUT} = 0.5[V_{OUT}^2 + (1.09 - 1)V_{IN}^2] \text{ [kPa]} \sim \text{Equation E}$$

Next, to define $P_{IN} - P_{OUT}$ in terms of flow Q in units of [L/s].

If Q = AV; therefore $V^2 = \frac{Q^2}{A^2}$

And $V_{IN}^2 = \frac{Q^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2}$ & $V_{OUT}^2 = \frac{\left[\frac{Q}{2}\right]^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2}$ ~ (Q in L/s)

From Equation E: $P_{IN} - P_{OUT} = 0.5\left[\frac{\left[\frac{Q}{2}\right]^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2} + (0.09)\frac{Q^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2}\right] \text{ [kPa]}$

Which reduces to: $P_{IN} - P_{OUT} = 0.015 * Q^2 \text{ [kPa]}$

Or, $\mathbf{\Delta P_S = 0.015 * Q^2 \text{ [kPa]}} \sim \text{Equation 3}$

Equation 3 can be used to predict the pressure drop due to flow resistance in units of kPa for a given flow in units of L/s when considering flow through both outlets of the FRNSW 1 into 2 breeching.

4.3.4 Determination of Equation 4 for flow through both outlets of the breeching using the simple pressure-drop equation

Starting with the *simple pressure-drop equation* below:

$$\Delta P = kq \times Q^2$$

Where: ΔP = Recorded *Differential Pressure* drop across the breeching in [kPa]

kq = the hydraulic resistance constant for the particular component

Q = Recorded flow rate in [L/s]

Re-arranging the *simple pressure-drop equation* to provide for kq:

$$kq = \frac{\Delta P}{Q^2} \text{ [kPa, L/s]} \sim \text{Equation F}$$

Equation F above was then used to calculate the "kq (individual)" values in Table 3 above, refer to row 10, from which the "kq (average)" value of "0.015" was calculated, refer to row 11 of the Table.

Inputting this "kq (average)" value of "0.015" from row 11 of Table 3 above into the *simple pressure drop equation* provides:

$$\mathbf{\Delta P = 0.015 * Q^2 \text{ [kPa]}} \sim \text{Equation 4}$$

Equation 4 can also be used to predict the pressure drop due to flow resistance in units of kPa for a given fire flow in units of L/s when considering flow through both outlets of the FRNSW 1-into-2 breeching.

4.3.5 Results for flow through both outlets of the breeching

Note that both the Bernoulli Energy Equation (Equation 3) and the simple pressure-drop equation (Equation 4) provided the same results, implying that the Bernoulli Energy equation reduces to the *simple pressure-drop equation.*

To demonstrate the close correlation between the discrete measured values and the two developed equations their values were entered in Figure 5 below.

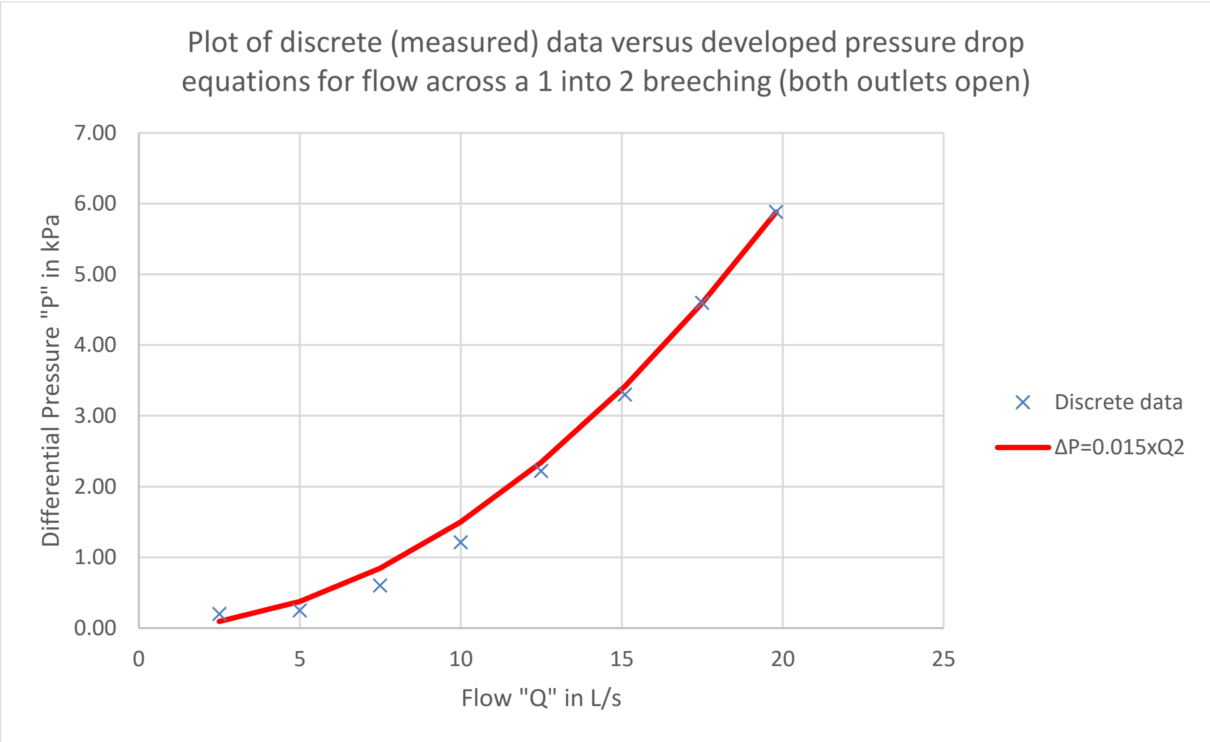

Figure 5: Plot of discrete (measured) data versus developed pressure drop equations for flow across a 1-into-2 breeching (both outlets open)

4.3.6 Determination of Equation G for flow through one outlet of the breeching using the Bernoulli Energy equation

Starting with the Bernoulli Energy equation below.

$$\underbrace{\frac{P_{IN}}{\rho g}+\frac{V_{IN}^2}{2g}}_{\text{Energy IN}} = \underbrace{\frac{P_{OUT}}{\rho g}+\frac{V_{OUT}^2}{2g}}_{\text{Energy OUT}} + \underbrace{hl}_{\text{Energy lost}}$$

Where: P_{IN} = Pressure in the Inlet in [Pa]

P_{OUT} = Pressure at the Outlet in [Pa]

Diameter of Inlet and Outlet = ⌀65mm

V_{IN} = Velocity at the Inlet in [m/s]

V_{OUT} = Velocity at the Outlet in [m/s] = V_{IN}

ρ = water density of 1000 [kg/m^3]

g = acceleration due to gravity [m/s^2]

$hl = k\frac{V_{IN}^2}{2g}$ = the Energy lost through the breeching in [m].

Note 1: As the elevation heads of Z_{IN} and Z_{OUT} above the datum are the same, they have been excluded from the Bernoulli Energy equation.

Note 2: The hydraulic resistance constant “k” above was based on the internal diameter of the Inlet i.e. Ø65mm.

Inputting $hl = k\frac{V_{IN}^2}{2g}$, $V_{IN} = V_{OUT}$ and $P_{IN} - P_{OUT} =$ Differential Pressure (Refer to row 2 of Table 4 above) into the above Bernoulli Energy equation and making “k” the subject of the equation provides:

$$k = \frac{2[P_{DIFF}]}{V_{IN}^2} \sim \text{Equation G}$$

Equation G above was then used to calculate the “k (individual)” values in Table 4 above, refer to row 5, from which the “k (average)” value of “1.59 “was derived, refer to row 6 of the Table.

