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TITLE

ASSESSMENT OF TOTALLY ENCLOSED PROPELLED SURVIVAL CRAFT (TEMPSC) HULL DESIGN PERFORMANCE IN ICE COVERED WATERS

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SUMMARY

Hazards in offshore operations, such as gas leaks, explosions, fires, collisions and icebergs, can result in emergencies that necessitate evacuation of the installation. These emergencies can arise in calm weather, during storms or in ice covered waters. Therefore, evacuation system performance must be assessed in a wide range of weather conditions i.e. wind, waves and ice. The focus of this report is TEMPSC (Totally Enclosed Motor Propelled Survival Craft) performance in broken ice.

Lifeboats are often used as one of the secondary means of evacuation. In the east coast of Canada and in different parts of the world, broken ice is a common occurrence. Pack ice can surround an offshore platform or a vessel. If abandonment of a platform or a vessel is warranted, then the lifeboat may need to be able to travel through ice to a safe area beyond the hazardous area boundary to escape dangers such as toxic fumes and smoke.

There are many factors that affect TEMPSC performance in ice, including ice concentration, ice thickness, ice strength, ice floe size etc. The speed and navigability of the craft are expected to deteriorate with worsened ice conditions.

It is important in the evaluation of evacuation systems and in the preparation of an emergency preparedness plan that these factors are taken into account. Therefore, it is essential to investigate how lifeboat performance can be limited by different ice conditions. If the performance of lifeboats is inadequate for the expected operating environmental conditions, consideration needs to be given to complement them with other means of evacuation.

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April 2005

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1.0 Introduction

Hazards in offshore operations, such as gas leaks, explosions, fires, collisions and icebergs, can result in emergencies that necessitate evacuation of the installation. These emergencies can arise in calm weather, during storms or in ice covered waters. Therefore, evacuation system performance must be assessed in a wide range of weather conditions i.e. wind, waves and ice. The focus of this report is TEMPSC (Totally Enclosed Motor Propelled Survival Craft) performance in broken ice.

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It is important in the evaluation of evacuation systems and in the preparation of an emergency preparedness plan that these factors are taken into account. Therefore, it is essential to investigate how lifeboat performance can be limited by different ice conditions. If the performance of lifeboats is inadequate for the expected operating environmental conditions, consideration needs to be given to complement them with other means of evacuation.

2.0 Project Objectives and Scope

These series of experiments are part of a large program to investigate TEMPSC performance in ice. In 2003 test series (Elliott 2003, Simões Ré 2003), the performance of a 1:13 scale conventional lifeboat in broken ice was studied in various ice concentrations, floe size and thickness, and with different lifeboat power. The goal was to identify the performance boundaries of the lifeboat in different broken ice conditions. In 2004, the same TEMPSC hull form model was tested in wave and ice (Barker 2004). The goal was to study the effects on craft performance in waves and broken ice.

The objective of this study is to assess the performance of three (3) different TEMPSC hull form designs in broken ice of different concentrations and thicknesses. The 1:7 scale physical models are of conventional TEMPSC (IOT 627), a free-fall TEMPSC (IOT 628) and a new lifeboat concept design (IOT 667). The goals are:

1. To determine an open water performance baseline.

2. To determine the operating limits imposed by ice conditions on the lifeboats. To assess if hull form design and powering have any measurable effect on lifeboat performance in ice.

3. To assess the manoeuvrability of these lifeboats in ice.

4. To assess the average deceleration of these lifeboats as they hit ice pieces of different sizes and mass.

5. To get a coarse measure of global loads on the crafts as they impact with ice floes.

6. To assess, qualitatively, the coxswain's view from inside the different lifeboat canopy designs and their effect on lifeboat navigability.

7. To identify the best practice of manoeuvring lifeboats in ice floes, so the information can be passed on to training organizations.

Only calm conditions were considered in these tests. The effects of wind and waves were investigated in a previous experimental test series (Barker 2004) for one hull design. Later in the spring the effects of ice and waves on all three (3) hull designs will be studied. The results are meant as a preliminary benchmark for performance comparison of different lifeboat hull forms.

The project focused on the simplest characteristic of a broken ice cover – ice concentration, ice thickness and ice floe size and how it affected lifeboat performance. Once the performance limit was established, investigation on how it might be extended was investigated by adding more power to the lifeboat.

The lifeboat models had to navigate their way through the ice to a point 7.5 lifeboat length away by either manoeuvring around the ice floes or bumping into them along the way. The lifeboats were not intended to operate as icebreakers.

3.0 Test Program and Test Setup

3.1 Test Facility

The test program was conducted in the Ice Tank at the Institute for Ocean Technology. The Ice Tank is 90 m long, 12 m wide and 3 m deep, with a useable ice sheet length of 76 m. It is equipped with a main carriage and a service carriage. Temperatures are computer controlled and can be varied between -30° C and 15° C. The ice tank is equipped with a VMS and Windows based distributed client/server data acquisition system.

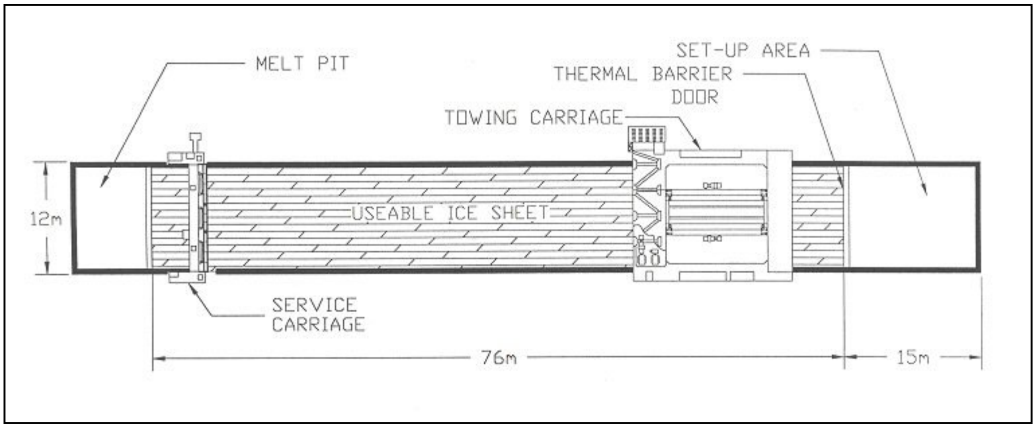

Figure 3.1 Ice Tank

3.2 Ice

The model ice used was NRC EG/AD/S (define EG/AD/S) ice (Jones, 2000). EG/AD/S ice is a model ice material developed at the Canadian Hydraulics Center of National Research Council Canada (Timco, 1986). It is single-layered and columnar in structure.

3.3 Ice Sheet Preparation

There were two nominal ice thicknesses, 46 and 69 mm, used throughout this test series. For each ice sheet two pools were cut, one with large pieces and one with small pieces. For the thin ice sheet, the larger ice piece sizes were square in shape, 1m x 1m, with a mass of approximately 32 kg, about the same as the lifeboats mass in air. The small ice pieces were triangular in shape and made by cutting the 1m x 1m square ice pieces diagonally. The mass of the small pieces was approximately 16 kg (i.e. half of the lifeboats mass in air). Similarly for the thick ice sheet, 69 mm, two pools, one with large square pieces and one with small triangular ice pieces were made. The ice pieces (small and large) were made the same way as those of the thin ice sheet, the only difference being in the size in order to maintain the same ratios of ice piece mass to lifeboat mass (1:1 for large pieces, 1:2 for small pieces). For the thick ice sheet the large ice pieces were cut into squares 0.75m x 0.75m. Only the IOT 667 model was tested in the 69 mm thick ice sheet. The nominal piece size volume and weights before the corners were removed are reported below.

	Ice Floe			
Thickness [m]	Size	Volume [m^3]	Density [kg/m^3]	Mass [kg]
0.046	Large	0.046	875.5	40.27
0.069	Large	0.039	919	35.66
0.046	Small	0.023	875.5	20.14
0.069	Small	0.019	919	17.83

Table 3.1 Comparison of 46mm and 69mm thick ice floe mass

The ice sheets are grown and tempered. The thickness was adjusted by selecting the appropriate freeze time, while the strength was adjusted by altering the time allowed for warm-up. There were two nominal ice thicknesses, 46 and 69 mm, used throughout the test series.

The ice sheet preparation for testing started by cutting an 8m wide by 10m long pool. Then a strip of ice cover was removed to bring the total concentration down to the target. The test started with 9/10th concentration.

The remaining internal ice cover was cut into strips and then into squares. Following this, the four corners of each ice floe square were broken off. The pool was then populated with ice floes. The pool was stirred until the ice floes are uniformly distributed. Then, the tests were conducted at the given ice concentration. After those tests are completed, the pool was lengthened slightly to lower the concentration and then the tests continued. This proceeded until all the concentrations were tested. For repeat runs, the model was returned to the starting position and then the ice pieces were redistributed until they were uniformly distributed. Pictures of large rectangular and small triangular ice floes are shown below.

Figure 3.2 Large rectangular ice floes

Figure 3.3 Small triangular ice floes

As testing progressed in the first pool, a second pool was prepared further down the ice sheet. In the new pool, the small triangular ice floes were prepared using the same procedure described earlier.

It took 12 hours to complete all the tests with one lifeboat in two pools in a single ice sheet. The flexural strength of the ice was calculated periodically throughout each day by performing cantilever beam strength tests.

3.4 Lifeboat Models

The test series was carried out with 1:7 scale lifeboat physical models. Each lifeboat model has two powers settings – one corresponding to that required to make 6 knots in calm open water (designated as P1) as required by regulation and another at a higher power (designated as P2). P2 power was obtained for each lifeboat by limiting the maximum motor current to 4 amps. This is the nominal rating of the batteries, which were used to supply power to the lifeboats. The power of each lifeboat is estimated in Section 6.3.

The dimensions of the lifeboat models are shown below.

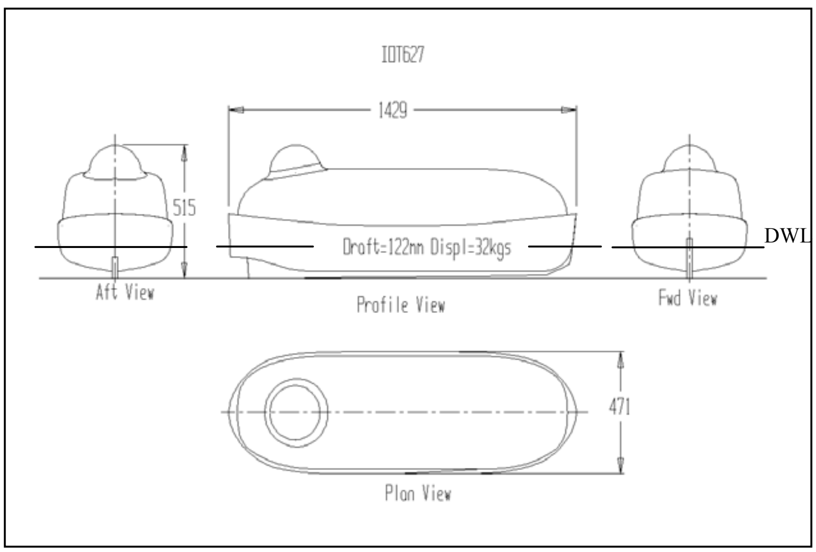

Figure 3.4 IOT 627 lifeboat model (All dimensions in mm)

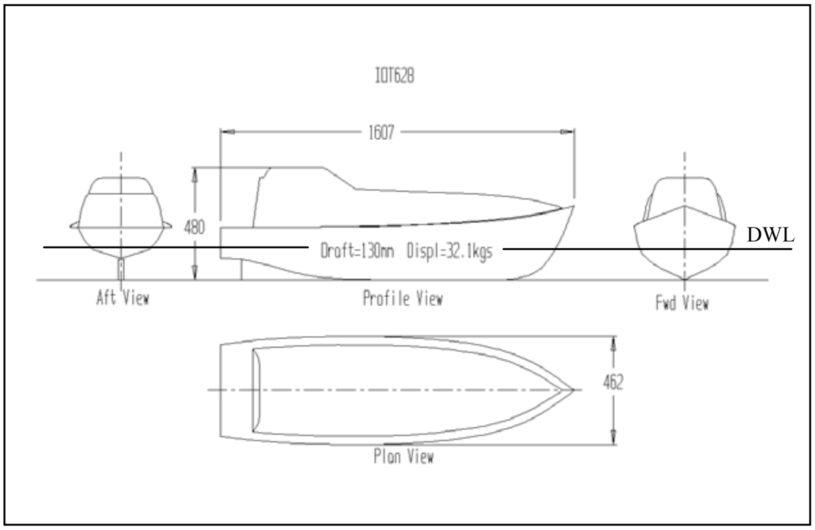

Figure 3.5 IOT 628 lifeboat (All dimensions in mm)

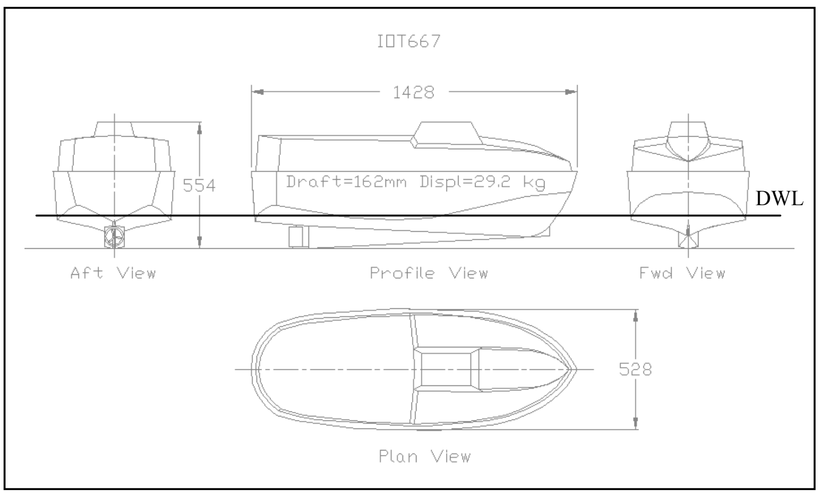

Figure 3.6 IOT 667 lifeboat (All dimensions in mm)

The models were made of moulded fibreglass in two pieces – hull and canopy. All models were propelled by an electric motor drawing on rechargeable batteries. A 63.5mm diameter, 51mm pitch, four-bladed right-handed propeller in a nozzle was used to drive TEMPSC models IOT 627 and IOT 628. A 70mm diameter, 55mm pitch, 3-bladed right-handed propeller in a nozzle was used to drive IOT 667 TEMPSC design concept. The nozzle assemblies can rotate to provide steering capability.

Each model was fitted with a remote camera at the coxswain's position and operated remotely by a technician. The technician uses the camera view of the tank to manoeuvre the lifeboats through the broken ice. Other instrumentation on board of the lifeboats include a Motionpak II 6 degrees-of-freedom motion sensor, Qualisys markers for 6 degrees-of-freedom optical tracking system, a high response rate roll sensor, remote control hardware, a PIC acquisition system and a radio transmitter.

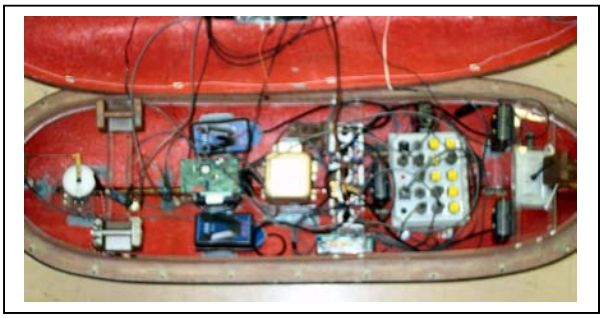

Figure 3.7 IOT 627 lifeboat instrumentation

Figure 3.8 IOT 627 lifeboat

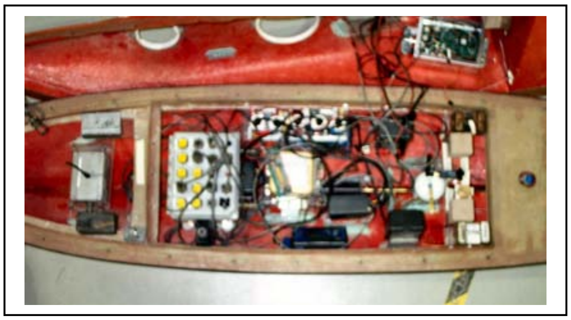

Figure 3.9 IOT 628 lifeboat instrumentation

Figure 3.10 IOT 628 lifeboat

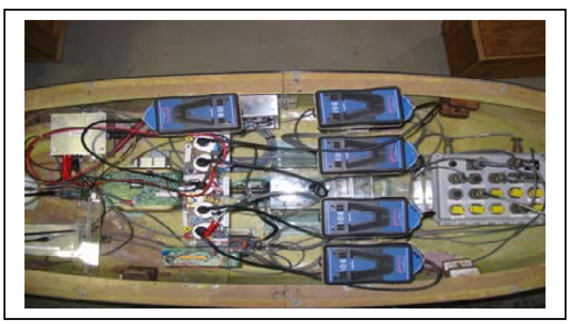

Figure 3.11 IOT 667 lifeboat instrumentation

Figure 3.12 IOT 667 lifeboat

The hydrostatics and mass properties of the lifeboats are shown in the tables below.

			IOT627		IOT628		IOT667	
Condition		Units	1:1	1:7	1:1	1:7	1:1	1:7
Length Overall	LOA	m	10.00	1.429	11.25	1.607	10.00	1.429
Length Waterline	LWL	m	9.67	1.381	10.65	1.521	9.471	1.353
Beam	B	m	3.19	0.456	2.89	0.413	3.55	0.507
Displacement (fw)	Δ	tonnes/kg	11.27	32.05	11.29	32.10	10.00	29.15
Centre of gravity Baseline	CG	m	1.30	0.186	1.49	0.213	1.32	0.189
Long. centre gravity	LCG	m	5.08	0.726	4.96	0.709	5.18	0.740

Table 3.2 Hydrostatic and mass properties for IOT 627, IOT628 and IOT667 TEMPSC models

4.0 Instrumentation

4.1 Data Acquisition

Two data acquisition systems were used in the test program. One system was used to acquire signals from the lifeboats and another used to acquire signals on shore. In the lifeboats, the signals were collected by a PIC (Programmable Integrated Circuit) acquisition system, which in turn was connected, to a radio transmitter. The acquired signals were transmitted to shore wirelessly and acquired by GDAC (GEDAP Data Acquisition and Control) client-server acquisition system. On shore, signals were directly wired to the GDAC client-server acquisition system.

Signals collected on the lifeboats:

Signal	Instrumentation	Sample Rate
Surge, sway and heave accelerations (-3g to 3g) Yaw, pitch and roll rates (-75 deg/s to 75 deg/s)	MotionPak II 6 degrees-of-freedom motion sensor	250 Hz
Roll rate (-200 deg/s to 200 deg/s)	High response roll sensor	250 Hz
Signal to synchronize onboard boat acquisition system with shore side acquisition signal	Pulse	50 Hz
Rudder angle	Rudder potentiometer	50 Hz
Propeller revolutions	RPM unit	50 Hz
Motor power	Current monitor	50 Hz
Pull force for bollard pull test	Load cell	50 Hz
Video at coxswain’s position	Remote digital video camera	30 Hz

Table 4.1 Acquired lifeboat model signals

Signal collected on shore:

Signal	Instrumentation	Sample Rate
Surge, sway and heave, yaw, pitch, roll and RMS error	Qualisys optical tracking system	50 Hz
Carriage speed		50 Hz
Carriage position		50 Hz
Signal to synchronize shore side acquisition system with onboard boat acquisition signal	Pulse	50 Hz
Aft side camera	Video camera	30 Hz
Overhead camera	Video camera	30 Hz

Table 4.2 Acquired on shore signals

4.2 Co-ordinate System

4.2.1 Qualisys and Motionpak Co-ordinates

Qualisys optical tracking system and Motionpak use a right-hand co-ordinate system. The positive X-axis is defined as down the tank towards the melt pit. The Y-axis is defined as positive pointing towards left when one is looking down the tank. The Z-axis is defined as positive pointing up.

5.0 Test Program

5.1 Tests in Calm Water

The test program began with calm water speed tests. In these test, the lifeboat speeds under P1 and P2 powers were calibrated and verified. In P1 power, the lifeboats were set to operate at 6 knots full scale. In P2 power, the lifeboat speeds were set by limiting the maximum motor current to 4 amps. Three runs were conducted with each power settings for each boat.

In addition, decay tests in heave, roll and pitch were conducted on each lifeboat model to determine their decay periods and damping coefficients. For each lifeboat, three decay runs were conducted for heave, roll and pitch respectively. Bollard pull tests were also conducted using an inline load cell to measure pull force of the lifeboats and P1 and P2 power.

5.2 Tests in 46 mm Thick Ice

To investigate whether the design of the lifeboat hull form and/or power has a measurable influence on its performance, three lifeboat designs were tested in 46mm (nominal) thick ice. The three hull designs corresponded to a conventional TEMPSC hull, a freefall TEMPSC hull and a new third generation ice transiting TEMPSC hull.

In each pool, tests started at $9/10^{th}$ concentration. Straight course tests with P2 power were conducted. If the lifeboat failed to reach 7.5 nominal boat lengths, the ice concentration was adjusted downward in steps of $1/10^{th}$. The 7.5 nominal boat lengths was criteria set in the previous test programs to determine pass or fail. A nominal boat length is 1.5m.

For each concentration, if the lifeboat passed the straight course test, the test was repeated two more times. If the lifeboat model passed all three straight course tests, manoeuvring tests followed. These included 6 turning circle runs, three to port and three to starboard.

After the tests with P2 power were completed, tests with P1 power were conducted using the same procedure described above.

5.3 Tests in 69 mm Thick Ice

To investigate the effect of ice thickness on lifeboat performance, the new ice transiting concept hull design was tested in 69mm (nominal) ice sheet while keeping the floe mass to lifeboat mass in the same ratios as before (1:1 and 1:2). The same tests and procedures were used in the 69mm thick ice as in 46mm one.

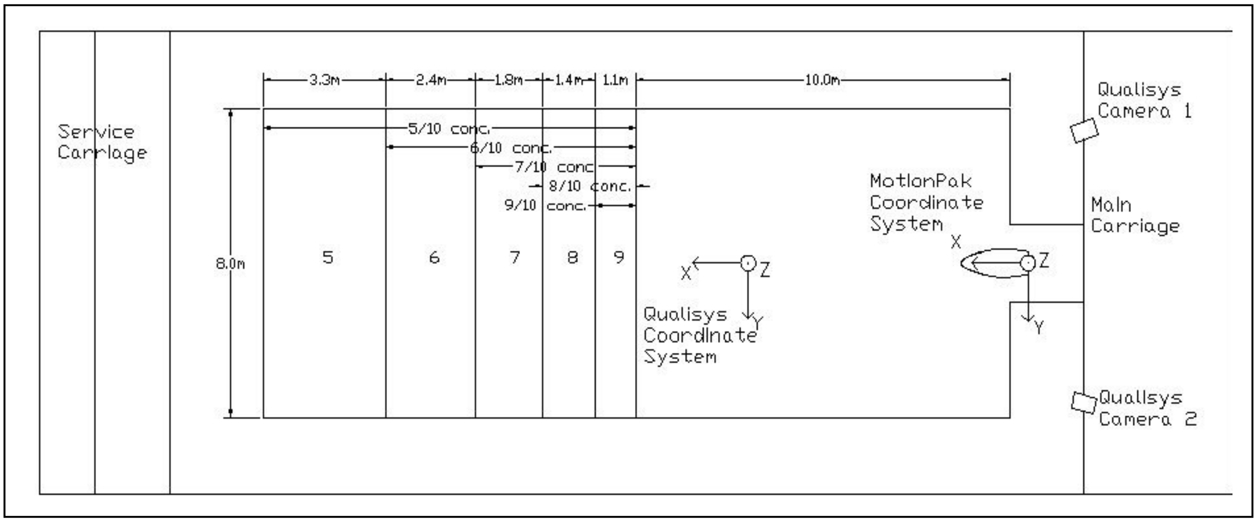

Figure 5.1 Test program setup in ice tank and co-ordinate systems

6.0 Results and Discussions

6.1 Measured Ice Flexural Strength

Three 46mm thick ice sheets were used in this study, one for each lifeboat. An additional 69mm thick ice sheet was used to test the new concept ice transiting hull design. For each ice sheet, the lifeboats were tested in a pool with large ice floes and another pool with small ice floes. All tests with each 46mm ice sheet were completed in one day. Tests with the 69mm ice sheet were conducted over 2 days. In the first day, tests were conducted in the pool with large floes. In the second day, tests were conducted in the pool with small floes. The temperature was kept at 0 degree throughout the test duration.

The ice flexural strength was measured at the beginning and end of each lifeboat test and reported below. Since the tests were conducted at different times on different days, depending on setup time, test duration, location of the pool in the tank, internal melting etc. there were minor variations in flexural strength. As the lifeboats were not operated like an icebreaker breaking ice but pushing ice floes around, it is not expected that the differences in flexural strength would have any significant influence on the test results.

IOT Model	Ice Thickness [mm]	Floe size Large/Small	Flexural Strength [kPa]	
			Start	End
627	46	Large	41	24
628	46	Large	51	39
667	46	Large	53	38
627	46	Small	23	20
628	46	Small	38	32
667	46	Small	37	30
667	69	Small	12	10
667	69	Large	25	21

Table 6.1 Measured ice flexural strength

6.2 Decay Tests

The free-floating lifeboats were oscillated in roll, pitch and heave to determine their natural periods and linear damping coefficients. The results are summarized below.

	Natural Periods [s]			Damping Coefficient		
IOT Model	Roll	Pitch	Heave	Roll	Pitch	Heave
627	1.09	0.93	1.33	0.05	0.15	0.30
628	1.63	0.94	1.47	0.03	0.24	0.44
667	1.30	0.88	1.02	0.03	0.23	0.29

Table 6.2 Natural periods and damping coefficients

6.3 Calm Water Speed Tests

The results of each lifeboat in calm water speed test, using P1 and P2 power are shown below. Selected plots of the lifeboat tracks are included in Appendix A.

The power for each lifeboat was estimated using the formula
P = VI,

where
P = Power [Watts] or [W]
V= voltage [Volts], and
I= current [Amp]

	Power P1		Velocity		Power P2		Velocity	
	[kW]	[W]	[Knots]	[m/s]	[kW]	[W]	[Knots]	[m/s]
IOT Model	1:1	1:7	1:1	1:7	1:1	1:7	1:1	1:7
627	97.1	107	5.91	1.15	113.4	125	6.32	1.23
628	79.9	88	5.97	1.16	117.1	129	6.79	1.32
667	108.9	120	5.94	1.16	123.4	136	6.34	1.23

Table 6.3 Calm water Speed at powers P1 and P2

At P1 power, all lifeboats are supposed to operate at 6 knots full-scale speed, as required by regulation. The P1 power speed test results show that the measured model lifeboat speed, down the tank, matches closely the target speed. For all lifeboats, the maximum motor current of 4 amps limits P2 power. The actual speed achieved by each TEMPSC model at P2 power depended on hull form and powering arrangements etc. associated with the various designs.

6.4 Bollard Pull Test

The bollard pull test results for the three lifeboats at P1 and P2 power are shown in the table below.

	Power P1			Power P2		
IOT Model	RPM	Tow Force [N]		RPM	Tow Force [N]	
	1:7	1:7	1:1	1:7	1:7	1:1
627	3288	6.40	2195	3490	7.05	2418
628	3005	5.31	1821	3576	6.96	2387
667	2276	8.99	3083	2490	10.17	3488

Table 6.4 Bollard pull test results

The reason model 667 was able to deliver higher tow force at much lower RPM than the other lifeboats with the same motor and power supply is probably because of its hull design and high torque propeller.

6.5 Calm Water Turning Circle

The calm water turning circle results are shown below. Turning circle diameter is non-dimensionalized by the length of the model at the waterline. Selected plots of the lifeboat tracks are included in Appendix A.

IOT Model	Power	Turn	Speed [m/s]	Roll [deg]	Rudder Angle [deg]	Non-dimensional Turning Circle Diameter
627	P1	Port	0.79	0.33	-33.23	3.24
628	P1	Port	0.78	1.31	-33.81	3.28
667	P1	Port	0.81	1.78	-33.96	2.61
627	P1	Stbd	0.77	-0.09	34.41	3.15
628	P1	Stbd	0.70	-3.61	45.03 *	3.08
667	P1	Stbd	0.86	-1.49	33.27	2.84

Table 6.5 Turning circle in calm water, P1 power

IOT Model	Power	Turn	Speed [m/s]	Roll [deg]	Rudder Angle [deg]	Non-dimensional Turning Circle Diameter
627	P2	Port	0.84	0.47	-34.85	3.22
628	P2	Port	0.95	2.49	-33.07	3.27
667	P2	Port	0.89	2.15	-33.04	2.65
627	P2	Stbd	0.82	-0.02	33.82	3.25
628	P2	Stbd	0.82	-4.86	44.66 *	3.09
667	P2	Stbd	0.95	-1.81	32.14	2.95

Table 6.6 Turning circle in calm water, P2 power

There was a problem with the rudder angle limit in the IOT 628 lifeboat during starboard turns, allowing the rudder to turn to 45 degrees. The rudder angle limit was originally set at around ± 34 degrees to match the performance of full-scale lifeboats.

The results show that, in most cases, IOT 667 lifeboat model has the fastest turning circle speed and achieved the smallest turning diameter among all TEMPSC designs tested.

6.6 Operating Limits Imposed by 46mm Thick Ice

The pass / fail results of the straight course test in 46 mm thick ice for the three lifeboats, with P1 and P2 power, are shown below.

Thickness	Floe Size	IOT Model	Power	Ice Concentration			
				5	6	7	8
46 mm	Large	627	P2		4P 2B	1B 1F	1F
46 mm	Large	628	P2	3P	2P 1B	2B	1F
46 mm	Large	667	P2		4P	2B	1F

Table 6.7 Straight course test in 46mm thick ice and large floe size, with P2 power

Thickness	Floe Size	IOT Model	Power	Ice Concentration			
				5	6	7	8
46 mm	Large	627	P1	2P	2P 1B		
46 mm	Large	628	P1	3P			
46 mm	Large	667	P1		3P		

Table 6.8 Straight course test in 46mm thick ice and large floe size with P1 power

Thickness	Floe Size	IOT Model	Power	Ice Concentration			
				5	6	7	8
46 mm	Small	627	P2		6P	1B	1F
46 mm	Small	628	P2		7P	1B	1F
46 mm	Small	667	P2		6P	1B 1F	1F

Table 6.9 Straight course test in 46mm thick ice and small floe size with P2 power

Thickness	Floe Size	IOT Model	Power	Ice Concentration			
				5	6	7	8
46 mm	Small	627	P1		6P		
46 mm	Small	628	P1		7P		
46 mm	Small	667	P1		6P		

Table 6.10 Straight course test in 46mm thick ice and small floe size with P1 power

"P" indicates that the lifeboat successfully reached 7.5 boat lengths - Pass
"B" indicates that the lifeboat reached at least 5.0 boat lengths – Borderline Pass
"F" indicates that the lifeboat did not reach 5.0 boat lengths - Fail

It should be noted that the lifeboats tend to push ice floes to the side and towards the end of the pool while they travel. Since the pool has a fixed boundary, the ice concentration at the end and at the side of the pool would be higher than the specified concentration. This would also occur in real life because the ice floes at a distance would impose a physical boundary similar to that imposed by the tank.

The TEMPSC model transit through the different ice concentrations, piece sizes and ice thickness was accomplished by using the view provided by the remote camera in the coxswain's station. This view is equivalent to that at full scale.

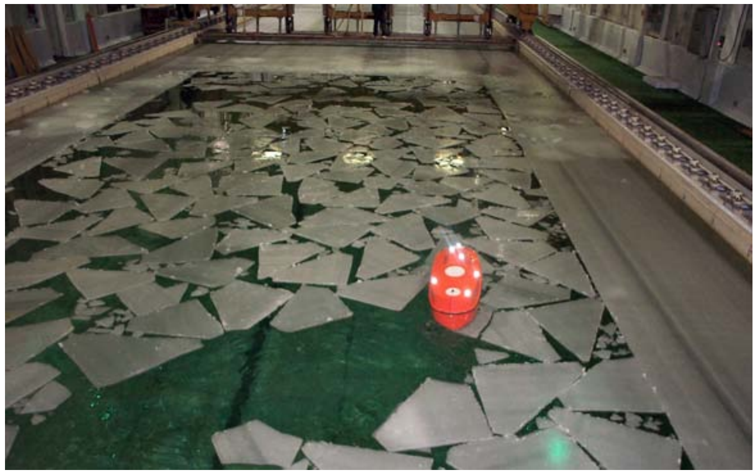

Figure 6.1 Lifeboat straight course test

Figure 6.2 Technician driving lifeboat using remote camera in coxswain's position

Selected plots of the lifeboat tracks are included in Appendix A for illustration. At the beginning of the test program, there were a few runs with the IOT 627 and IOT 628 lifeboats where the first few meters of the straight course test in ice were not tracked by the optical system. The constant distance that was not tracked was measured and the analysis results were compared with video records. The comparison agreed well. The test methodology was subsequently refined and the entire straight courses were tracked optically in later runs.