4.3.7 Determination of Equation 5 for flow through one outlet of the breeching using the Bernoulli Energy equation

Inputting of $hl = k\frac{V_{IN}^2}{2g}$ into the above Bernoulli Energy equation, converting the units from [Pa] to [kPa] by dividing by 1000 (thus cancelling out ρ), and making $P_{IN} - P_{OUT}$ the subject of the equation provides:

$$P_{IN} - P_{OUT} = k\frac{V_{IN}^2}{2} \text{ [kPa]}$$

Inputting the “k (average)” value of “1.59” from row 6 of Table 4 above provides for:

$$P_{IN} - P_{OUT} = 0.795 * V_{IN}^2 \text{ [kPa]} \sim \text{Equation H}$$

Next, to define $P_{IN} - P_{OUT}$ in terms of flow Q in units of [L/s]:

If Q = AV; therefore $V^2 = \frac{Q^2}{A^2}$

And $V_{IN}^2 = \frac{Q^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2} \sim (Q \text{ in } L/s)$

From Equation H above: $P_{IN} - P_{OUT} = 0.795 * \left[\frac{Q^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2} \right] \text{ [kPa]}$

Which reduces to: $P_M - P_S = 0.072 * Q^2 \text{ [kPa]}$

Or, $\mathbf{\Delta P = 0.072 * Q^2 \text{ [kPa]}} \sim \text{Equation 5}$

Equation 5 can be used to predict the pressure drop due to flow resistance in units of kPa for a given flow in units of L/s when considering flow through one outlet only of the FRNSW 1-into-2 breeching.

4.3.8 Determination of Equation 6 for flow through one outlet of the breeching using the simple pressure-drop equation

Starting with the *simple pressure-drop equation* below:

$$\Delta P = kq \times Q^2$$

Where: $\Delta P =$ Recorded *Differential Pressure* drop across the breeching in [kPa]

kq = the hydraulic resistance constant for the particular component

Q = Recorded flow rate in [L/s]

Re-arranging the *simple pressure-drop equation* to provide for kq:

$$kq = \frac{\Delta P}{Q^2} \text{ [kPa, L/s]} \sim \text{Equation I}$$

Equation I above was used to calculate the “kq (individual)” values in Table 4 above, refer to row 7, from which the “kq (average)” value of “0.072“ was calculated, refer to row 8 of the Table.

Inputting the “kq (average)” value of 0.072 from row 8 of Table 4 above into the *simple pressure-drop equation* provides:

$$\mathbf{\Delta P = 0.072 * Q^2 \text{ [kPa]}} \sim \text{Equation 6}$$

Equation 6 can be used to predict the pressure drop due to flow resistance in units of kPa for a given flow in units of L/s when considering flow through one outlet of the FRNSW 1-into-2 breeching.

4.3.9 Results for flow through one outlet of the breeching

Note that both the Energy equation (Equation 5) and the simple pressure-drop equation (Equation 6) provided the same results, implying that the Bernoulli Energy equation reduces to the *simple pressure-drop equation.*

To demonstrate the close correlation between the discrete measured values and the two developed equations these values were entered in Figure 6 below.

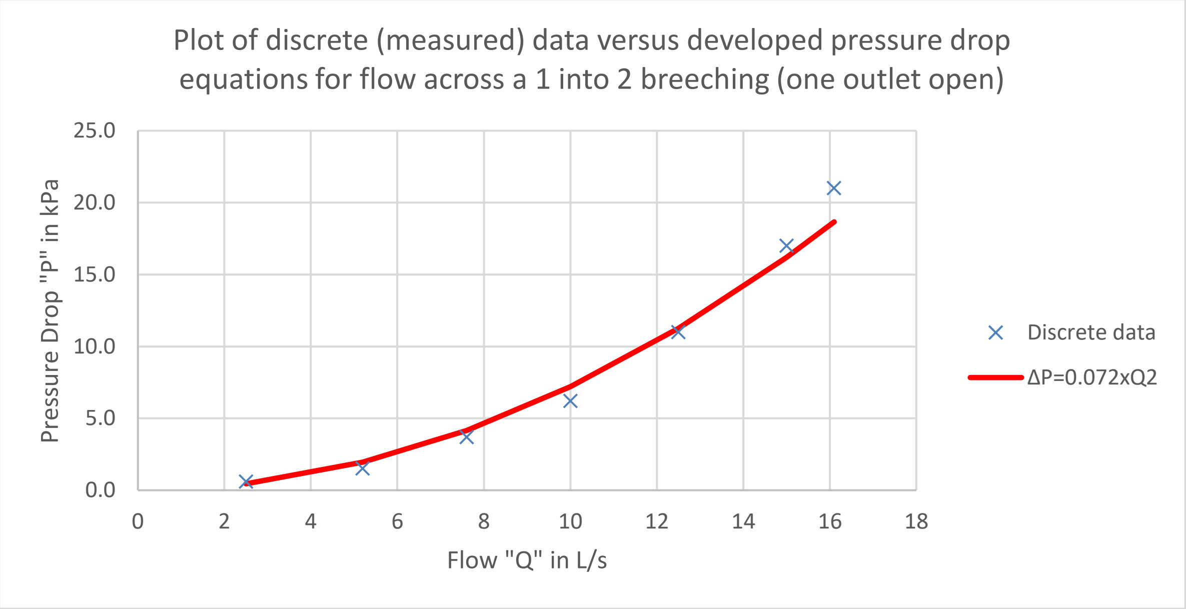

Figure 6: Plot of discrete (measured) data versus developed pressure drop equations for flow across a 1-into-2 breeching (one outlet open)

4.4 MHL Test results C3 (70mm hose)

The aim of this test was to develop equations that can be used to predict the pressure drop due to flow resistance for a given fire flow along a single length of FRNSW Ø70mm x 30m canvas lay-flat hose. Refer to Figure 7 for the test rig arrangement.

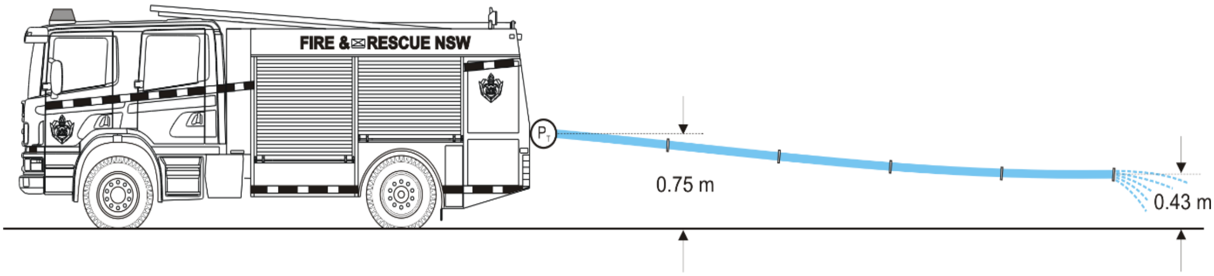

Figure 7: MHL Figure 2-11: Test C3 and Test C4 setup

4.4.1 MHL Test Results

Table 5 below shows the results for Test C3 and has been reproduced from MHL Table 3-10: Test C3 results (70mm hose). It is noted that some slight modifications have been made to the table, such as additional descriptions included, to provide further clarification.