It is clear that no lifeboats successfully navigate through 8/10th ice concentration regardless of power settings, ice floe size and hull design.

At 7/10th ice concentration, lifeboats operated limitedly, some achieved a borderline pass by reaching 5 boat lengths but there was no consistency. Most lifeboats achieved borderline pass in one run and fail in another run.

At 6/10th ice concentration and small ice pieces, all lifeboats achieved the pass criteria, however, the large ice floes still restricted navigation to IOT 627 and IOT 628, as both did not consistently achieve pass criteria. IOT 667 lifeboat was the only boat that consistently achieved pass criteria in 6/10th concentration regardless of ice floe size and power settings. However, its average forward speed had a larger than normal standard deviation, indicating that the boat had more problem navigating through ice in some runs.

At 5/10th ice concentration and with either small or large ice pieces, IOT 627 and IOT 628 had no problem achieving the pass criteria.

Comparing the results between P1 and P2 power in the same condition for all three lifeboats, it is not obvious that the additional power has any major effect in extending the operating limits. In the 2003 test series (Simões Ré 2003), it was concluded that additional power only eased the performance limits modestly, if at all.

It was also observed during the tests that some ice floes got underneath the hull of the lifeboats. This happened more often with the IOT 667 lifeboat than the IOT 627 and IOT 628 lifeboats.

6.7 Average Forward Speed in Reaching 7.5 Boat Lengths in 46mm Thick Ice

The average forward speed achieved by the three lifeboat models in the thin ice sheet (46 mm, nominal) at 6/10ths concentration and powers P1 and P2 are shown below.

			Floe size							
			Large				Small			
IOT Model	Nominal Thickness [mm]	Conc. [10ths]	P1 [W]	V1avg. [m/s]	P2 [W]	V2avg. [m/s]	P1 [W]	V1avg. [m/s]	P2 [W]	V2avg. [m/s]
627	46	6	107	0.22	125	0.23	107	0.31	125	0.27
628	46	6	88	NA	129	0.33	88	0.26	129	0.29
667	46	6	120	0.34	136	0.29	120	0.29	136	0.33

Table 6.11 Average speed in 46 mm ice, 6/10ths concentration over 7.5 lifeboat lengths at powers P1 and P2

At 6/10th concentration, large floes and P1 power test condition, IOT 667 reached the target distance the fastest.

At 6/10th concentration, small floes and P1 power test condition, IOT 627 reached the target distance the fastest.

At 6/10th concentration, large floes and P2 power test condition, IOT 628 reached the target distance the fastest. It should be noted that the 0.34 m/s has a larger than normal standard deviation (0.14 m/s versus 0.06 m/s). This indicated that the boat had more problems navigating through ice in some repeat runs. It may be because the progress of the boat was blocked more by the ice floes in one run than another. It may also indicate that the operator needed to take a longer path to avoid ice floes in some runs.

At 6/10th concentration, small floes and P2 power test condition, IOT 667 reached the target distance fastest.

These results indicate no lifeboat consistently outperformed the others in thin ice, 46 mm nominal thickness and 6/10^{ths} concentration.

Comparing the performance in the same ice condition using P1 and P2 power, the results showed that the boats do not necessary reached the target distance faster with a higher power. For example, IOT 667 boat using P2 power to navigate through large floes is actually slower than P1 power (0.29 m/s at P2 power versus 0.34 m/s at P1 power). However, IOT 667 boats reached the target distance faster with P2 power than P1 power with small floes (0.33 m/s at P2 power versus 0.29 m/s at P1 power). These results indicate that higher power does not guarantee consistent better speed performance in ice conditions.

6.8 Deceleration When Impact with 46mm Thick Ice Floes

When the lifeboats travel down the tank, they often bumped into ice. Sometimes the impact was a direct hit and sometimes it was a glancing hit. In these cases, it caused a sudden change in velocity and direction. A 6 degree-of-freedom MotionPak measured the decelerations at 250 Hz throughout the tests. The x-deceleration and y-deceleration were used to compute a resultant deceleration. The largest three resultant decelerations from all the runs in a test condition were averaged and reported below. Global loads were estimated using the formula

$F = ma$,

where;

m = mass of the lifeboat in kg, and

a = average x-y resultant deceleration in m/s^2.

IOT Model	P1 Power [W]	Ice Thickness [mm]	Conc. [10^{ths}]	Floe Size	Avg. Deceleration [g]	Global Load [N]
627	107	46	6	Large	0.57	179.2
628	88	46	6	Large	NA	NA
667	120	46	6	Large	0.42	120.1
627	107	46	6	Small	0.55	172.9
628	88	46	6	Small	0.23	72.4
667	120	46	6	Small	0.25	71.5

Table 6.12 Average deceleration, P1 power, 46mm thick ice

IOT Model	Power [W]	Ice Thickness [mm]	Conc. [10^{ths}]	Floe Size	Avg. Deceleration [g]	Global Load [N]
627	125	46	6	Large	0.73	229.5
628	129	46	6	Large	NA	NA
667	136	46	6	Large	0.44	125.8
627	125	46	6	Small	0.63	198.1
628	129	46	6	Small	0.27	85.0
667	136	46	6	Small	0.26	74.3

Table 6.13 Average deceleration, P2 power, 46mm thick ice

There was no data for IOT628 at $6/10^{ths}$ concentration. It is unclear why the IOT 627 lifeboat consistently experienced higher deceleration than the other lifeboats. It is speculated that the higher values could have resulted from structural vibration, depending on how and where the instruments were mounted, because there was more ringing in IOT 627 x-y accelerometers time series.

Impact tolerance studies (for example, United States Naval Flight Surgeon's Manual, 1991) have shown that humans can withstand 10g of deceleration over durations of 0.001 second to 1.0 second without injury. Therefore, the average deceleration experienced in all lifeboats should not cause injury if the occupants are safely secured in their seats.

Higher global loads are observed at P2 power than at P1 power. The largest global load observed from the average deceleration was 229.5 N in model-scale (or 78.5 kN in full-scale). Using the formula (A Guide to Quantitative Risk Assessment for Offshore Installations 1999),

$E = 0.5\ (M/1000)\ (k)\ (v^2)$

where,

E = Impact Energy (MJ)

M = Vessel Mass (tones), 11.3 tones full scale

V = Vessel Speed (m/s), 0.87 m/s full scale (0.33 m/s model scale)

k = hydrodynamic added mass constant = 1.1 for head-on powered impact

it can be shown that E = 0.005 MJ, which is classified as minor damage to facility. There are, however, repeated impacts when a lifeboat navigates through ice. The impact energy from repeated impacts may result in damage of the hull or propulsion system, for example damage to the propeller blade.

6.9 Turning Circle in 46mm thick Ice

The turning circle results in 46mm thick ice are shown below. As mentioned before, there was a problem with the starboard rudder angle limit in the IOT 628, which allowed the nozzle to turn up to 45 degrees. The steering nozzle angle limit was set to around ± 34 degrees to match full-scale lifeboat performance. There also appeared to be a small roll offset error in the IOT 628 lifeboat for port turns. Other than these, the data was very consistent. Turning circle diameter is non-dimensionalized by the length of the model at the waterline. Selected plots of the lifeboat tracks are included in Appendix A.

IOT Model	Power P1 [W]	Turn	Conc [10^{ths}]	Speed [m/s]	Roll [deg]	Rudder Angle [deg]	Non-dimensional Turning Circle Diameter
627	107	Port	5	0.53	-0.64	-34.38	2.44
628	88	Port	5	0.26	-3.72	-34.07	3.07
667	120	Port	5	NA	NA	NA	NA
627	107	Stbd	5	0.53	0.61	34.70	2.60
628	88	Stbd	5	0.42	-0.47	44.86	2.37
667	120	Stbd	5	NA	NA	NA	NA

Table 6.14 Turning circle in ice, P1 power, 46mm thick large floes

IOT Model	Power P1 [W]	Turn	Conc [10^{ths}]	Speed [m/s]	Roll [deg]	Rudder Angle [deg]	Non-dimensional Turning Circle Diameter
627	107	Port	6	0.49	-0.27	-32.90	2.74
628	88	Port	6	0.41	-2.72	-34.18	2.73
667	120	Port	6	0.66	0.25	-32.52	2.34
627	107	Stbd	6	0.43	0.78	35.44	2.27
628	88	Stbd	6	0.33	-0.54	42.59	2.31
667	120	Stbd	6	0.59	0.16	33.26	2.70

Table 6.15 Turning circle in ice, P1 power, 46mm thick small floes

IOT Model	Power P2 [W]	Turn	Conc [10ths]	Speed [m/s]	Roll [deg]	Rudder Angle [deg]	Non-dimensional Turning Circle Diameter
627	125	Port	6	0.34	-0.30	-34.87	2.59
628	129	Port	6	NA	NA	NA	NA
667	136	Port	6	0.79	0.47	-33.98	2.31
627	125	Stbd	6	0.64	0.23	34.81	2.35
628	129	Stbd	6	NA	NA	NA	NA
667	136	Stbd	6	0.74	-0.43	33.28	2.45

Table 6.16 Turning circle in ice, P2 power, 46mm thick large floes

Boat	Power P2 [W]	Turn	Conc [10ths]	Speed [m/s]	Roll [deg]	Rudder Angle [deg]	Non-dimensional Turning Circle Diameter
627	125	Port	6	0.42	-1.07	-34.76	2.47
628	129	Port	6	0.43	-3.74	-34.10	2.50
667	136	Port	6	0.60	-0.91	-30.41	2.50
627	125	Stbd	6	0.49	0.54	33.56	2.18
628	129	Stbd	6	0.46	-0.02	43.76	2.51
667	136	Stbd	6	0.68	-0.12	31.87	2.65

Table 6.17 Turning circle in ice, P2 power, 46mm thick small floes

For all lifeboats, the turning circle diameters in 46mm thick ice are smaller than those in open water. This is because the side of the lifeboat away from the center of the turning circle is often impacting ice. Each time there is an impact, the lifeboat bounced, changed direction abruptly and turned in tighter circles.

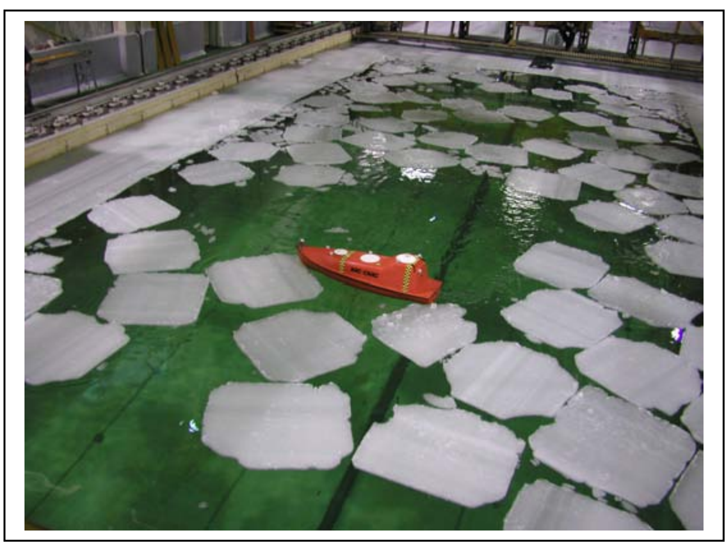

Figure 6.3 Lifeboat turning circle test.

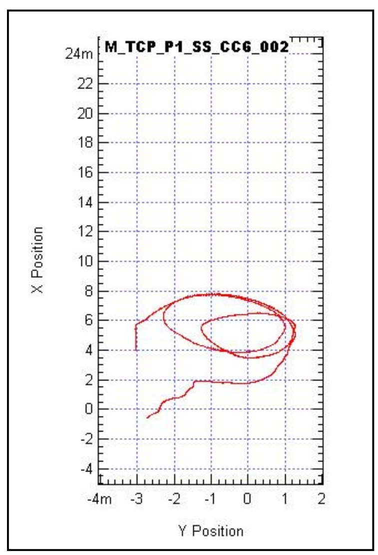

Figure 6.4 Turning circle plot

The turning circle speed of lifeboats in ice is slower than those in calm water. This is expected because the lifeboats have to push the ice floes around.

Turning circle speeds were not observed to be consistently higher at P2 power than those at P1 power. This indicates that higher power does not necessarily results in higher turning circle speed.

In most cases, the results show that the IOT 667 lifeboat was turning at a higher speed than the other two lifeboats. Also, in most cases, the turning circle diameters of IOT 667 lifeboat were smaller.

As in the straight course experiments, some ice floes got underneath the hull of lifeboats. This occurred more frequently with the IOT667 than the other two lifeboat models.

6.10 Operating Limits Imposed by 69mm Thick Ice

The pass / fail results of the straight course test in 69 mm thick ice for the IOT 667 lifeboat, with P1 and P2 power, are shown below.

IOT	Power [W]		Floe Size		Ice concentration [10^{ths}]			
Model	P1	P2	Small	Large	5	6	7	8
667	120		x				3P	
667		136	x				3P	
667	120			x		3P		
667		136		x		3P	1B 1F	

Table 6.18 Straight course tests results for the 69 mm ice thick ice and small and large floes

In the pool with the large 69mm thick ice floes (which are 15% smaller in volume and 12% lighter in mass than the large 46mm thick ice floes), there was no noticeable change in operating limits from that in 46mm thick ice for the IOT 667 lifeboat. The IOT 667 lifeboat was still unable to successfully navigate in 7/10th ice concentration. This indicated that the small decrease in volume and mass in large ice floes were not adequate to change the operating limit of the boat. Larger decrease in volume and mass may be required.

However, in the pool with the small ice floes, the boat operating limits were extended. The IOT 667 lifeboat was able to operate in 7/10th condition in 69mm thick ice when it could not operate in the same concentration in 46mm thick ice before. This could be partly due to the fact that the 69mm thick small floes were 17% smaller in volume and 12% lighter in mass than the 46mm thick small floes, which make them easier to push around.

Another possible factor may be the weaker ice flexural strength. The tests with small floes were conducted on the second day while the tests with large floes were conducted on the first day. Even though the temperature was maintained overnight around 0 degree C, the flexural strength of the ice was much weaker. The ice flexural strength in the second day was 12 to 10 kPa, compared to 25 to 21 kPa in the first day.

It was observed occasionally during the tests that due to weaker ice strength, the boat could impact a piece of ice floe and break off part of it. This makes the ice floes easier to push around. When this happened, the ice floes were less likely to lock together, preventing the passage of the boat. No repeat runs were conducted with the large floes on the second day.

6.11 Average Forward Speed in Reaching 7.5 Boat Lengths in 69mm Thick Ice

The average forward speeds for the IOT 667 to travel a distance of 7.5 boat lengths in large ice floes are shown below. The test results from the 46mm ice sheet in 6/10th concentration are duplicated here for ease of comparison.

IOT Model	Power [W]		Thickness [mm]	Conc. [10^{ths}]	Floe Size	Nominal Floe Mass [kg]	Average Speed [m/s]
	P1	P2					
667		136	69	6	Large	35.66	0.27
667		136	46	6	Large	40.27	0.29
667	120		69	6	Large	35.66	0.21
667	120		46	6	Large	40.27	0.34

Table 6.19 Average speed over 7.5 boat lengths, 69mm thick large floe

Comparing the speed results in 6/10th concentration, with 69mm thick and 46mm thick large ice floes, little difference was observed at P2 power (0.27 m/s versus 0.29 m/s respectively).

However, the speed difference is much larger when comparing results in 69mm thick and 46mm thick large ice floes with P1 power (0.21 m/s versus 0.34 m/s respectively). The IOT667 lifeboat reached the target distance faster in 46mm thick ice than in 69mm thick ice, even though the ice floe mass and size are larger in the former case.

It should be noted that the 0.34 m/s has a much larger standard deviation (±0.14 m/s) than the other average speed, which is around ±0.06 m/s. This inconsistency may be one reason why there was a large speed difference between tests in 69mm and 46mm thick large ice floes with P1 power. The large standard deviation indicated that the boat, in same ice conditions, has larger speed variations in reaching the target distance in repeat runs. This may be because the progress of the boat was blocked more by the ice floes in one run than another. It may also indicate that the operator needed to take a longer path to avoid ice floes in one run but not another.

The average forward speeds for the IOT 667 lifeboat to travel a distance of 7.5 boat lengths in small ice floes are shown below. Since the IOT 667 lifeboat failed to travel through 46mm thick ice at 7/10th concentration, the results in 6/10th concentration are listed in the table for comparison.