1	Flow Q	L/s	12.4	13.7	14.6	15.5	16.2	17.1	17.5	18.4	18.9	19.7	20.3	Measured
2	P_{IN} (Pressure at hose Inlet)	kPa	290	350	400	450	500	550	600	650	700	750	800	Measured
3	Z_{IN} (Elevation at hose Inlet)	m	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	elevation head of 0.75m above datum
4	Velocity at hose Inlet	m/s	3.7	4.1	4.4	4.7	4.9	5.2	5.3	5.5	5.7	5.9	6.1	V_{IN} = Q/A - Based on ø65mm
5	Velocity Head at hose Inlet	m	0.71	0.87	0.99	1.11	1.22	1.36	1.42	1.57	1.66	1.80	1.91	$V_{IN}^2/(2g)$
6	Total Head at hose Inlet	m	31.1	37.3	42.6	47.8	53.0	58.2	63.4	68.7	73.9	79.1	84.3	$P_{IN}/\rho g + V_{IN}^2/2g + Z_{IN} = H_{IN}$
7	P_{OUT} (Pressure at hose Outlet)	kPa	0	0	0	0	0	0	0	0	0	0	0	0 kPa
8	Z_{OUT} (Elevation at hose Outlet)	m	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	elevation head of 0.43m above datum
9	Velocity at hose Outlet	m/s	3.2	3.6	3.8	4.0	4.2	4.4	4.5	4.8	4.9	5.1	5.3	V_{OUT} = Q/A - Based on ø70mm
10	Velocity Head at hose Outlet	m	0.53	0.65	0.73	0.83	0.90	1.01	1.06	1.17	1.23	1.34	1.42	$V_{OUT}^2/(2g)$
11	Total Head at hose Outlet	m	0.96	1.08	1.16	1.26	1.33	1.44	1.49	1.60	1.66	1.77	1.85	$P_{OUT}/\rho g + V_{OUT}^2/2g + Z_{OUT} = H_{OUT}$
12	Total Head loss over 5 lengths	m	30.1	36.3	41.4	46.5	51.7	56.8	61.9	67.1	72.2	77.3	82.5	$H_{IN} - H_{OUT}$
13	Average Head loss per length	m	6.0	7.3	8.3	9.3	10.3	11.4	12.4	13.4	14.4	15.5	16.5	$(H_{IN} - H_{OUT}) / 5$
14	k* (5 lengths)		56.8	56.1	56.4	56.2	57.1	56.4	58.7	57.5	58.7	57.8	58.1	$\left[\frac{P_{IN}}{\rho g} + \frac{V_{IN}^2}{2g} + Z_{IN} - Z_{OUT} - \frac{V_{OUT}^2}{2g}\right] / \left(\frac{V_{OUT}^2}{2g}\right)$
15	k* (average 5 lengths)		57.2											
16	k* (1 lengths)		11.4	11.2	11.3	11.2	11.4	11.3	11.7	11.5	11.7	11.6	11.6	k* (5 lengths)/5
17	k* (average 1 length)		11.45											
18	kq (5 lengths)	[kPa], [L/s]	1.89	1.86	1.88	1.87	1.91	1.88	1.96	1.92	1.96	1.93	1.94	$k_Q = P_{IN}/Q^2$
19	kq (average 5 lengths)		1.91											
20	kq (single length)	[kPa], [L/s]	0.38	0.37	0.38	0.37	0.38	0.38	0.39	0.38	0.39	0.39	0.39	$k_Q/5$
21	kq (average single length)	[kPa], [L/s]	0.38											

** k is based on the ø70mm ID of the hose outlet*

Table 5: MHL Table 3-10: Test C3 results (70mm hose)

Note 1: Table 3-10 on page 27 of the MHL report does not include rows for the relative elevations of 0.75m and 0.43m for the hose Inlet and hose Outlet respectively. The table above is an expanded version of the MHL table that now includes additional rows to show these values for completeness only. However, these values are dropped out at the end of calculations to provide final equation that is relative to the hose being laid on flat ground.

Note 2: The term "*Hydraulic head at truck*" in the MHL report is the sum of pressure head and elevation.

4.4.2 Determination of Equation J using the Bernoulli Energy equation

Starting with the Bernoulli Energy equation below.

$$\underbrace{\frac{P_{IN}}{\rho g} + \frac{V_{IN}^2}{2g} + Z_{IN}}_{\text{Energy In}} = \underbrace{\frac{P_{OUT}}{\rho g} + \frac{V_{OUT}^2}{2g} + Z_{OUT}}_{\text{Energy Out}} + \underbrace{hl}_{\text{Energy lost}}$$

Where: P_{IN} = Pressure at the hose Inlet in [Pa]

P_{OUT} = Pressure at the outlet of the hose = 0 Pa

Diameter of pipe at the hose Inlet pressure gauge = ⌀65mm

Diameter at the hose Outlet = ⌀70mm

V_{IN} = Velocity at the hose Inlet pressure gauge in [m/s]

V_{OUT} = Velocity at the hose Outlet in [m/s]

Z_{IN} = 0.75 m ~ elevation of the hose Inlet above the datum height.

Z_{OUT} = 0.43 m ~ elevation of the hose Outlet above the datum height.

ρ = water density of 1000 [kg/m^3]

g = acceleration due to gravity of 9.797 [m/s^2]

$hl = k\frac{V_{OUT}^2}{2g}$ ~ Energy lost from hose Inlet to hose Outlet in [m].

The hydraulic resistance constant "k" above was based on Ø70mm being an estimate of the internal diameter at the hose Outlet.

Testing was conducted over 5 lengths of hose with the final result divided by 5 to provide the pressure drop for a single length of hose.

Inputting of $hl = k\frac{V_{OUT}^2}{2g}$ and $P_{OUT} = 0$ into the above Bernoulli Energy equation and making "k" the subject of the equation provides:

$$k = \left[\frac{P_{IN}}{\rho g} + \frac{V_{IN}^2}{2g} + Z_{IN} - Z_{OUT} - \frac{V_{OUT}^2}{2g}\right] / \left(\frac{V_{OUT}^2}{2g}\right) \sim \text{Equation J}$$

Equation J above was then used to calculate the individual values for "k (5 lengths)" in Table 5 above, refer row 14, from which the "k (average 5 lengths)" value of "57.2" was calculated, refer row 15 in Table.

4.4.3 Determination of Equation 7 using the Bernoulli Energy equation

Inputting $hl = k\frac{V_{OUT}^2}{2g}$ into the above Bernoulli Energy equation and making $P_{IN} - P_{OUT}$ the subject of the equation provides:

$$P_{IN} - P_{OUT} = \rho g\left[\frac{V_{OUT}^2}{2g} - \frac{V_{IN}^2}{2g} + Z_{OUT} - Z_{IN} + k\frac{V_{OUT}^2}{2g}\right] \quad [\text{Pa}]$$

Inputting "k (average 5 lengths)" value of "57.2" (from row 15 of Table 5 above), ρ = 1000, g = 9.797, $Z_{OUT} = 0.43\text{m}$, $Z_{IN} = 0.75\text{m}$, and converting the units from [Pa] to [kPa] by dividing by 1000 provides:

$$P_{IN} - P_{OUT} = 9.797\left[(58.2)\frac{V_{OUT}^2}{2g} - \frac{V_{IN}^2}{2g} - 0.32\right] \quad [\text{kPa}] \sim \text{Equation K}$$

Next, to define $P_{IN} - P_{OUT}$ in terms of flow Q in units of [L/s]:

If Q = AV; therefore $V^2 = \frac{Q^2}{A^2}$

And $V_{OUT}^2 = \frac{Q^2/1000^2}{\left[\frac{\pi(0.070^2)}{4}\right]^2}$ & $V_{IN}^2 = \frac{Q^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2}$ ~ (Q in L/s)

Equation K: $$P_{IN} - P_{OUT} = 9.797\left[(58.2)\frac{\frac{Q^2/1000^2}{\left[\frac{\pi(0.070^2)}{4}\right]^2}}{2g} - \frac{\frac{Q^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2}}{2g} - 0.32\right] [kPa]$$

Which reduces to:

$$P_{IN} - P_{OUT} = 1.92 * Q^2 - 3.135 \text{ [kPa] for 5 lengths of hose.}$$

If this same hose test had been conducted on flat ground so that $Z_{IN} = Z_{OUT}$ then the term "3.135" drops out of the above equation. Then, for a single length of FRNSW Ø70mm x 30m canvas lay-flat hose the above equation becomes:

$$P_{IN} - P_{OUT} = 1.92/5 * Q^2 \quad [kPa]$$

Or, $$\mathbf{\Delta P = 0.38 * Q^2 \quad [kPa]} \sim \text{Equation 7}$$

Equation 7 can be used to predict the pressure drop due to flow resistance in units of kPa for a given fire flow in units of L/s for a single length of FRNSW Ø70mm x 30m canvas lay-flat hose laid on flat ground.

4.4.4 Determination of Equation 8 using the simple pressure-drop equation

Starting with the *simple pressure-drop equation* below:

$$\Delta P = kq \times Q^2$$

Where: ΔP = Recorded *Differential Pressure* drop along 5 lengths of hose in [kPa]

kq = the hydraulic resistant constant for the particular component

Q = Recorded flow rate in [L/s]

Re-arranging the *simple pressure-drop equation* to provide for kq:

$$kq = \frac{\Delta P}{Q^2} \quad [kPa, L/s] \sim \text{Equation L}$$

Equation L above was then used to calculate the individual "kq (5 lengths)" values in Table 5 above, refer to row 18, from which the "kq (average 5 lengths)" value of "1.91" was derived, refer to row 19 of the Table.

Further, dividing the "kq (average 5 lengths)" value of "1.91" by 5 provided the "kq (average single length)" value of "0.38" for a single length of hose, refer to row 21 of the Table. Inputting this value into the *simple pressure-drop equation* provides:

$$\mathbf{\Delta P = 0.38 * Q^2 \ [kPa]} \sim \text{Equation 8}$$

Equation 8 can also be used to predict the pressure drop due to flow resistance in units of kPa for a given fire flow in units of L/s for a single length of FRNSW Ø70mm x 30m canvas lay-flat hose laid on flat ground.