IOT Model	Power [W]		Thickness [mm]	Conc. [10^{ths}]	Floe Size	Nominal Floe Mass [kg]	Average Speed [m/s]
	P1	P2					
667		136	69	7	Small	17.83	0.13
667	120		69	7	Small	17.83	0.17
667		136	46	6	Small	20.14	0.33
667	120		46	6	Small	20.14	0.29

Table 6.20 Average speed over 7.5 boat lengths, 69mm thick small floe

The results in 7/10th concentration with 69mm thick ice small floes show a sharp decrease in forward speed as compare to results in 6/10th concentration with 46mm thick small floes.

6.11 Deceleration When Impact with 69mm Thick Ice Floes

The average deceleration and global load of the IOT 667 lifeboat in 69mm thick ice computed as described in section 6.8 are shown below. Results in 46mm thick ice were presented here again for ease of comparison.

IOT Model	Power P1 [Watt]	Ice Thickness [mm]	Conc. [10^{ths}]	Floe Size	Avg. Deceleration [g]	Global Load [N]
667	120	69	6	Large	0.36	102.9
667	120	46	6	Large	0.42	120.1
667	120	69	6	Small	NA	NA
667	120	46	6	Small	0.25	71.5
667	120	69	7	Small	0.25	71.5

Table 6.21 Average deceleration, P1 power, 69mm thick ice

IOT Model	Power P2 [Watt]	Ice Thickness [mm]	Conc. [10^{ths}]	Floe Size	Avg. Deceleration [g]	Global Load [N]
667	136	69	6	Large	0.41	117.2
667	136	46	6	Large	0.44	125.8
667	136	69	6	Small	No data	No Data
667	136	46	6	Small	0.26	74.3
667	136	69	7	Small	0.26	74.3

Table 6.22 Average deceleration, P2 power, 69mm thick ice

The tests in 46mm thick ice with large floes have the largest average deceleration and global load. The difference is not significantly greater from those values observed in 69mm thick ice with large floes. For small floes, essentially the same average deceleration and global load were observed in both 46mm and 69mm thick ice, in $6/10^{th}$ and $7/10^{th}$ concentration respectively. These results indicate that the change in ice condition did not cause any significant change in deceleration and global load. As humans are able to withstand 10g of deceleration over durations of 0.001 second to 1.0 second without injury, these decelerations should not cause serious injury if the occupants are safely secured in their seats. The energy from repeated impacts may result in damage of the hull and propulsion system, for example damage to the propeller blade.

6.13 Turning Circle in 69mm Thick Ice

The turning circle results in 69mm thick ice are shown below. Turing circle results in 46mm thick ice are presented here again for ease of comparison. Turning circle diameter is non-dimensionalized by the length of the model at the waterline.

IOT Model	Power P1 [Watt]	Turn	Conc [10^{ths}]	Speed [m/s]	Roll [deg]	Rudder Angle [deg]	Non-dimensional Turning Circle Diameter
46mm thick ice							
667	120	Port	6	0.64	-0.41	-30.66	2.18
667	120	Stbd	6	0.77	-0.93	33.74	2.79
69mm thick ice							
667	120	Port	6	0.59	-0.30	-33.59	2.20
667	120	Stbd	6	0.42	2.29	28.86	2.65

Table 6.23 Turning circle in ice, P1 power, 69mm thick large floes

IOT Model	Power P2 [Watt]	Turn	Conc [10^{ths}]	Speed [m/s]	Roll [deg]	Rudder Angle [deg]	Non-dimensional Turning Circle Diameter
46mm thick ice							
667	136	Port	6/10	0.79	0.47	-33.98	2.31
667	136	Stbd	6/10	0.74	-0.43	33.28	2.45
69mm thick ice							
667	136	Port	6/10	0.66	0.09	-33.62	2.65
667	136	Stbd	6/10	0.57	1.00	31.75	2.37

Table 6.24 Turning circle in ice, P2 power, 69mm thick large floes

It was observed that there was a measurable decrease in turning circle average speed in 69mm thick large ice floes for the same ice concentration. However, the turning circle diameter is not significantly different for the two ice thicknesses.

IOT Model	Power P1 [Watt]	Turn	Conc [10^{ths}]	Speed [m/s]	Roll [deg]	Rudder Angle [deg]	Non-dimensional Turning Circle Diameter
69mm thick ice							
667	120	Port	7/10	0.49	-0.73	-33.80	2.54
667	120	Stbd	7/10	0.49	0.86	32.63	2.60

Table 6.25 Turning circle in ice, P1 power, 69mm thick small floes

IOT Model	Power P2 [Watt]	Turn	Conc [10^{ths}]	Speed [m/s]	Roll [deg]	Rudder Angle [deg]	Non-dimensional Turning Circle Diameter
69mm thick ice							
667	136	Port	7/10	0.46	-0.88	-34.56	2.09
667	136	Stbd	7/10	0.44	0.98	29.46	2.90

Table 6.26 Turning circle in ice, P2 power, 69mm thick small floes

Comparing the small floes results for 7/10th concentration with P1 and P2 power, it is observed that the turning circle speed with P2 power was actually lower. With P2 power, the turning circle diameter is decreased in port turns but is increased in starboard turns. There are additional indications that the performance in ice may not necessarily be better with additional power.

6.14 Qualitative Assessment of Coxswain View inside Different Lifeboats

The pictures below from the lifeboat coxswain position video camera, showed the effect the coxswain field of view had on lifeboat navigability. A sample of the video records from the coxswain position video camera of each boat is included in Appendix B. IOT667 has its coxswain cockpit placed just forward of midships while the coxswain cockpit of IOT627 and IOT628 were near the stern.

When approaching the ice floes from a distance, it was found that there is an advantage in placing the coxswain cockpit closer to the bow. It helps the coxswain see the open water leads better and navigation is easier. IOT667 had approximately 10% less large impacts with ice floes than IOT627 & IOT628. This is estimated from averaged number of impacts per run between models in 6/10th concentration with 46mm thick large floes and P2 power. It is believed that the better coxswain frontal view helped IOT 667 navigate through ice.

However, it should be noted that none of the lifeboats coxswain cockpit position allowed the coxswain to see the area immediately in front of the lifeboat. For visual navigation the coxswain must estimate the positions of the ice floes relative to the moving TEMPSC. In this series of experiments this need is somewhat minimized since there were no waves to randomly move the ice floes around. Also, the coxswain could not see when a large piece of ice were lodged in front of the bow and if this happened for a prolonged period, the lifeboat forward speed was reduced quickly, hindering its travel.

Figure 6.5 Coxswain's view, IOT 627

Figure 6.6 Coxswain's view, IOT 628

Figure 6.7 Coxswain's view, IOT 667

6.15 Best Practices in Navigating Through Ice Observed in the Test Program

In the test program, the technicians attempted different ways to navigate through ice floes. It was observed that the most effective means of navigating through ice floes was to manoeuvre like "blind man walking". If possible, navigate through the open water in between ice floes. When stuck in front of a piece of ice floe, do not forcefully push forward because the lifeboat can quickly lose momentum. Try steering to one side and then another to get free. Sometimes, the technician may have to turn the boat almost sideways.

A couple of tests were also conducted in slush ice. Although no quantitative data was collected because the lifeboats could not navigate through slush ice, it was observed that by rocking back and forth, the lifeboat could make very limited travel over time.

7.0 Conclusions

1. Open water speed tests, demonstrated that all lifeboats using P1 power could repeatedly achieve a speed close to 6 knots full scale. The estimated P1 power for IOT627, IOT628 and IOT667 lifeboats were 107W, 88W and 120W, respectively.

   At P2 power, all lifeboats achieved a faster speed, which was obtained by limiting the maximum motor current to 4 amps, the nominal rating of the batteries used to power the lifeboat models. The estimated P2 power for IOT627, IOT 628 and IOT 667 lifeboats were 125W, 129W and 136W respectively. The speeds achieved by the three lifeboats at P2 power were 6.32 knots, 6.79 knots and 6.34 knots respectively.

IOT Model	Power P1 [Watts]	Speed V1 [knots]	Power P2 [Watts]	Speed V2 [knots]	% Increase P	% Increase V
627	107	5.91	125	6.32	16.8	6.9
628	88	5.97	129	6.79	46.6	13.7
667	120	5.94	136	6.34	13.3	6.7

The variations in speed among the different lifeboat models were attributed to hull design, resistance etc. associated with different design.

2. Bollard pull tests showed that tow force using P2 power was increased by 10%, 31% and 13% over P1 power for IOT 627, 628 and 667 respectively. Model 667 was able to deliver higher tow force at lower RPM than the other lifeboats with the same motor and power supply because of its hull design and high torque propeller.

3. Decay tests showed that IOT 667 has lower damping coefficient in roll, pitch and heave than IOT 627 and 628. It also has the lowest pitch and heave natural periods.

4. Open water turning circle test results showed that the IOT 667 lifeboat had the fastest turning speed for both P1 and P2 powers and consistently achieved the smallest turning circle diameter.

5. In the straight course tests in 46mm thick ice to determine the operating limits of lifeboats, the results demonstrated that –

   a. IOT 667 lifeboat was the only boat that consistently achieved pass criteria in $6/10^{th}$ concentration regardless of the power settings and ice floe size. The IOT 627 and IOT 628 lifeboats were only able to consistently achieve pass criteria in $6/10^{th}$ concentration with small ice floes but not with large floes.

   b. IOT 627 and IOT 628 were able to consistently achieve pass criteria in $5/10^{th}$ concentration with large floes regardless of power setting.

c. At 7/10th concentration, all lifeboats operated limitedly. Some achieved borderline pass in one run and failed in another run. There was no consistency.

d. No lifeboat was able to navigate successfully in 8/10th concentration.

e. Higher P2 power was not seen to have significant effects in extending the operating limits.

6. In the straight course tests in 69mm thick ice to determine the operating limits of lifeboats, the results showed that –

   a. Operating limits for IOT 667 in 69mm thick large ice floes did not change from those in 46mm thick large ice floes. IOT 667 was still unable to achieve consistent passage in 7/10th ice concentration with either P1 or P2 power. The large 69mm thick ice floes are 15% smaller in volume and 12% lighter in mass than the large 46mm thick ice floes. Perhaps a larger decrease in ice floe volume and mass are required to extend the boat operational limit.

   b. Operating limits for IOT 667 lifeboat in 69mm thick small ice floes was eased from those in 46mm thick small ice floes. The IOT 667 lifeboat was able to achieve consistent pass in 7/10th ice concentration. The 69mm thick small floes were 17% smaller in volume and 12% lighter in mass than the 46mm thick small floes, which may make them easier to push around. Another possibility was that the weaker ice strength enabled the lifeboat to occasionally break the ice it impacted into smaller pieces, which became easier to move around. The exact change in ice conditions that eased the operating limits for the IOT 667 lifeboat were not found in these tests. It may be worthwhile to investigate the effects of ice flexural strength on lifeboat travel through ice in the future.

7. The speed results for straight course tests in 46mm ice showed that no single lifeboat consistently reached the target distance fastest in all ice conditions. (At P1 power, 6/10th ice concentration, IOT 667 and IOT 627 reached the target distance fastest in large and small ice floe conditions respectively. At P2 power, 6/10th ice concentration, the IOT 628 and IOT 667 reached the target distance fastest in large and small floe conditions respectively.) The open water gains due to P2 were not translated for ice.

   Also, lifeboats when equipped with higher P2 power were not seen to consistently reach the target distance faster. In some cases, lifeboats actually reached the target distance faster with P1 power than with P2 power. In ice, additional power does not necessarily guarantee better speed performance. The variation could be due to random ice floe distribution causing more impacts or the operator took a longer path to avoid ice.

8. The IOT 667 lifeboat speed results for straight course tests in 6/10th concentration, with 69mm thick large floes showed the following -

    a. At P2 power, minor change in large ice floe mass and size did not cause measurable performance change. There was little difference in speed from tests conducted in 46mm ice with large floes.

    b. At P1 power, there was a measurable speed difference between tests conducted in 69mm thick ice and 46mm thick ice. The IOT 667 lifeboat reached the target distance faster in 46mm thick ice than in 69mm thick ice, even though the ice floe mass and size are slightly larger in the former case. It should be noted that there was a larger than normal standard deviation in the IOT 667 speed in 46mm thick ice, which may explain the speed difference observed.

9. The averaged largest x-y deceleration measured when lifeboats impacted ice floes in 46mm and 69mm thick ice ranged from 0.2 to 0.7g. The decelerations were measured using an accelerometer at 250Hz sample rate. These deceleration values are not expected to cause serious injuries to occupants if they are securely fastened in their seats.

10. The global force observed when lifeboats impacted ice floes in 46mm and 69mm thick ice ranged from 71 to 230 N in model scale. The impact energy from repeated impacts with ice floes may result in damage of the hull and propulsion system.

11. The turning circle results in 46mm thick ice showed that the IOT 667 was turning at higher speeds and achieving smaller turning circle diameters than other lifeboats, in most ice conditions and power settings.

    In 6/10th concentration with 69mm thick ice large floes, there was no significant change in turning circle diameter when the IOT 667 lifeboat was tested. However, there was a measurable decrease in turning circle speed in the thick ice, for the same ice concentration. The cause for the decrease in speed is not known because the size and mass of 69mm thick large ice floe were nominally smaller than those of the 46mm thick large ice floe.

    Comparing the small floes results for 7/10th concentration with P1 and P2 power, it is observed that the turning circle speed with P2 power was actually lower. With P2 power, the turning circle diameter is decreased in port turns but is increased in starboard turns. These inconsistent results are additional indications that the performance in ice may not necessarily be better with additional power.

12. It was observed during the tests that some ice floes got underneath the hull of the lifeboats. The happened much more often with the IOT 667 boat than the IOT 627 and IOT 628 lifeboats. This may be due to hull shape design of IOT 627.

13. Qualitatively there seems to be an advantage in placing the coxswain's cockpit forward of midships and closer to the bow. It seems the coxswain frontal field of view is better and aids in the selection of open water in the ice field from a distance. It is believed that the improved coxswain view helped IOT 667 navigate through the different ice conditions. However, none of the lifeboats designs allows the coxswain to see the area immediately forward of the lifeboat. If relying on visual navigation the coxswain must estimate the position of ice floes relatively to the moving TEMPSC. While this is possible in the current test series (calm, no wave conditions), it will be a challenge when waves are added and they randomly move the ice floes around.

14. The best practice to navigate through ice floes seemed to be to maneuver the lifeboat like "blind man walking". If possible, navigate through the open water in between ice floes. When stuck in front of a piece of ice floe, do not forcefully push forward because the lifeboat would quickly lose momentum. Attempt steering to one side and then another to get free. Sometimes, the lifeboat might have to turn almost sideways.

15. The best practice to navigate through slush ice was to rock back and forth.

8.0 References

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9.0 Acknowledgement

The financial support of the PERD Marine Transportation and Safety Committee is gratefully acknowledged.

Appendix A

Selected plots of the lifeboat tracks

File Naming Convention

Boat_Test_Power_FloeSize_CC_TestNumber
Where

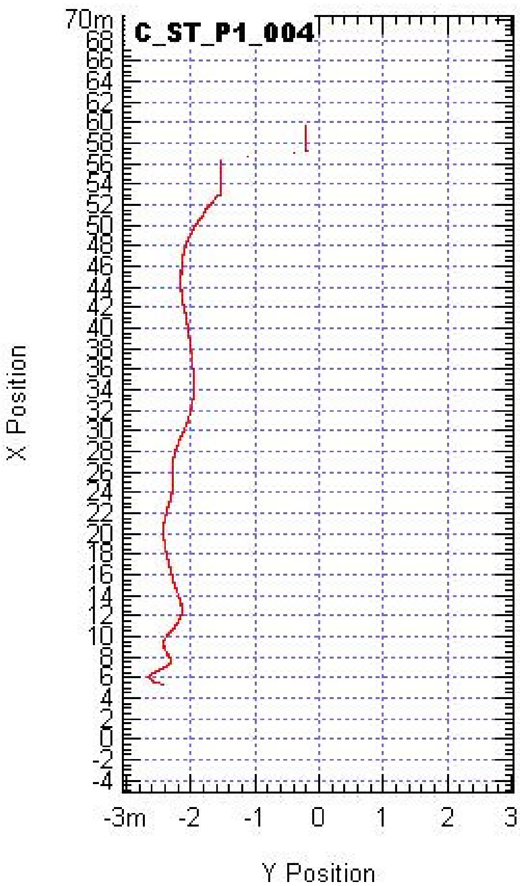
Boat = C = IOT 627 lifeboat
Boat = FF = IOT 628 lifeboat
Boat = MR = IOT 667 lifeboat

Test = ST = Straight course
Test = TCP = Turning circle port
Test = TCS = Turning circle starboard

Power = P1 = Power for 6 knot full scale
Power = P2 = Additional power

FloeSize = SL = Large floe
FloeSize = SS = Small floe

CC = Concentration (If *CC* is absent, it is an calm water run)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64
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34
32
30
28
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14
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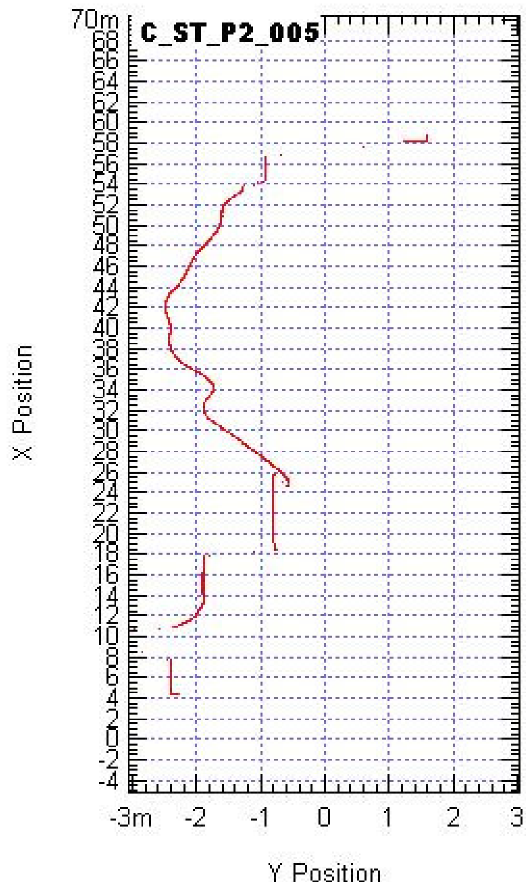
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32
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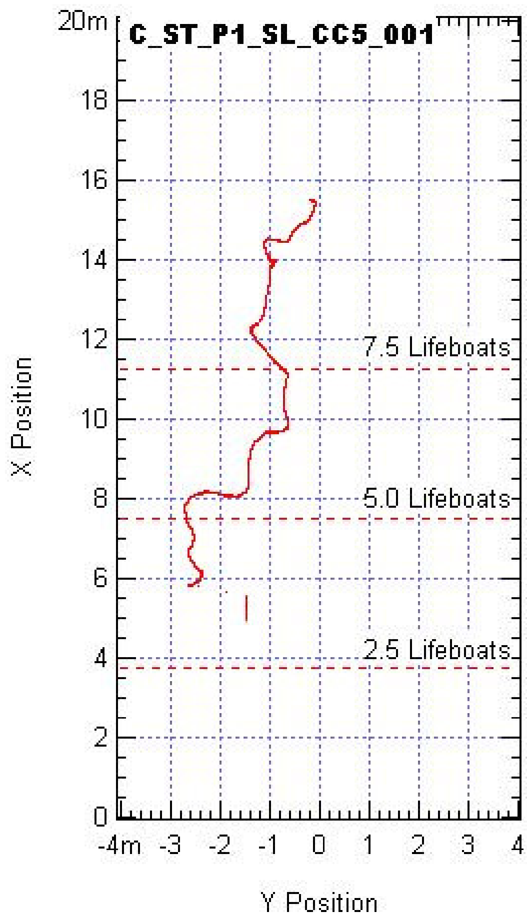

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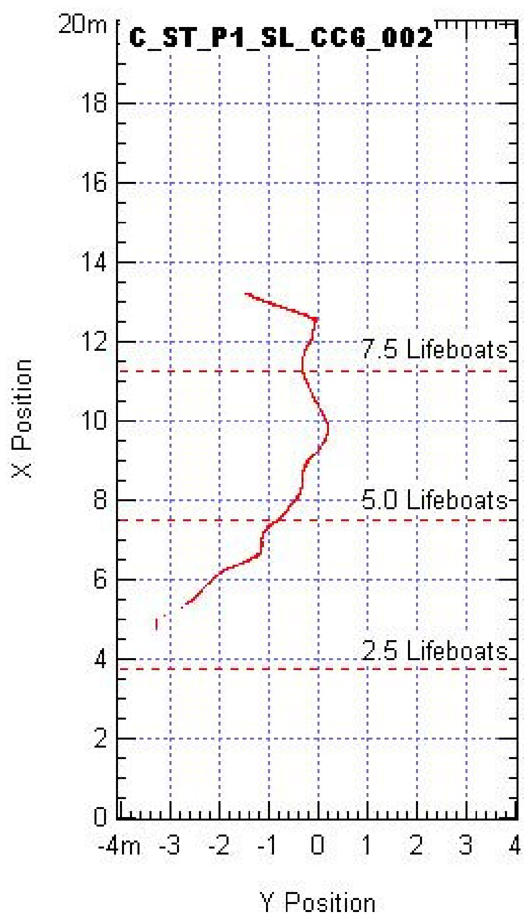
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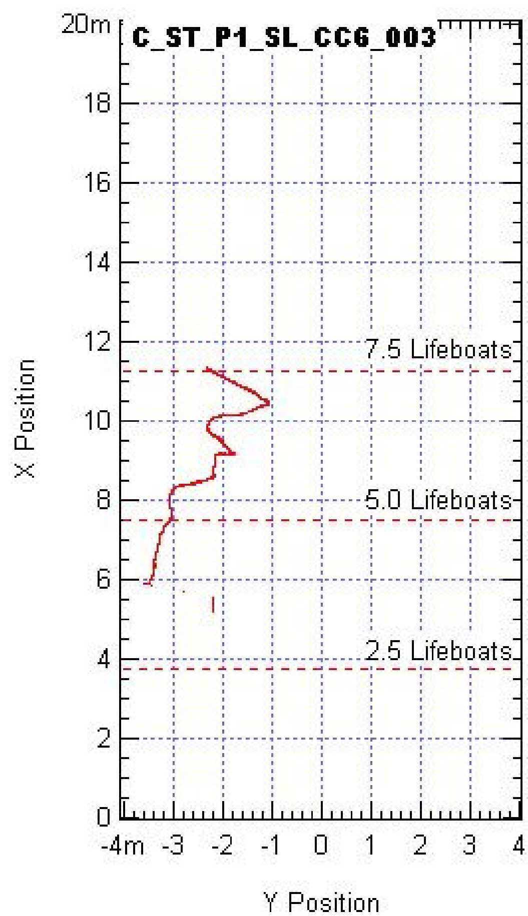
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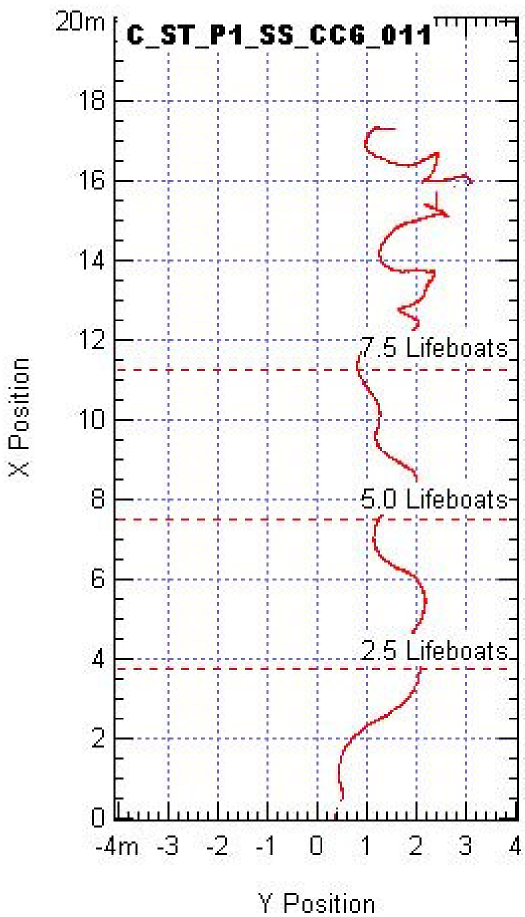

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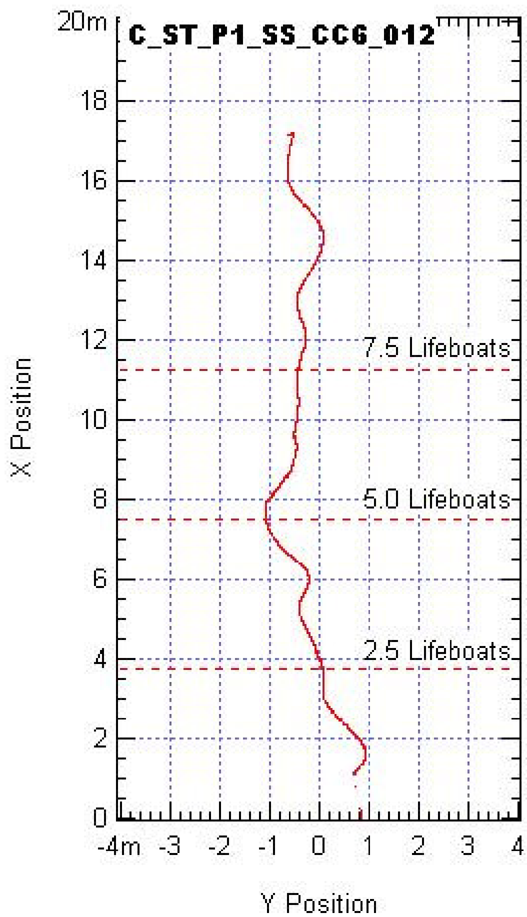

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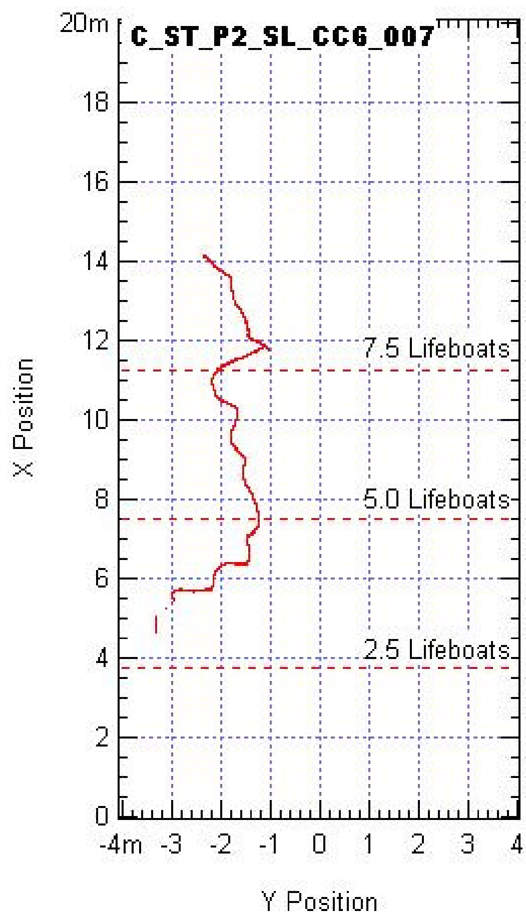