4.4.5 Results

Note that both the Energy equation (Equation 7) and the simple pressure-drop equation (Equation 8) provided the same results.

To demonstrate the close correlation between the discrete measured values and the two developed equations these values were entered in Figure 8 below. It is noted that the discrete measured values are for the pressure drop due to the hose and do not include elevation.

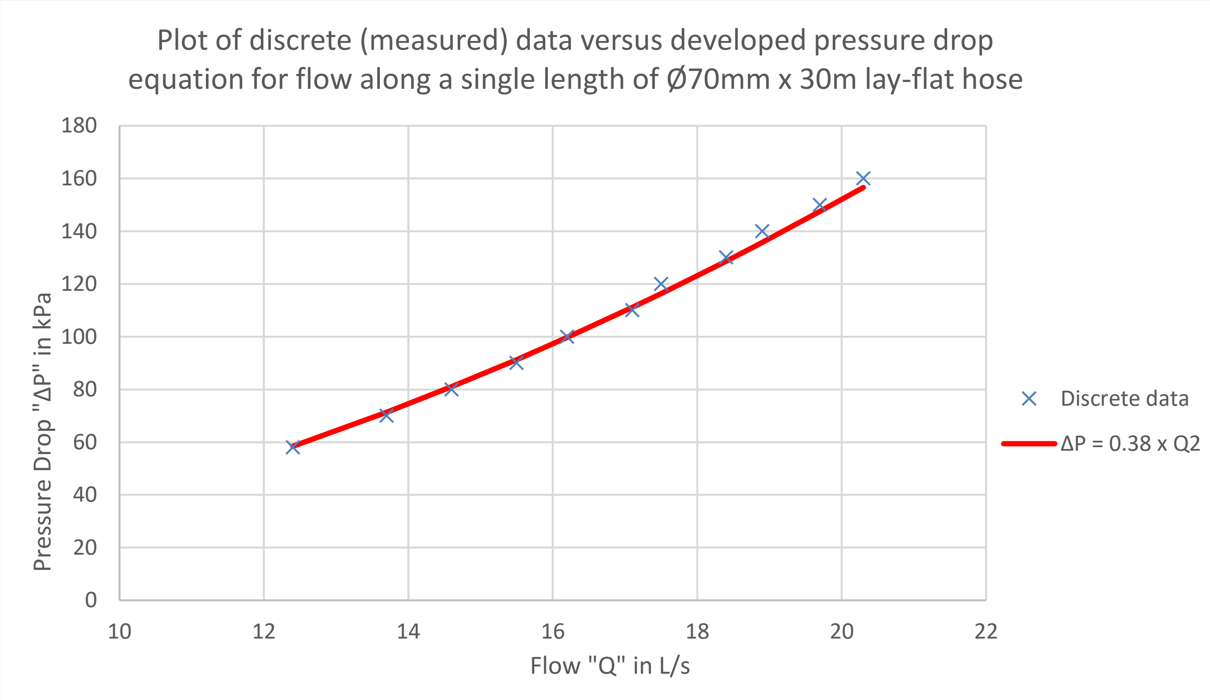

Figure 8: Plot of discrete (measured) data versus developed pressure drop equation for flow along a single length of Ø70mm x 30m lay-flat hose

4.5 MHL Test results C4 (64 mm hose)

The aim of this test was to develop equations that can be used to predict the pressure drop due to flow resistance for a given fire flow along a single length of RFS Ø64mm x 30m canvas lay-flat hose. Refer to Figure 9 for the test rig arrangement.

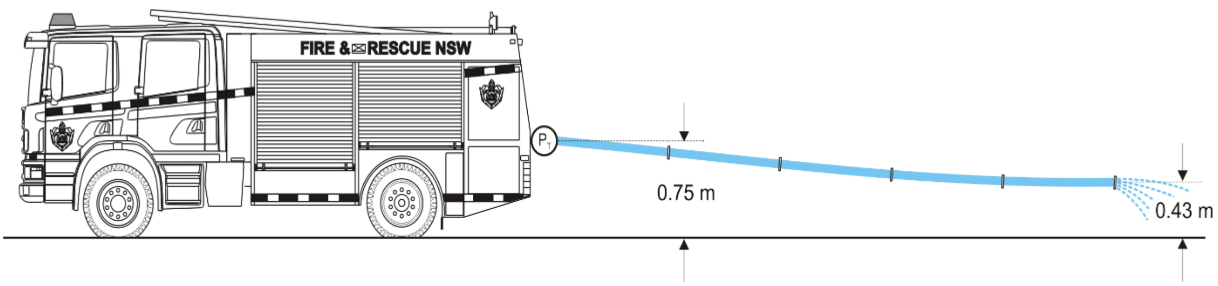

Figure 9 MHL Figure 2-11: Test C3 and Test C4 setup

4.5.1 MHL Test Results

Table 6 below shows the results for Test C4 and has been reproduced from MHL Table 3-11: Test C4 results (64mm hose). It is noted that some slight modifications have been made to the table, such as additional descriptions included, to provide further clarification.

1	Flow Q	L/s	10.5	12.3	13.2	14.5	15.3	16.1	16.8	17.6	18.3	18.9	19.6	Measured
2	P_{IN} (Pressure at hose Inlet)	kPa	240	330	380	460	500	550	600	650	700	750	800	Measured
3	Z_{IN} (Elevation at hose Inlet)	m	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	elevation head of 0.75m above datum
4	Velocity at hose Inlet	m/s	3.16	3.71	3.98	4.37	4.61	4.85	5.06	5.30	5.51	5.70	5.91	V_{IN} = Q/A - Based on ø65mm
5	Velocity Head at hose Inlet	m	0.51	0.70	0.81	0.97	1.08	1.20	1.31	1.44	1.55	1.66	1.78	$V_{IN}^2/(2g)$
6	Total Head at hose Inlet	m	25.8	35.1	40.3	48.7	52.9	58.1	63.3	68.5	73.8	79.0	84.2	$P_{IN}/\rho g + V_{IN}^2/2g + Z_{IN} = H_{IN}$
7	P_{OUT} (Pressure at hose Outlet)	kPa	0	0	0	0	0	0	0	0	0	0	0	0 kPa
8	Z_{OUT} (Elevation at hose Outlet)	m	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43		elevation head of 0.43m above datum
9	Velocity at hose Outlet	m/s	3.26	3.8	4.1	4.5	4.8	5.0	5.2	5.5	5.7	5.9	6.1	V_{OUT} = Q/A - Based on ø64mm
10	Velocity Head at hose Outlet	m	0.5	0.7	0.9	1.0	1.2	1.3	1.4	1.5	1.7	1.8	1.9	$V_{OUT}^2/(2g)$
11	Total Head at hose Outlet	m	0.97	1.18	1.29	1.47	1.58	1.71	1.82	1.96	2.08	2.19	1.89	$P_{OUT}/\rho g + V_{OUT}^2/2g + Z_{OUT} = H_{OUT}$
12	Total Head loss over 5 lengths	m	24.8	34.0	39.1	47.2	51.3	56.4	61.5	66.6	71.7	76.8	82.3	$H_{IN} - H_{OUT}$
13	Average Head loss per length	m	5.0	6.8	7.8	9.4	10.3	11.3	12.3	13.3	14.3	15.4	16.5	$(H_{IN} - H_{OUT}) / 5$
14	k* (5 lengths)		45.6	45.5	45.5	45.5	44.4	44.1	44.2	43.6	43.4	43.6	43.4	$\left[\frac{P_{IN}}{\rho g} + \frac{V_{IN}^2}{2g} + Z_{IN} - Z_{OUT} - \frac{V_{OUT}^2}{2g}\right] / \left(\frac{V_{OUT}^2}{2g}\right)$
15	k* (avarage 5 lengths)		44.436											
16	k* (1 lengths)		9.1	9.1	9.1	9.1	8.9	8.8	8.8	8.7	8.7	8.7	8.7	k* (5 lengths)/5
17	k* (average 1 length)		8.9											
18	kq (5 lengths)	[kPa], [L/s]	2.2	2.2	2.2	2.2	2.1	2.1	2.1	2.1	2.1	2.1	2.1	$k_Q = P_{IN}/Q^2$
19	kq (average 5 lengths)		2.1											
20	kq (single length)	[kPa], [L/s]	0.44	0.44	0.44	0.44	0.43	0.42	0.43	0.42	0.42	0.42	0.42	$k_Q/5$
21	kq (average single length)	[kPa], [L/s]	0.43											

** k is based on the ø64mm ID of the hose outlet*

Table 6: MHL Table 3-11: Test C4 results (64mm hose)

Note 1: Table 3-11 on page 28 of the MHL report advises that k was based on ø64mm ID hose, however the calculations provided in the MHL table suggest that k was actually based on ø65mm, as was the diameter at the inlet. For accuracy, the calculations in the table above in this document were calculated using k = ø64mm at the hose outlet, with the inlet diameter being calculated on the nominal pipe diameter at the pressure gauge pipe; i.e. ø65mm. However, it must be understood that the final equation (Equation 9) is the same regardless of whether ø64mm or ø65mm was used in the calculations.