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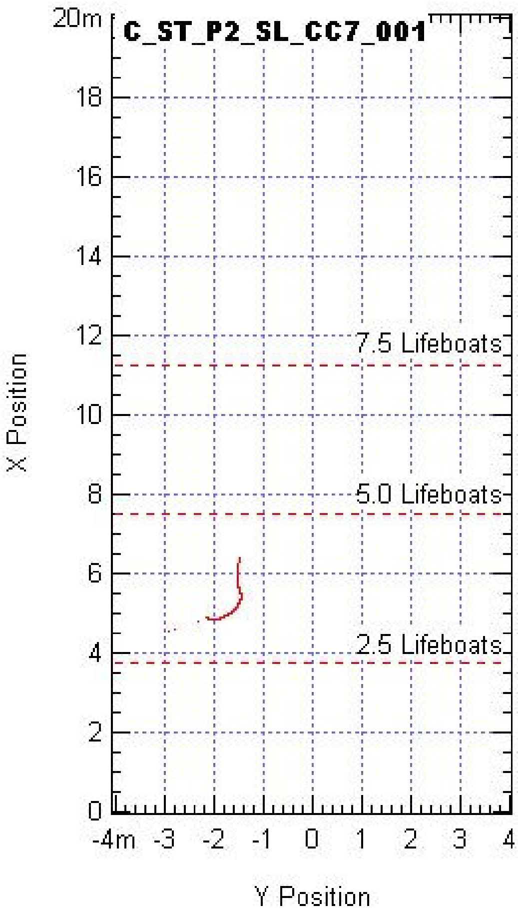
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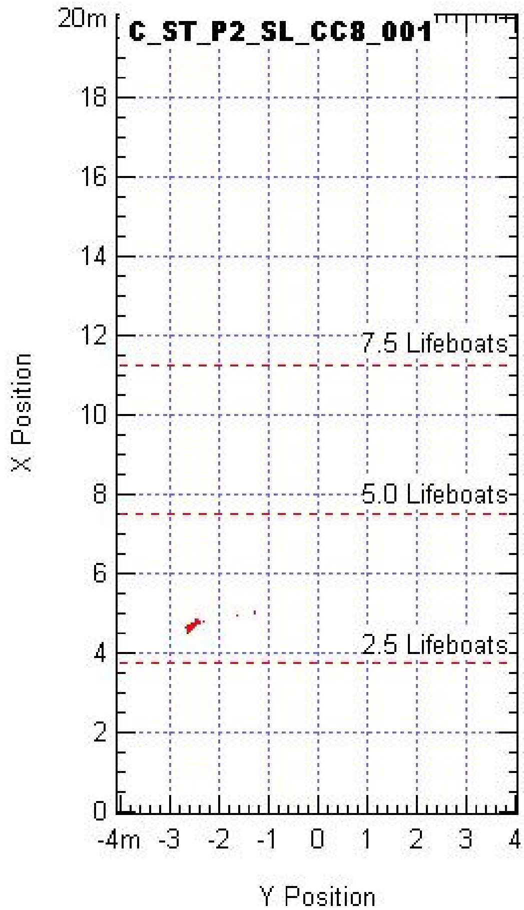
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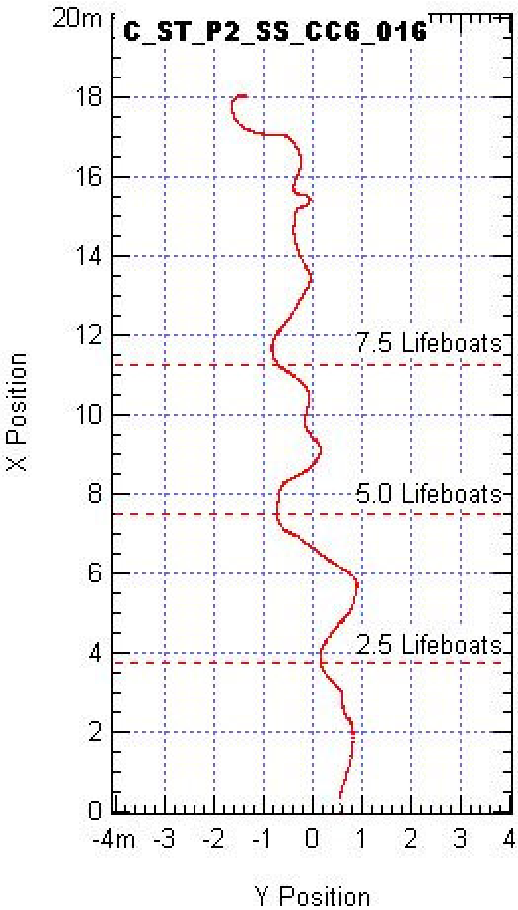
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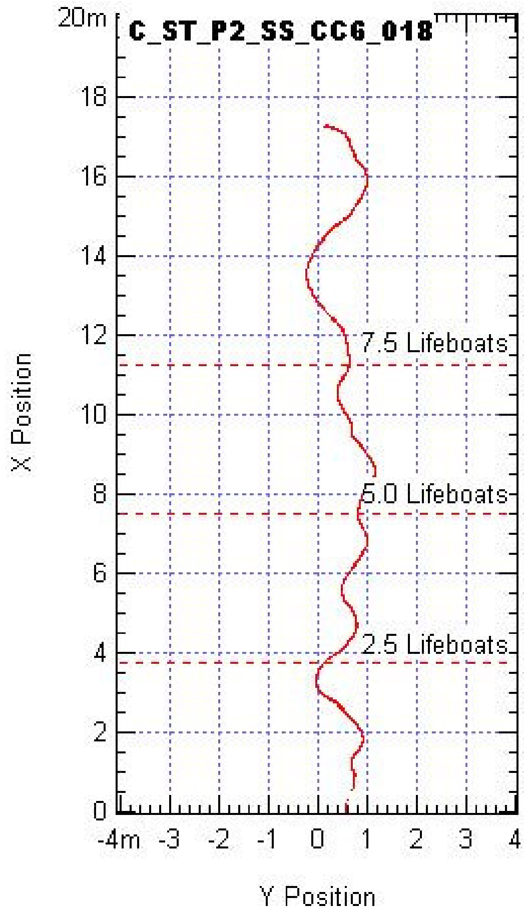
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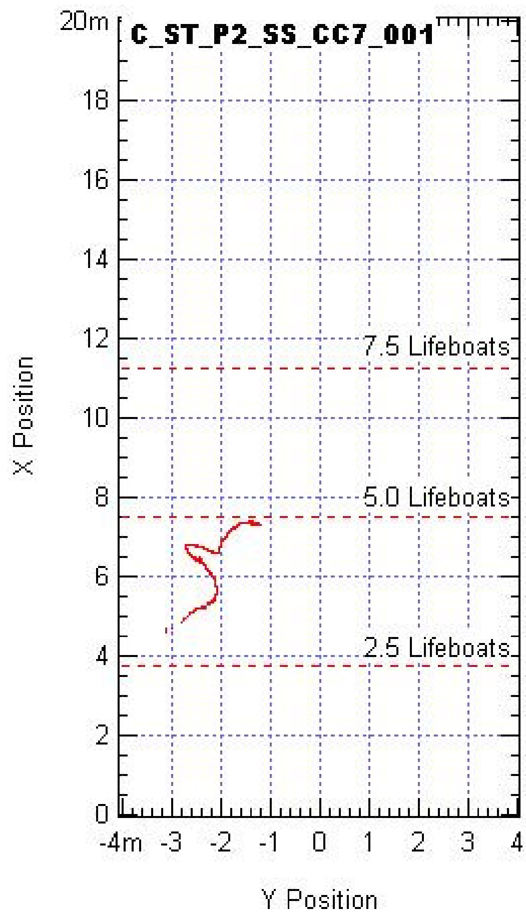
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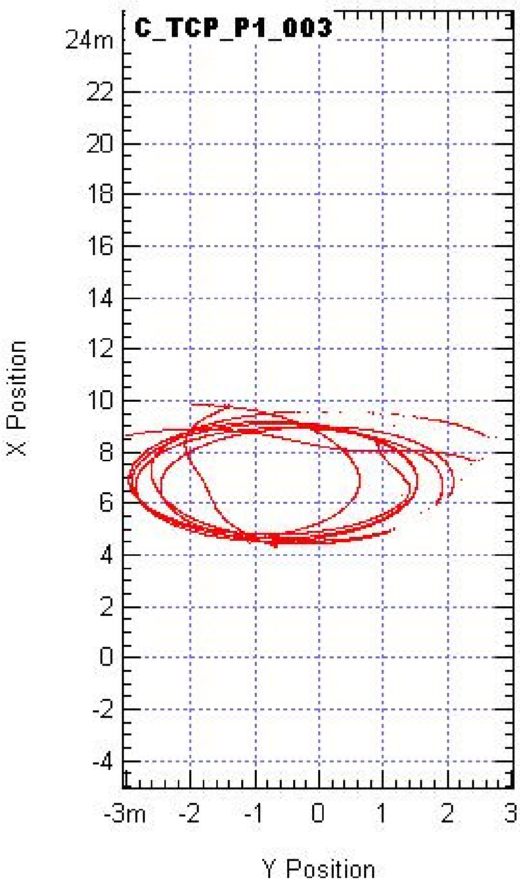
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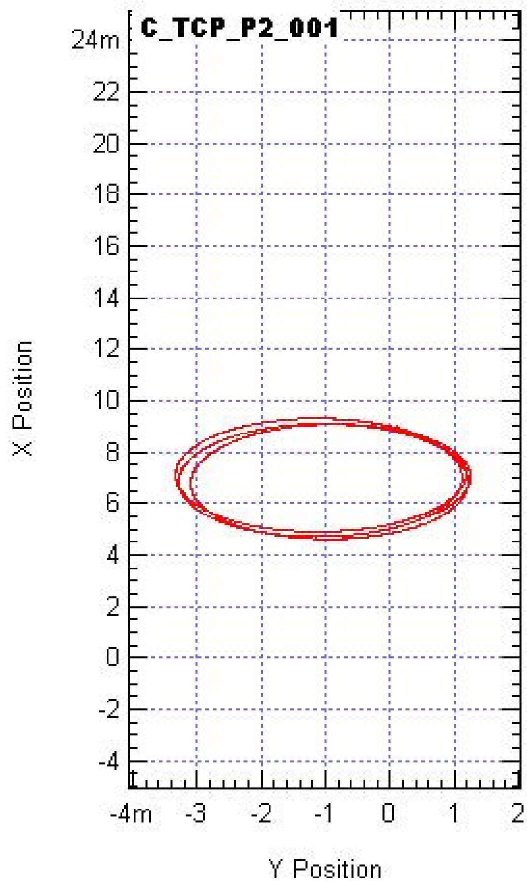
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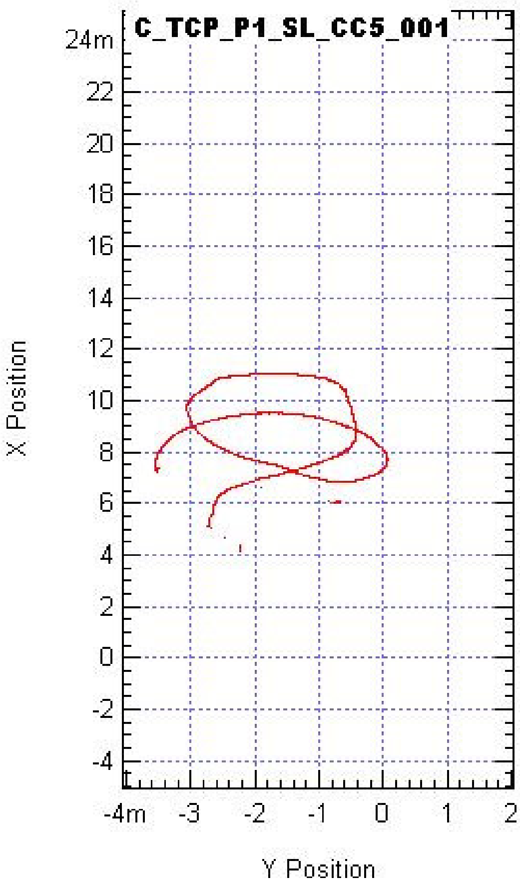
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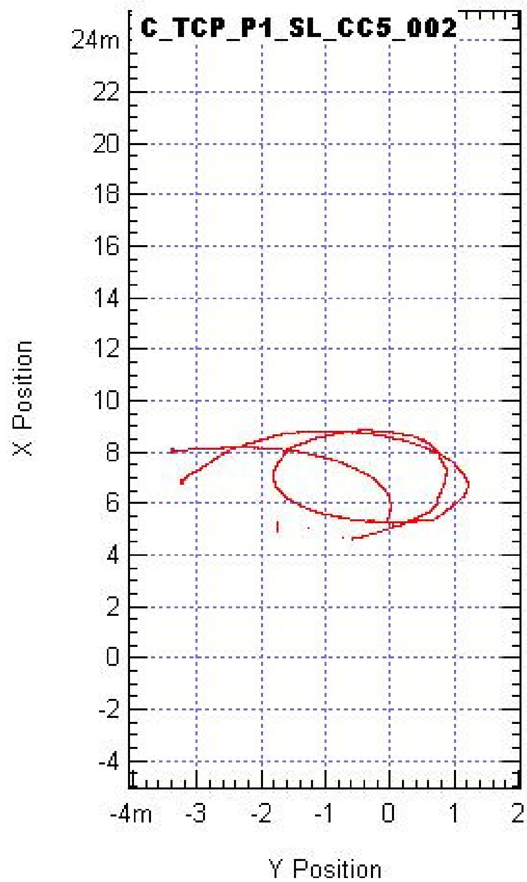
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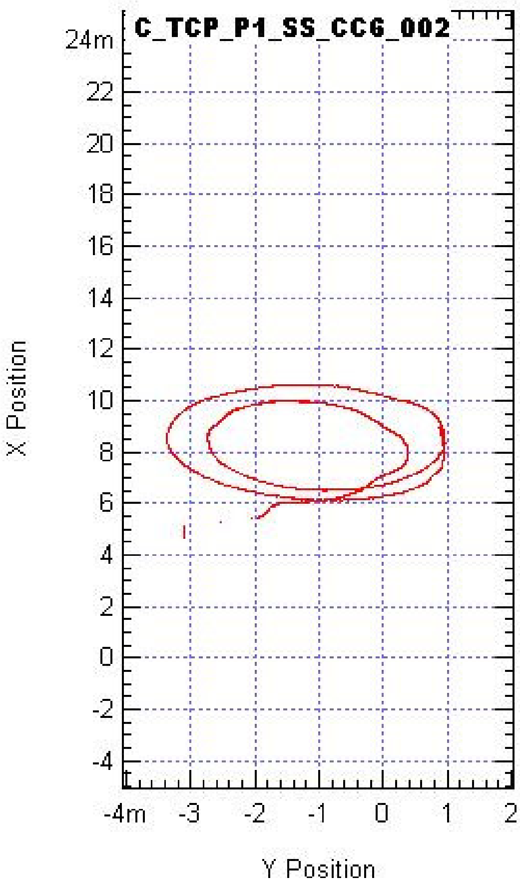
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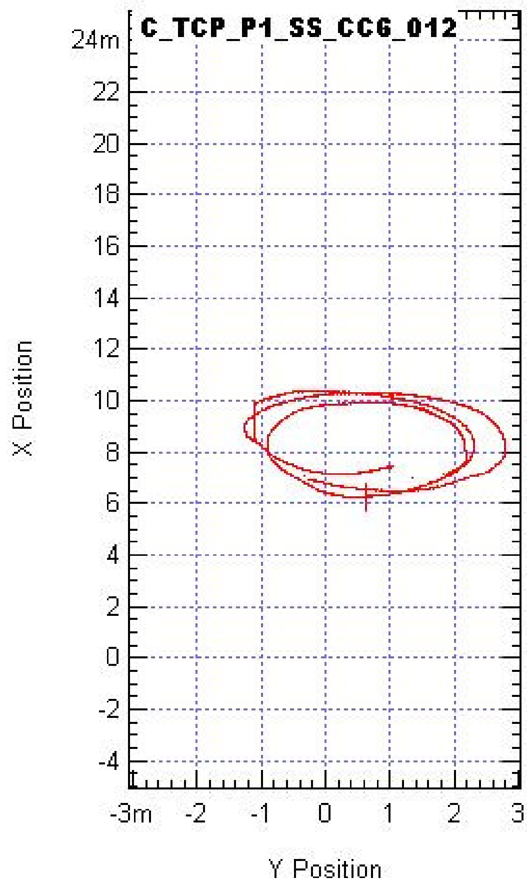
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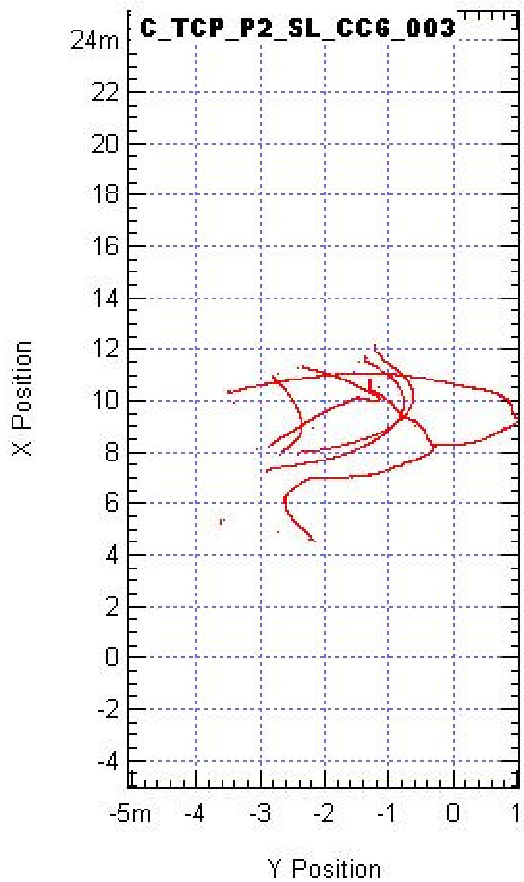
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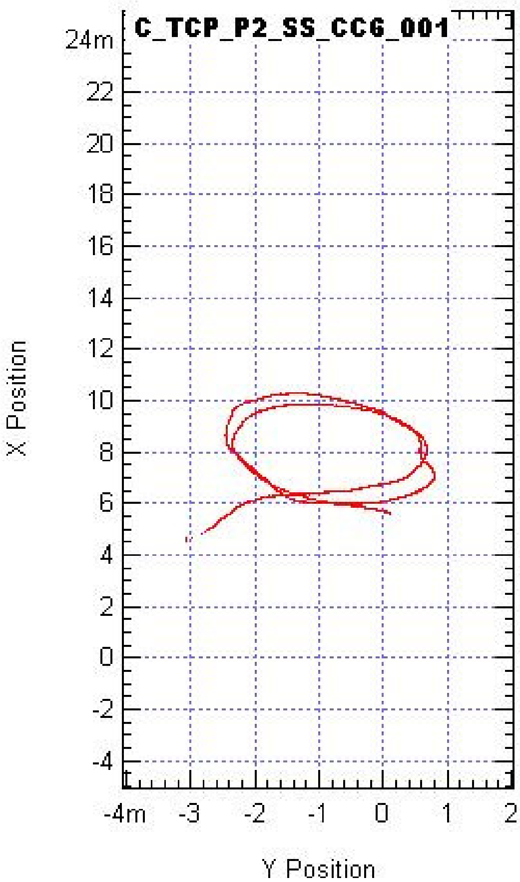

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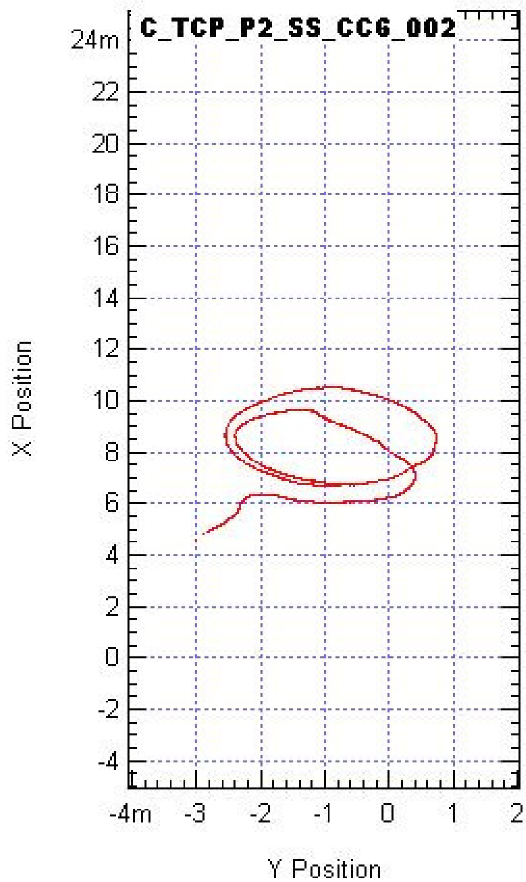

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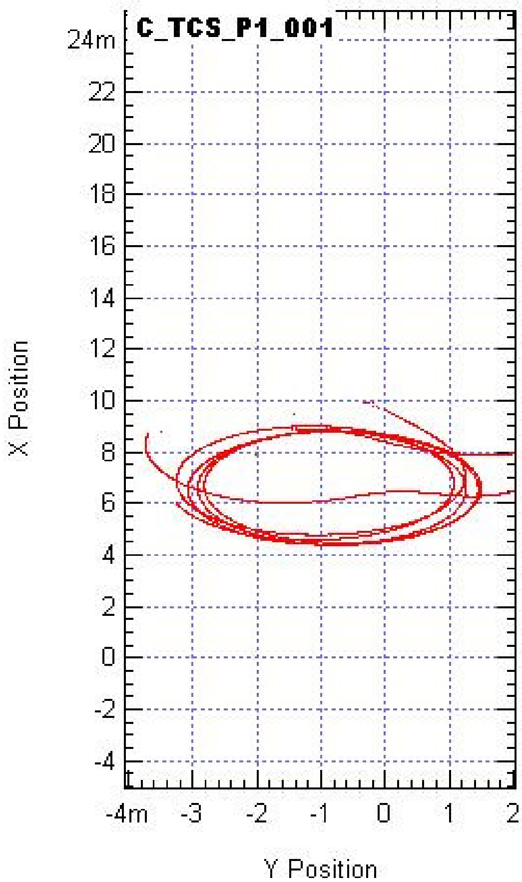
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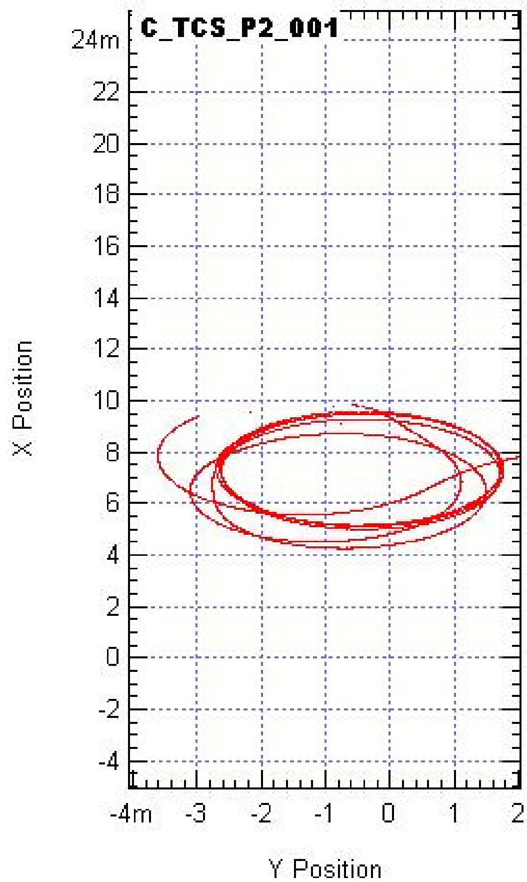
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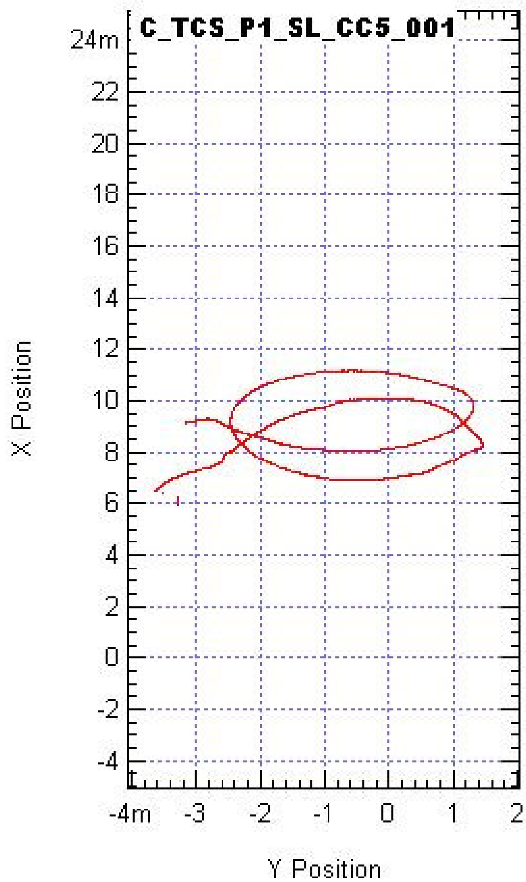
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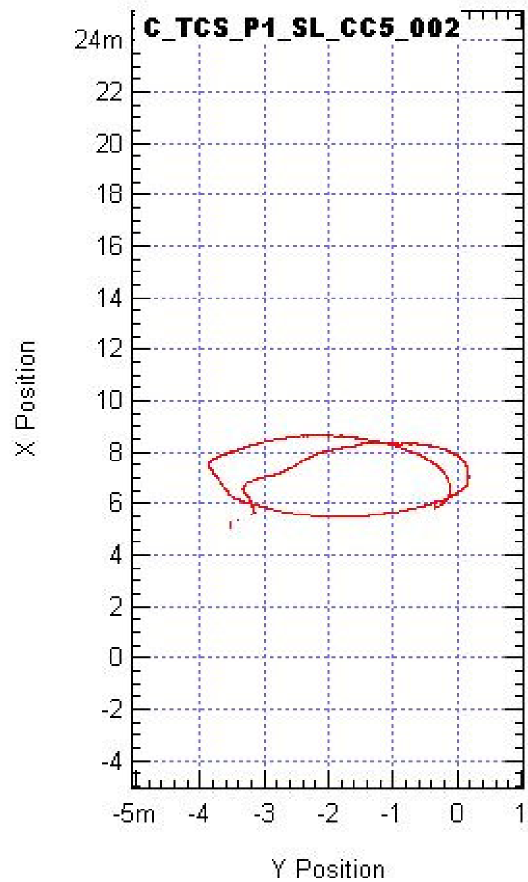
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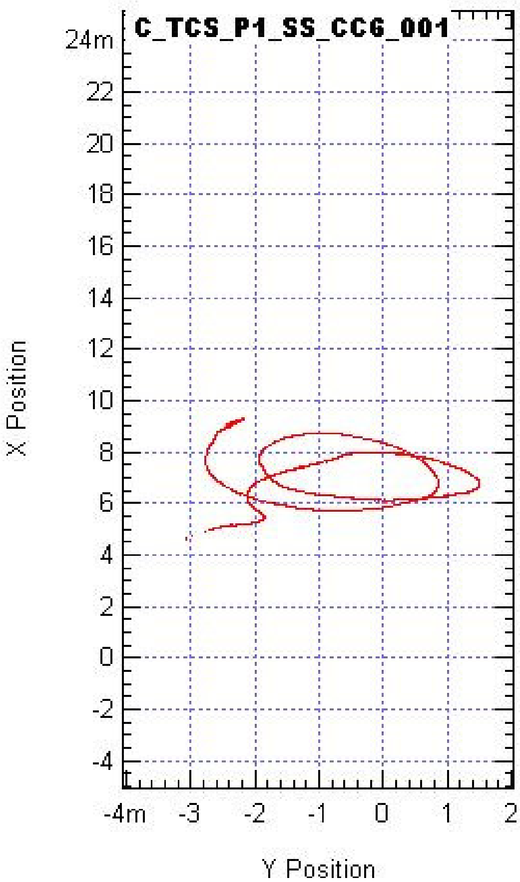
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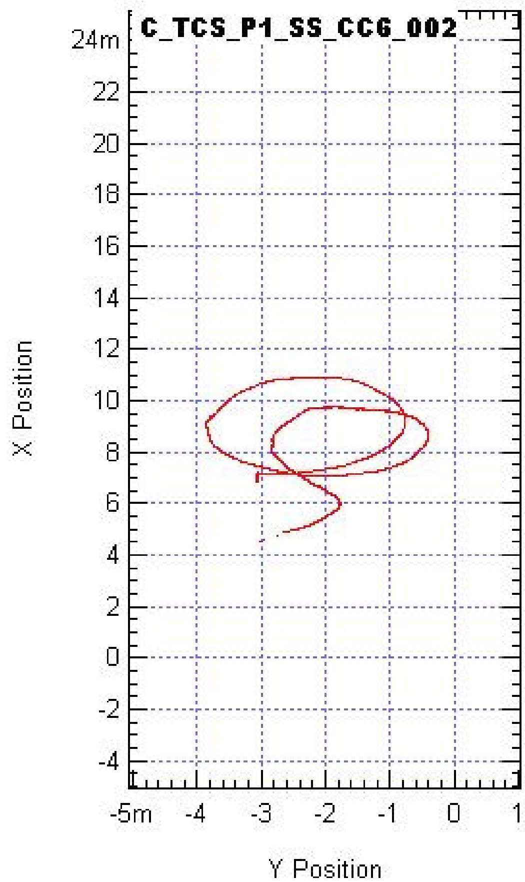
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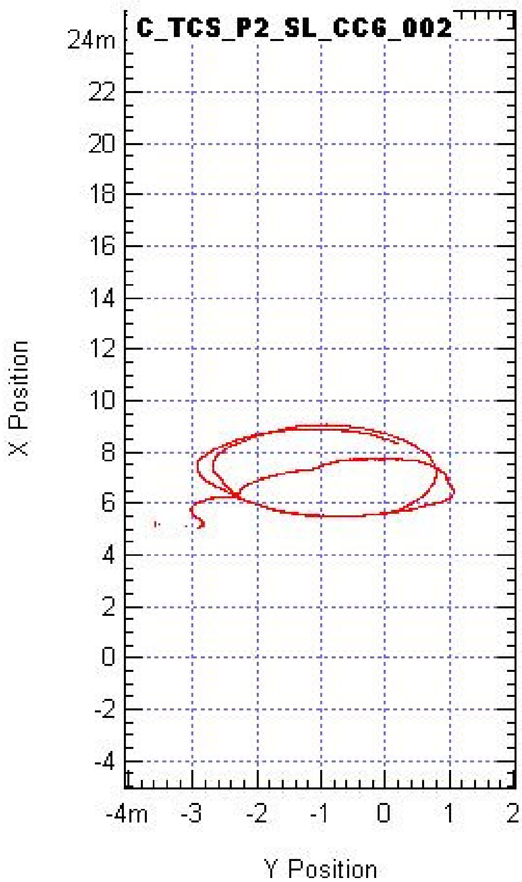
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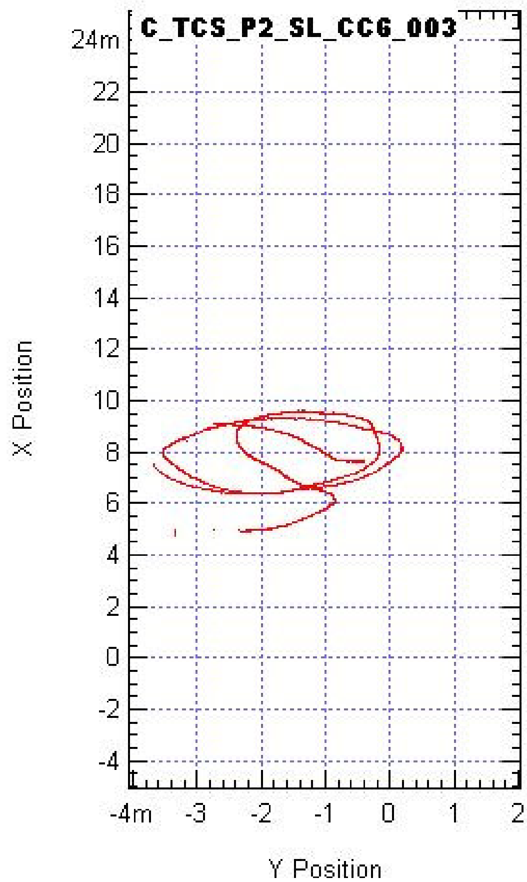
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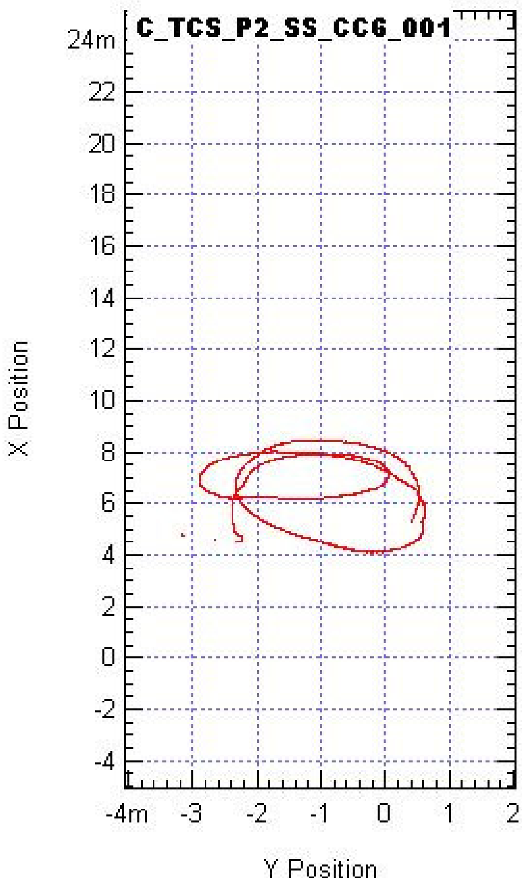
Y Position


C_TCS_P2_SS_CCG_001
24m
22
20
18
16
14
12
10
8
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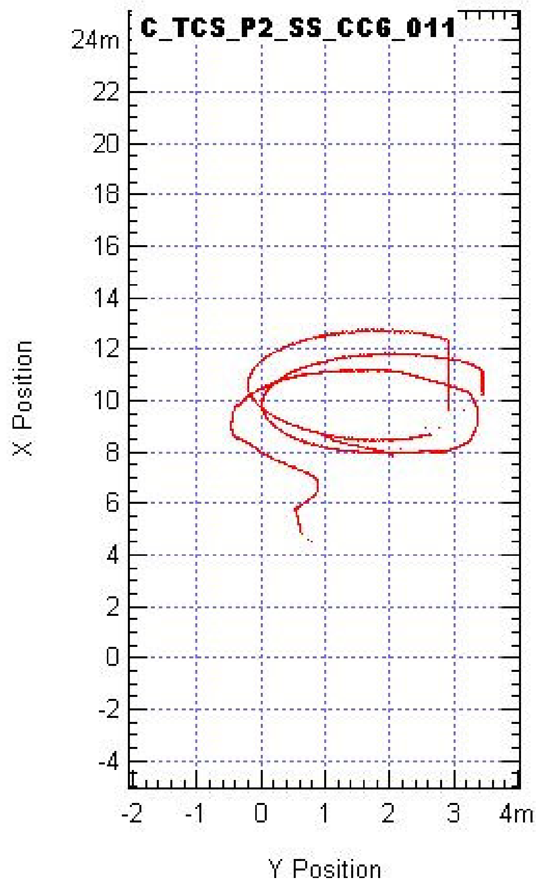
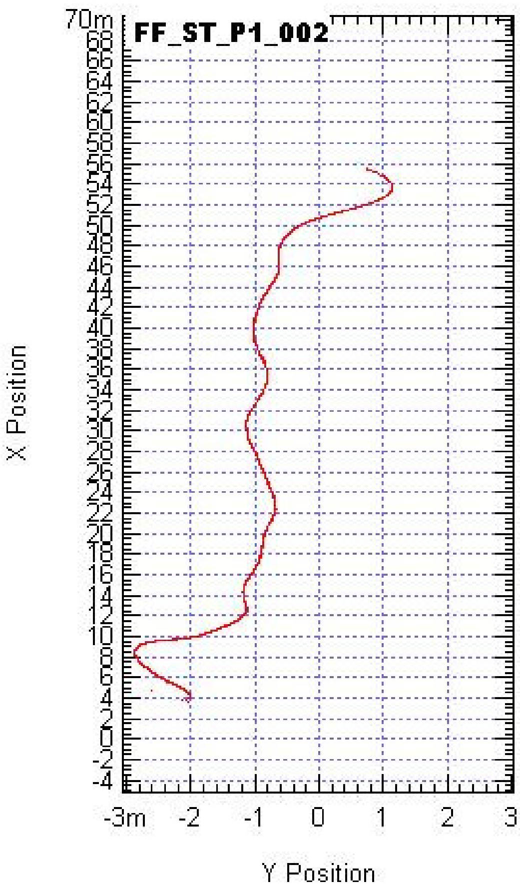
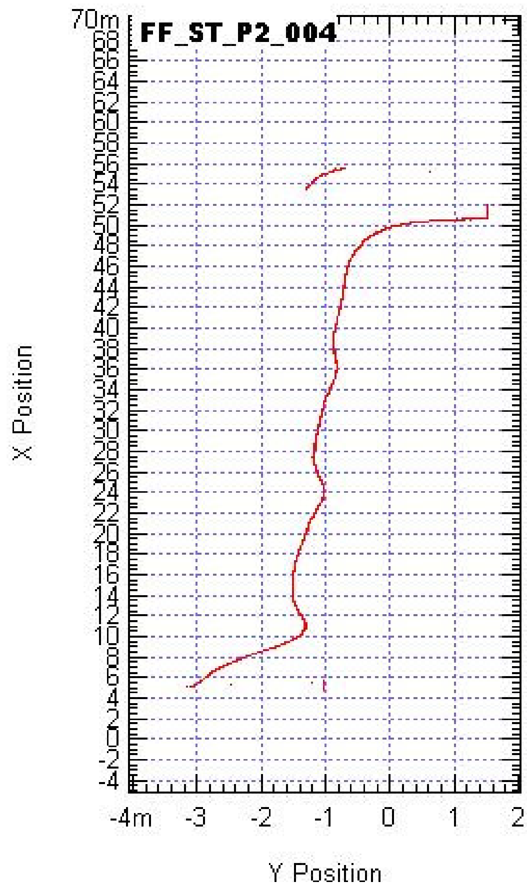
4
2
0
-2
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position


C_TCS_P2_SS_CCG_011
24m
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
X Position
-2
-1
0
1
2
3
4m
Y Position