Note 2: Table 3-11 on page 28 of the MHL report does not include rows for the relative elevations of 0.75m and 0.43m for the hose Inlet and hose Outlet respective. The table above is an expanded version of the MHL table that now includes additional rows to show these values for completeness only. However, these values are dropped out at the end of calculations to provide a final equation that is relative to the hose being laid on flat ground.

Note 3: The term “*Hydraulic head at truck*” in the MHL report is the sum of pressure head and elevation.

4.5.2 Determination of Equation M using the Bernoulli Energy equation

Starting with the Bernoulli Energy equation below.

$$\underbrace{\frac{P_{IN}}{\rho g} + \frac{V_{IN}^2}{2g} + Z_{IN}}_{\text{Energy In}} = \underbrace{\frac{P_{OUT}}{\rho g} + \frac{V_{OUT}^2}{2g} + Z_{OUT}}_{\text{Energy Out}} + \underbrace{hl}_{\text{Energy lost}}$$

Where: P_{IN} = Pressure at the hose Inlet in [Pa]

P_{OUT} = Pressure at the outlet of the hose = 0 Pa

Diameter of pipe at the hose inlet pressure gauge = ø65mm

Diameter at the hose Outlet = ø64mm

V_{IN} = Velocity at the hose Inlet pressure gauge in [m/s]

V_{OUT} = Velocity at the hose Outlet in [m/s]

Z_{IN} = 0.75 m = elevation of the hose Inlet above the datum height.

Z_{OUT} = 0.43 m = elevation of the hose Outlet above the datum height.

ρ = water density of 1000 [kg/m^3]

g = acceleration due to gravity of 9.797 [m/s^2]

$hl = k\frac{V_{OUT}^2}{2g}$ = Energy lost from hose Inlet to hose Outlet in [m].

The hydraulic resistance constant “k” above was based on Ø64mm being an estimate of the internal diameter at the hose outlet.

Again, testing was conducted over 5 lengths of hose with the final result divided by 5 to provide the pressure drop for a single length of hose.

Inputting $hl = k\frac{V_{OUT}^2}{2g}$ and $P_{OUT} = 0$ into the above Bernoulli Energy equation and making “k” the subject of the equation provides:

$$k = \left[\frac{P_{IN}}{\rho g} + \frac{V_{IN}^2}{2g} + Z_{IN} - Z_{OUT} - \frac{V_{OUT}^2}{2g}\right] / \left(\frac{V_{OUT}^2}{2g}\right) \quad \sim \text{Equation M}$$

Equation M above was then used to calculate the individual values for “k (5 lengths)” in Table 6 above, refer row 14. From which the “k (average 5 length)” value of “44.436” was calculated, refer row 15 in the Table.

4.5.3 Determination of Equation 9 using the Bernoulli Energy equation

Inputting $hl = k\frac{V_{OUT}^2}{2g}$ into the above Bernoulli Energy equation and making $P_{IN} - P_{OUT}$ the subject of the equation provides:

$$P_{IN} - P_{OUT} = \rho g\left[\frac{V_{OUT}^2}{2g} - \frac{V_{IN}^2}{2g} + Z_{OUT} - Z_{IN} + k\frac{V_{OUT}^2}{2g}\right] \quad [\text{Pa}]$$

Inputting "k (average 5 lengths)" value of "44.436" (from row 15 of Table 6 above), ρ = 1000, g = 9.797, $Z_{OUT} = 0.43\text{m}$, $Z_{IN} = 0.75\text{m}$ and converting the units from [Pa] to [kPa] by dividing by 1000 provides:

$$P_{IN} - P_{OUT} = 9.797\left[(45.436)\frac{V_{OUT}^2}{2g} - \frac{V_{IN}^2}{2g} - 0.32\right] \ [\text{kPa}] \sim \text{Equation N}$$

Next, to define P_{IN} in terms of flow Q in units of [L/s] consider the following:

If Q = AV; therefore $V^2 = \frac{Q^2}{A^2}$

And $V_{OUT}^2 = \frac{Q^2/1000^2}{\left[\frac{\pi(0.064^2)}{4}\right]^2}$ & $V_{IN}^2 = \frac{Q^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2}$ ~ (Q in L/s)

Equation N:

$$P_{IN} - P_{OUT} = 9.797\left[(45.436)\frac{\frac{Q^2/1000^2}{\left[\frac{\pi(0.064^2)}{4}\right]^2}}{2g} - \frac{\frac{Q^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2}}{2g} - 0.32\right] [\text{kPa}]$$

Which reduces to:

$$P_{IN} - P_{OUT} = 2.15 * Q^2 - 3.135 \quad [\text{kPa}] \text{ for 5 lengths of hose.}$$

If this same hose test had been conducted on flat ground so that $Z_{IN} = Z_{OUT}$ then the term "3.135" drops out of the above equation. Then, for a single length of FRNSW Ø64mm x 30m canvas lay-flat hose the above equation becomes:

$$P_{IN} - P_{OUT} = 2.15/5 * Q^2 \quad [\text{kPa}]$$

$$\text{Or, } \mathbf{\Delta P = 0.43 * Q^2 \quad [kPa]} \sim \text{Equation 9}$$

Equation 9 can be used to predict the pressure drop due to flow resistance in units of kPa for a given fire flow in units of L/s for a single length of RFS Ø64mm x 30m canvas lay-flat hose laid on flat ground.

4.5.4 Determination of Equation 10 using the simple pressure-drop equation

Starting with the *simple pressure-drop equation* below.

$$\Delta P = kq \times Q^2$$

Where: $\Delta P =$ Recorded *Differential Pressure* drop along 5 lengths of hose in [kPa]

kq = the hydraulic resistance constant for the particular component

Q = Recorded flow rate in [L/s]

Re-arranging the *simple pressure-drop equation* to provide for kq:

$$kq = \frac{\Delta P}{Q^2} \quad [\text{kPa}, \text{L/s}] \sim \text{Equation O}$$

Equation O above was then used to calculate the individual "kq (5 lengths)" values in Table 6 above, refer to row 18. From which the "kq (average 5 lengths)" value of "2.1" was derived, refer to row 19 of the Table.

Further, dividing the "kq (average 5 lengths)" value of "2.1" by 5 provided the "kq (average single length)" value of "0.43" for a single length of hose, refer to row 21 of the Table. In-putting this above value into the *simple pressure-drop equation* provides:

$$\mathbf{\Delta P = 0.43 \, * \, Q^2 \quad [kPa]} \sim \text{Equation 10}$$

Equation 10 can be used to predict the pressure drop due to flow resistance in units of kPa for a given fire flow in units of L/s for a single length of RFS Ø64mm x 30m canvas lay-flat hose laid on flat ground.

4.5.5 Results

Note that both the Energy equation (Equation 9) and the simple pressure-drop equation (Equation 10) provided almost the same results.

To demonstrate the close correlation between the discrete measured values and the two developed equations these values were entered in Figure 10 below. It is noted that the discrete measured values are for the pressure drop due to the hose and do not include elevation.

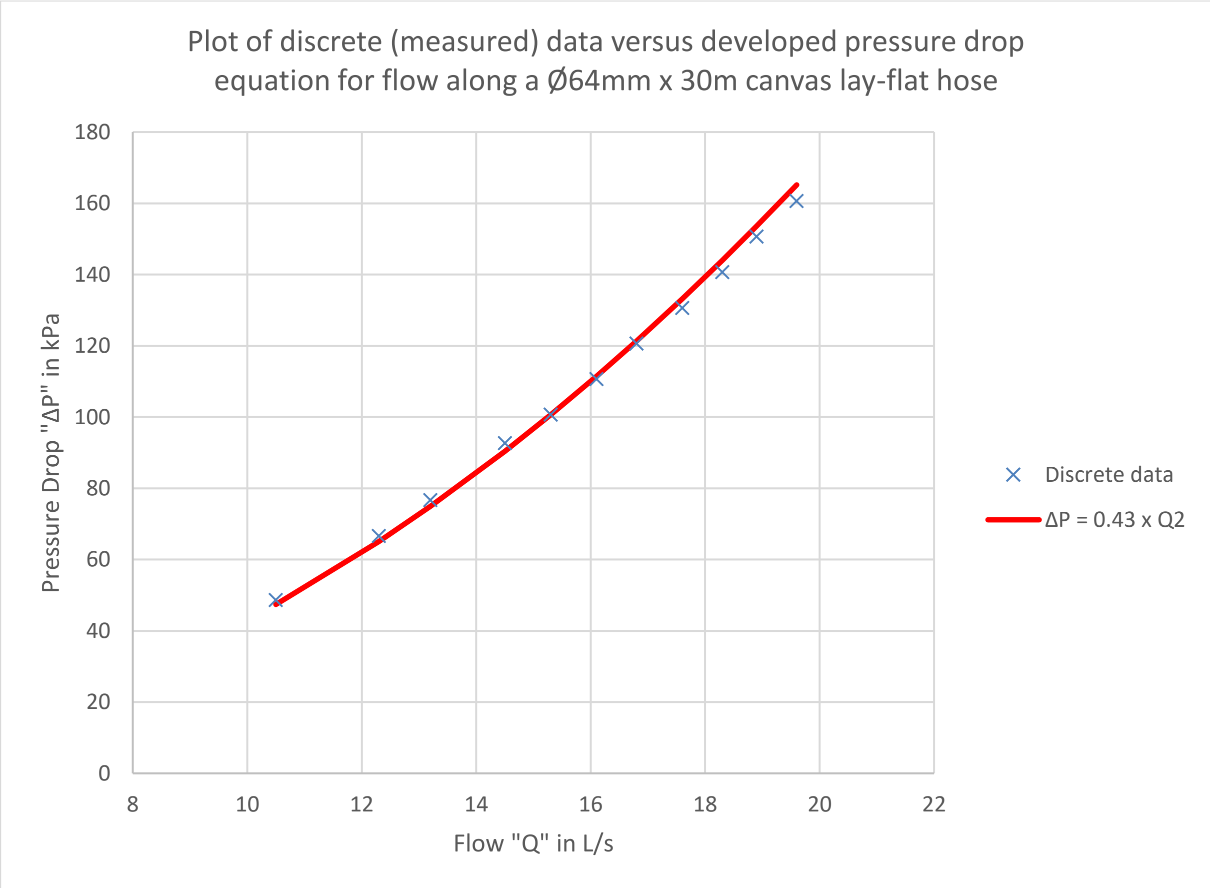

Figure 10: Plot of discrete (measured) data versus developed pressure drop equation for flow along a Ø64mm x 30m canvas lay-flat hose

4.6 MHL Test results C5 (Screw Valve Hydrant and Double Delivery)

The aim of this test was to develop equations that could be used to predict the pressure drop due to flow resistance for a given fire flow across a screw valve hydrant / double delivery combination.

This test considers the pressure drop due to flow resistance from the hydrant connection in the town main, through the screw valve hydrant / double delivery combination, through to the outlet of a FRNSW double delivery.

The procedure and testing is equivalent to MHL Test C1 for the standpipe. The test rig arrangement is the same as Figure 2 except that a double delivery replaces the standpipe and a screw valve hydrant replaces the spring valve hydrant.

4.6.1 MHL Test Results

Table 7 below shows the results for Test C5 and has been reproduced from MHL Table 3-12: Test C5 results (screw valve hydrant and double delivery). It is noted that some slight modifications have been made to the table, such as additional descriptions included, to provide further clarification.

1	Flow Q	L/s	2.5	4.9	7.4	9.9	12.4	15	17.5	19.9	22.5	24.9	27.5	28.1	Measured
2	Differential Pressure	kPa	1	4	8	14	21	30	40	51	66	80	98	103	Measured ~ P_{DIFF}
3	Differential Head	m	0.10	0.41	0.82	1.43	2.14	3.06	4.08	5.21	6.74	8.17	10.00	10.51	$P_{DIFF}/(\rho g)$
4	Velocity in Main	m/s	0.141	0.277	0.419	0.560	0.702	0.849	0.990	1.126	1.273	1.409	1.556	1.590	$V_M = Q/A$ - Based on ⌀150mm
5	Velocity Head in Main	m	0.001	0.004	0.009	0.016	0.025	0.037	0.050	0.065	0.083	0.101	0.124	0.129	$V_M^2/(2g)$
6	Velocity at Double Delivery	m/s	0.753	1.477	2.230	2.983	3.737	4.520	5.274	5.997	6.781	7.504	8.287	8.468	$V_D = Q/A$ - Based on ⌀65mm
7	Velocity Head at Double Delivery	m	0.029	0.111	0.254	0.454	0.713	1.043	1.419	1.835	2.346	2.874	3.505	3.660	$V_D^2/(2g)$
8	k* (individual)		2.56	2.70	2.25	2.18	2.04	1.97	1.91	1.87	1.91	1.88	1.89	1.91	$\left[\frac{P_{DIFF}}{\rho g} + \frac{V_M^2}{2g} - \frac{V_D^2}{2g}\right] / \frac{V_D^2}{2g}$
9	k* (average)		2.09												
10	kq (individual)	[kPa], [L/s]	0.16	0.17	0.15	0.14	0.14	0.13	0.13	0.13	0.13	0.13	0.13	0.13	$k = P_{DIFF}/Q^2$
11	kq (average)	[kPa], [L/s]	0.14												

** k is based on the 65mm ID of the Double Delivery outlet*

Table 7: MHL Table 3-12: Test C5 results (screw valve hydrant and double delivery)

4.6.2 Determination of Equation P using the Bernoulli Energy equation

Again, starting with the Bernoulli Energy equation below:

$$\underbrace{\frac{P_M}{\rho g} + \frac{V_M^2}{2g}}_{\text{Energy in Mains}} = \underbrace{\frac{P_D}{\rho g} + \frac{V_D^2}{2g}}_{\text{Energy at Double Delivery}} + \underbrace{hl}_{\text{Energy lost}}$$

Where: P_M = Pressure in the Mains adjacent to the hydrant in [Pa]

P_D = Pressure at the outlet of the Double Delivery in [Pa]

Diameter of the water Main = ⌀150mm

Diameter of pipe at the Double Delivery pressure gauge = ⌀65mm

V_M = Velocity in the Mains in [m/s]

V_D = Velocity at the Double Delivery pressure gauge in [m/s]

ρ = water density of 1000 [kg/m^3]

g = acceleration due to gravity [m/s^2]

$hl = k\frac{V_D^2}{2g}$ = Energy lost from town Main to the exit of the Double Delivery [m].

Note 1: Convention requires that the hydraulic resistance constant 'k' above should be based on the smaller of the internal diameters; i.e. that of the Double Delivery at Ø65mm.

Note 2: As a differential pressure gauge was used during testing, the difference in elevation head between the main (Z_M) and double delivery (Z_D), was not calculated during the MHL testing, and therefore not included within the MHL report. For consistency, it has also not been included in the above Bernoulli Energy equation. However, the difference in elevation heads for Z_M and Z_D would need to be considered in any application of the hydraulic resistance constants. For example, if 1.2 m is the height from the main up to the outlet of a typical standard FRNSW screw valve hydrant and double delivery, a 1.2 m difference in elevation would need to be accounted for, i.e. 12 kPa.

Inputting $hl = k\frac{V_D^2}{2g}$, & $P_{IN} - P_{OUT} = P_{DIFF}$ (refer to row 2 of Table 7 above) into the above Bernoulli Energy equation and making "k" the subject provides:

$$k = \left[\frac{P_{DIFF}}{\rho g} + \frac{V_M^2}{2g} - \frac{V_D^2}{2g}\right] / \frac{V_D^2}{2g} \sim \text{Equation P}$$

Equation P above was then used to calculate the "k (individual)" values in Table 7 above, refer to row 8. From which the "k (average)" value of "2.09 "was calculated, refer to row 9 of the Table.

4.6.3 Determination of Equation 11 using the Bernoulli Energy equation

Inputting $hl = k\frac{V_D^2}{2g}$ into the Bernoulli Energy equation and making $P_M - P_D$ the subject of the equation provides:

$$P_M - P_D = \rho g\left[\frac{V_D^2}{2g} - \frac{V_M^2}{2g} + k\left(\frac{V_D^2}{2g}\right)\right] \sim [\text{Pa}]$$

Converting the units from [Pa] to [kPa] by dividing by 1000 (thus cancelling out ρ) provides:

$$P_M - P_D = \frac{\not{\rho g}}{\not{1000}}\left[(k+1)\left(\frac{V_D^2}{2\not{g}}\right) - \frac{V_M^2}{2\not{g}}\right] \sim [\text{kPa}]$$

Inputting the value for "k (average)" of "2.09" from row 9 of Table 7 above provides:

$$P_M - P_D = \frac{(3.09)V_D^2 - V_M^2}{2} \ [\text{kPa}] \sim \text{Equation Q}$$

Next, to define $(P_M - P_D)$ in terms of flow Q in [L/s] consider the following:

If Q = AV; therefore $V^2 = \frac{Q^2}{A^2}$

And $V_D^2 = \frac{Q^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2}$ & $V_M^2 = \frac{Q^2/1000^2}{\left[\frac{\pi(0.15^2)}{4}\right]^2}$ ~ (Q in L/s)

Equation Q above becomes: $P_M - P_D = \frac{(3.09)\frac{Q^2/1000^2}{\left[\frac{\pi(0.065^2)}{4}\right]^2} - \frac{Q^2/1000^2}{\left[\frac{\pi(0.15^2)}{4}\right]^2}}{2}$ [kPa]

Which reduces to: $P_M - P_D = 0.14 * Q^2$ [kPa]

Or $\Delta \mathbf{P} = \mathbf{0.14} * \mathbf{Q^2}$ **[kPa]** ~ Equation 11

Equation 11 can be used to predict the pressure drop due to flow resistance in units of kPa for a given fire flow in units of L/s when considering the system from the hydrant connection in the town main, through the screw valve hydrant / double delivery combination, through to the outlet of a FRNSW double delivery.

4.6.4 Determination of Equation 12 using the simple pressure-drop equation

Starting with the *simple pressure-drop equation* below:

$$\Delta P = kq \text{ x } Q^2$$

Where: $\Delta P = \text{recorded } Differential\ pressure \text{ drop from Mains to double delivery [kPa]}$

kq = the hydraulic resistance constant for the particular component

Q = Recorded flow rate in [L/s]

Re-arranging the *simple pressure-drop equation* to provide for kq:

$$kq = \frac{\Delta P}{Q^2} \ [\text{kPa, L/s}] \ \sim \text{Equation R}$$

Equation R above was then used to calculate the “kq (individual)” values in Table 7 above, refer to row 10. From which the “kq (average)” value of “0.14“ was calculated, refer to row 11 of the Table.

Inputting the “kq (average)” value of “0.14” from row 11 of Table 7 above into the *simple pressure-drop equation* above provides:

$$\mathbf{\Delta P = 0.14 * \ Q^2\ [kPa]} \ \sim \text{Equation 12}$$

Equation 12 can also be used to predict the pressure drop due to flow resistance in units of kPa for a given fire flow in units of L/s when considering the system from the hydrant connection in the water main, through the screw valve hydrant / double delivery combination, to the outlet of the double delivery.

4.6.5 Results

Note that both the Bernoulli Energy equation (Equation 11) and the simple pressure-drop equation (Equation 12) provided the same results, implying that the Bernoulli Energy equation reduces to the *simple pressure-drop equation.*

To demonstrate the close correlation between the discrete measured values and the two developed equations these values were entered in Figure 11 below.

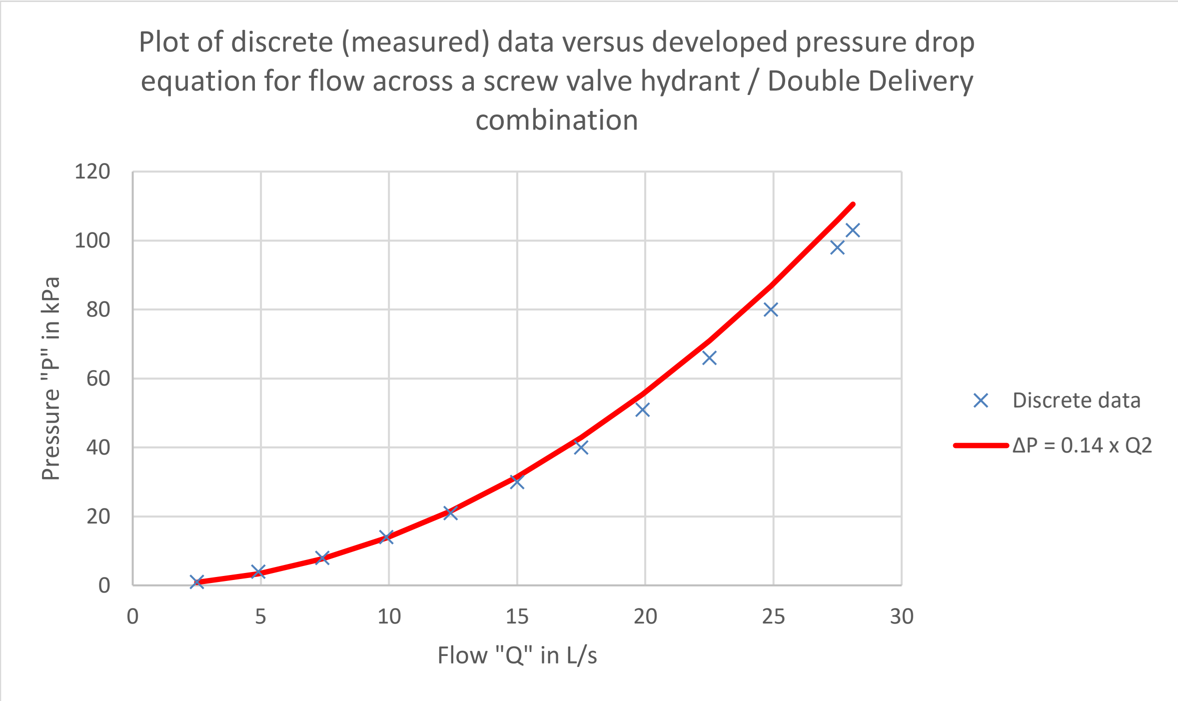

Figure 11:Plot of discrete (measured) data versus developed pressure drop equation for flow across a screw valve hydrant / double delivery combination

5 Results

Based on the derivations in Section 4 from the Type C tests, a summary of the pressure drop due to flow resistance versus flow equations for various individual firefighting components is presented in Table 8 below. Please note that these constants are for the pressure drop due to flow resistance only, and do not account for any other losses, differences in elevation head, etc.

Component Description	Corresponding MHL test description	Pressure Drop "ΔP" (kPa) due to flow resistance vs Flow Rate "Q" (L/s)
FRNSW spring valve hydrant / standpipe combination	MHL Test results C1	**$\Delta P = 0.23 \times Q^2$ Note 1**
FRNSW 1-into-2 breeching (both outlets open)	MHL Test results C2	**$\Delta P = 0.02 \times Q^2$**
FRNSW 1-into-2 breeching (one outlet open)	MHL Test results C2	**$\Delta P = 0.07 \times Q^2$**
FRNSW Ø70mm x 30m canvas lay-flat hose on flat ground	MHL Test results C3	**$\Delta P = 0.38 \times Q^2$**
RFS Ø64mm x 30m canvas lay-flat hose on flat ground	MHL Test results C4	**$\Delta P = 0.43 \times Q^2$**
FRNSW screw valve hydrant / double delivery combination	MHL Test results C5	**$\Delta P = 0.14 \times Q^2$ Note 1**

Table 8: Summary of expected pressure drop due to flow resistance versus flow equations for individual firefighting components

Note 1: The difference in elevation head between the main and equipment being tested was not calculated during the MHL testing and therefore is not included in these derivations. The pressure drop from this equation is due to flow resistance only.

It is noted, however, that the results provided from this testing are from measurements in a test environment which may not include all considerations necessary on a real fire ground, e.g. actual hose lay, mains pressure fluctuations, elevation differences, variations in equipment due to deterioration, repair processes or manufacturing tolerances, etc. Therefore, additional factors of safety are required to be considered.

6 Factors of Safety

The hydraulic resistance constants ‘k’ were developed under controlled laboratory conditions. However, on the fire ground there are other factors that can negatively impact on a component’s ability to replicate the predicted pressure drops, and consequently the available flows. Therefore, factors of safety should be considered when using the test results.

6.1 Hydraulic Resistance Constants

6.1.1 Canvas Hose

The laboratory developed hydraulic resistance constant ‘k’ for canvas hose was developed with the hose laid straight on the ground with no kinks. However, on the fire ground a straight hose lay would often not be possible. Therefore, preliminary testing was carried out by FRNSW to demonstrate that a factor of safety is required to be considered to account for more realistic hose lays on the fire ground.

This preliminary testing involved flowing water through a Ø70mm x 30m hose laid out on the ground with deliberate kinks to replicate a more realistic potential fire ground hose lay. Refer to Figure 12 to see the extent of the kinks during the development of this factor of safety. A pressure drop of 76 kPa was recorded for a flow of 10 L/s through this hose. This is twice the pressure drop (at 10 L/s) for a straight hose, therefore demonstrating that a factor of safety should be considered.

Figure 12: Canvas Hose Factor of Safety Testing

6.1.2 Standpipe/hydrant

The laboratory developed hydraulic resistance constant ‘k’ for the standpipe/hydrant (ball valve) combination was developed using a new (and smooth) ball valve hydrant supplied by Sydney Water. However, there is documented evidence suggesting that as hydrants age they undergo a build-up of encrusted mineral deposits over the flow surfaces which increases the resistance to flow. Therefore, preliminary testing of older in-field street hydrants was conducted by FRNSW to ascertain potential differences from the laboratory determined hydraulic resistance constant ‘k’ value of 0.23. Limited testing to date has demonstrated a hydraulic resistance constant ‘k’ value of 0.34, or approximately 50% greater than the laboratory developed value. This also demonstrates the need to consider an appropriate factor of safety.

6.1.3 Conclusion

It is noted that the preliminary testing referred to above were approximate only. The intent was to demonstrate that significant variation can occur in the pressure loss of more realistic scenarios when compared to the laboratory developed tests. Further justification of the appropriateness of the factors of safety would be expected if the test results presented in the MHL report or this report are to be used.

6.2 Minimum required pressure at the pump collector

It must be noted that pressure at the compound gauge is back pressure to the available flow from the hydrant, and if this pressure is greater than necessary it will reduce the flow available to the fire pump and therefore the firefighters on the branch line. Contrary to this, if pressure at the pump collector goes too far negative it will cause the pump to cavitate. So, a balance was sought between avoiding a negative pressure and the need to not factor in excessive back pressure at the collector.

When water is being supplied to a firefighting pumping appliance via a fire hydrant and canvas hose there are two mechanisms that can potentially cause pump cavitation. Firstly, if the residual pressure at the pump inlet is reduced to -70 kPa (as read on the compound gauge) cavitation will occur. Secondly, if the residual pressure in the lay-flat feed hose (as it enters the pump collector) drops to 0 kPa, the hose will collapse, and pump cavitation will occur.

An example of the cavitation commencing due to low residual pressure at the pump inlet can be seen in Table 3-3 of Test A4 of the MHL report reproduced below in Table 9 (note the right-side column of the table corresponding to a flow of 17.2 L/s). Cavitation commenced at this large flow not due to the feed hose collapsing with 20 kPa at the pump collector “Pc”, but due to the pressure at the inlet to the pump dropping to -70 kPa, as read on the compound gauge.

Table 3-3: Test A4 results

Measurement point	Units	Measurements								
Flow	l/s	10.8	11.9	12.6	13.6	14.3	15	15.9	16.5	17.2
Mains gauge pressure (P_m)	kPa	160	180	190	195	200	205	210	210	215
Mains hydraulic head	mH_2O	16.5	18.5	19.6	20.1	20.6	21.1	21.6	21.6	22.1
Standpipe gauge pressure (P_s)	kPa	150	150	150	150	150	150	150	150	150
Standpipe hydraulic head	mH_2O	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8
Collector gauge pressure (P_c)	kPa	100	90	80	70	60	50	40	30	20
Collector hydraulic head	mH_2O	10.8	9.8	8.7	7.7	6.7	5.7	4.7	3.6	2.6
Truck compound gauge	kPa	110	100	90	70	-10	-25	-40	-55	-70
Fire pump speed	RPM	2330	2600	2800	3020	3210	3400	3600	3810	4100
Mains gauge height	m	0.176								
Standpipe gauge height	m	1.527								
Collector gauge height	m	0.583								

Table 9: MHL Table 3-3: Test A4 results

Alternatively, an example of the cavitation commencing due to low residual pressure in the lay-flat feed hose as it enters the pump collector can be seen in Table 3-4 of Test A5 of the MHL report reproduced below in Table 10 (note the right-side column of the table). Cavitation commenced here not due to the residual pressure at the inlet to the pump dropping to -50 kPa on the compound gauge, but rather due to the feed hose collapsing at 0 kPa, as read on the collector pressure gauge termed "Pc" during the test.

Table 3-4: Test A5 results

Measurement point	Units	Measurements					
Flow	l/s	10.0	9.6	9.8	10.0	10.0	10.0
Standpipe gauge pressure (P_s)	kPa	200	150	125	100	75	60
Standpipe hydraulic head	mH_2O	20.9	15.8	13.3	10.7	8.2	6.7
Collector gauge pressure (P_c)	kPa	150	100	80	50	25	0
Collector hydraulic head	mH_2O	15.9	10.8	8.7	5.7	3.1	0.6
Truck compound gauge	kPa	200	150	100	80	-20	-50
Fire pump speed	RPM	3015	3100	3200	3250	3400	3550
Mains gauge height	m	0.176					
Standpipe gauge height	m	0.527					
Collector gauge height	m	0.583					

Table 10: MHL Table 3-4: Test A5 results

It is noted that a lay-flat hose will not fully collapse until the pressure inside the hose is less than the pressure outside the hose, i.e. atmospheric pressure (0 kPa gauge pressure).

However, running a pump with inlet pressures at the collector close to 0 kPa on the fire ground is not recommended. Some examples of this are that firstly, due to concerns for pump cavitation should there be an unexpected pressure drop in the mains due to additional competition for water from other standpipes etc. Secondly, should the branch operator unexpectedly adjust the flow setting on the branch to a higher flow setting this could potentially cause the pump to over-run supply and cause cavitation. A factor of safety is therefore needed in any calculations to address such concerns.

Therefore, to safeguard against pump cavitation and to ensure firefighter safety on the branch lines, it is recommended that a minimum residual pressure be allowed for in calculations at the point where the hose attaches to the pump collector. This pressure is independent of flow rate and should be added to any calculation to determine the required residual pressure further upstream.

Further work and development is required to determine the value of this minimum residual pressure.

7 Conclusion

The equations for various individual firefighting components presented in Table 8 can be used to predict the pressure drop due to flow resistance for a given fire flow when considering the various individual firefighting components tested and may be useful for a number of applications.

Additional observations from the tests also provide further understanding on the issues of minimum pressures.

It is noted however that the results provided from this testing are from measurements in a test environment which may not include all considerations necessary on a real fire ground, e.g. actual hose lay, mains pressure fluctuations, elevation differences, variations in equipment due to deterioration, repair processes or manufacturing tolerances, etc. Therefore, factors of safety should be considered when using the test results.

Any use or application of the results in the MHL Report or this report should be discussed with the Fire Safety Policy Unit in FRNSW to ensure that the appropriate considerations are being made.