FF_ST_P1_002
X Position
Y Position


FF_ST_P2_004
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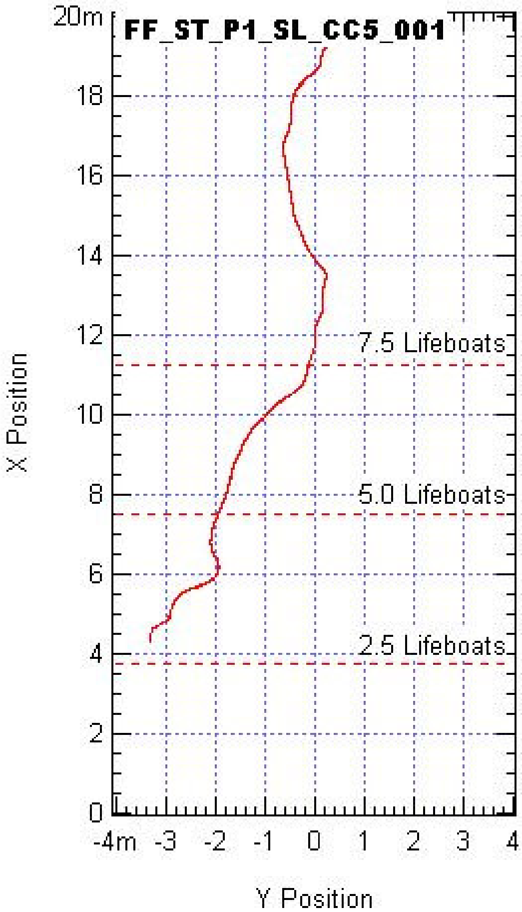
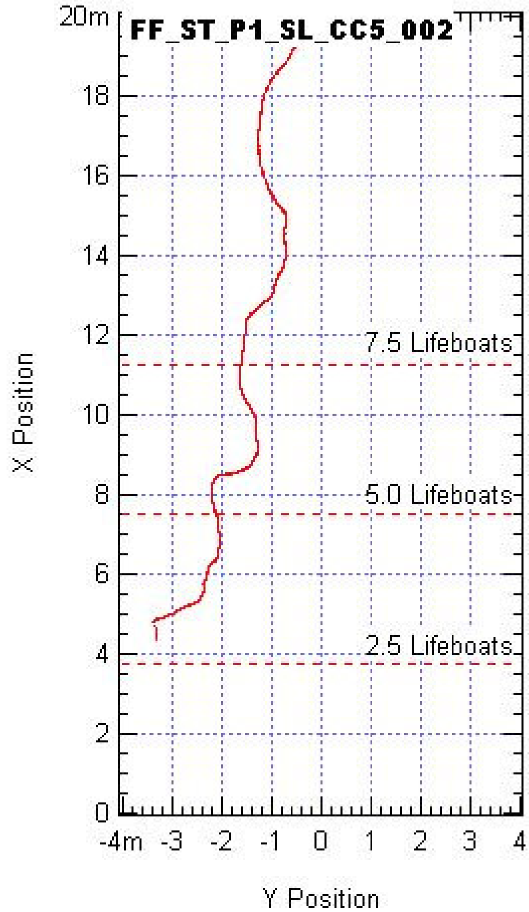
Y Position


FF_ST_P1_SL_CC5_001
20m
18
16
14
12
10
8
6
4
2
0
X Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
-4m -3 -2 -1 0 1 2 3 4
Y Position


FF_ST_P1_SL_CC5_002
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12
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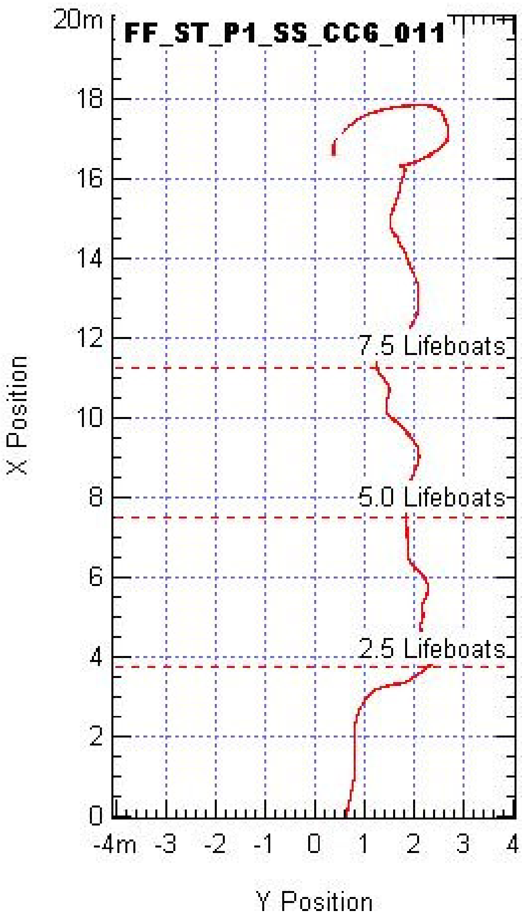
X Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
-4m -3 -2 -1 0 1 2 3 4
Y Position



FF_ST_P1_SS_CCG_011
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4
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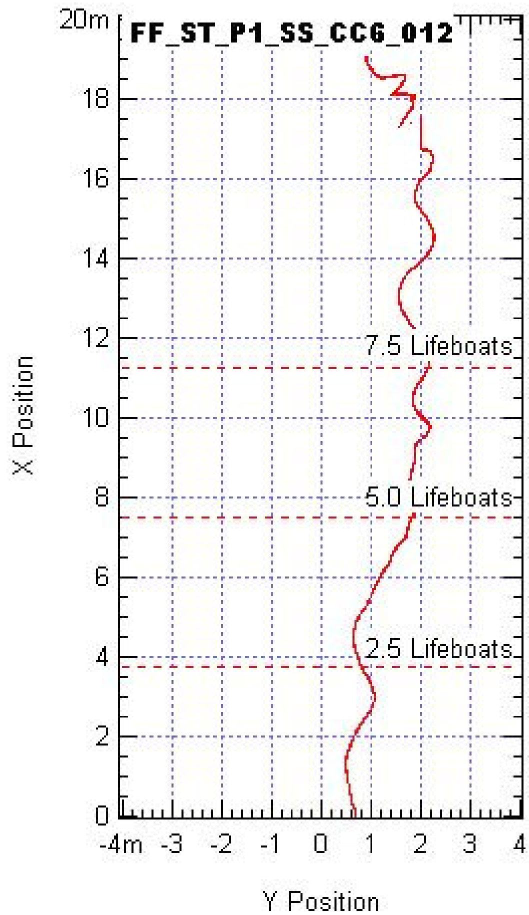
X Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
-4m -3 -2 -1 0 1 2 3 4
Y Position



FF_ST_P1_SS_CCG_012
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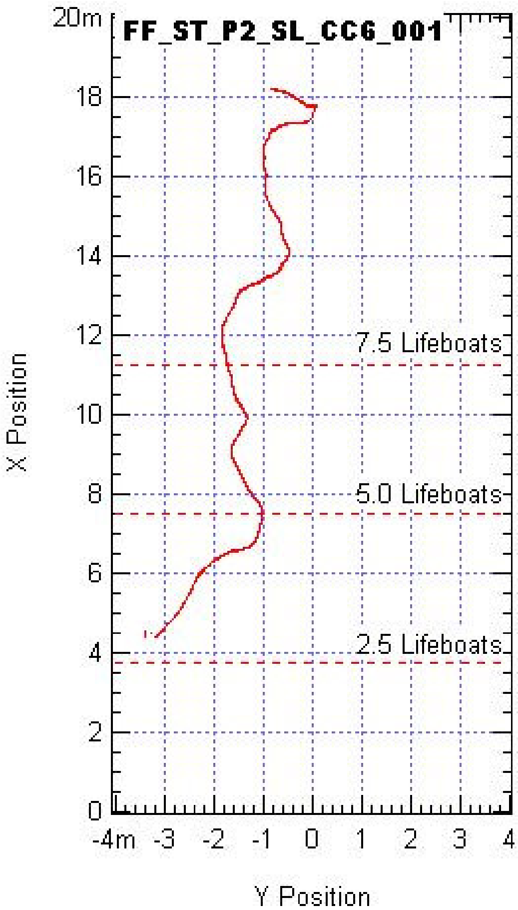
X Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
-4m -3 -2 -1 0 1 2 3 4
Y Position


FF_ST_P2_SL_CCG_001
20m
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12
10
8
6
4
2
0
X Position
-4m
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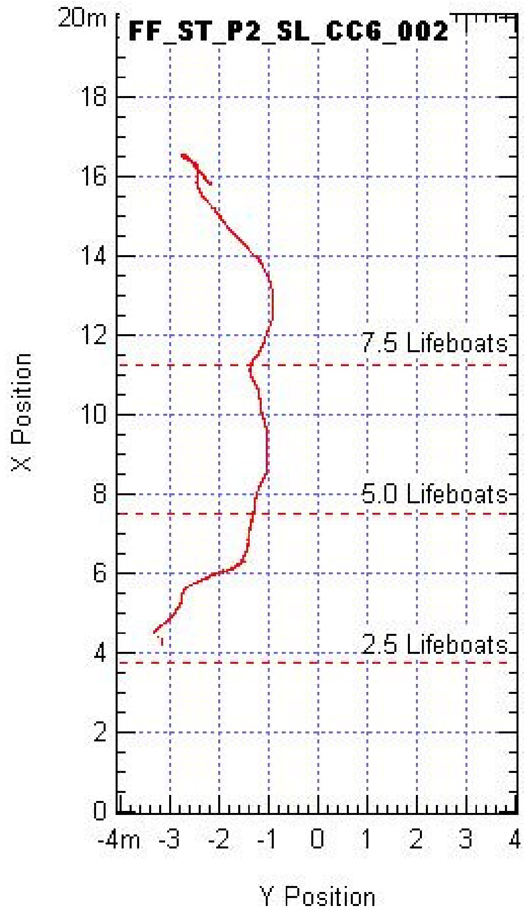
-2
-1
0
1
2
3
4
Y Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats


FF_ST_P2_SL_CCG_002
20m
18
16
14
12
10
8
6
4
2
0
X Position
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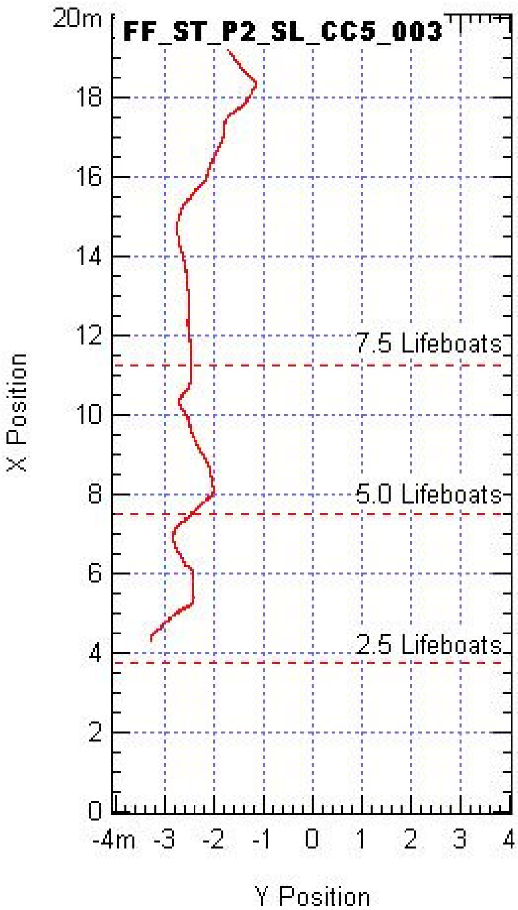
Y Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats


FF_ST_P2_SL_CC5_003
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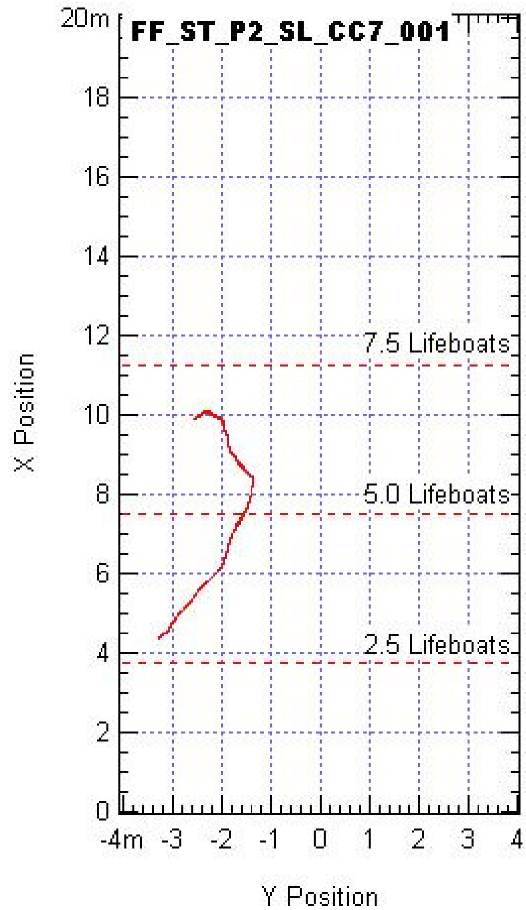
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
X Position
-4m -3 -2 -1 0 1 2 3 4
Y Position


FF_ST_P2_SL_CC7_001
20m
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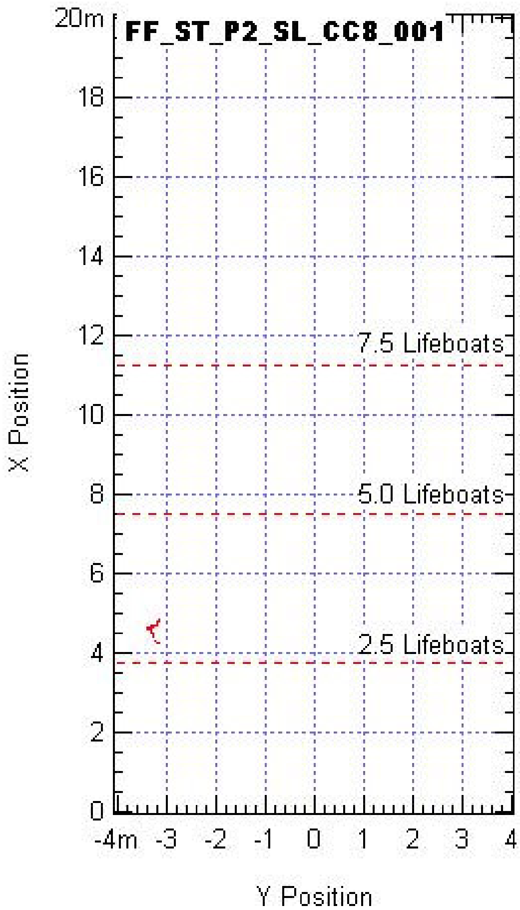
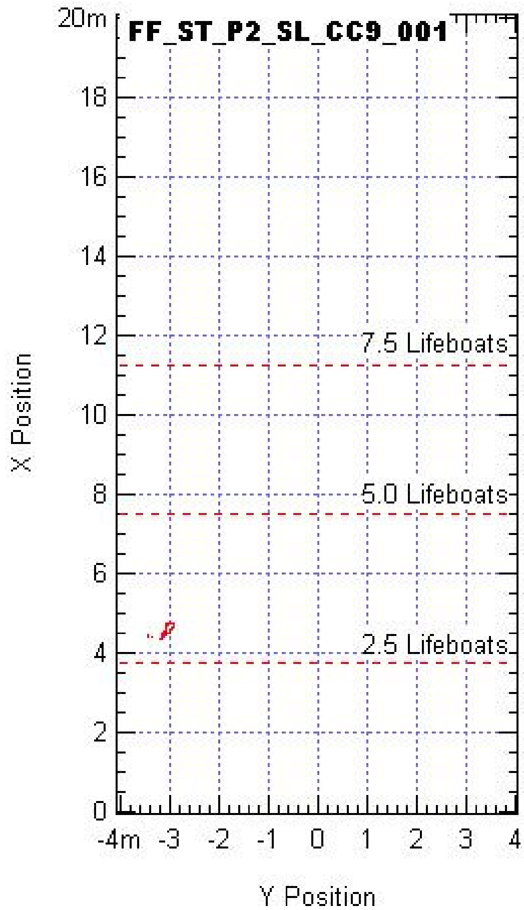
16
14
12
10
8
6
4
2
0
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
X Position
-4m -3 -2 -1 0 1 2 3 4
Y Position


FF_ST_P2_SL_CC8_001
20m
18
16
14
12
10
8
6
4
2
0
-4m -3 -2 -1 0 1 2 3 4
X Position
Y Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats


FF_ST_P2_SL_CC9_001
20m
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16
14
12
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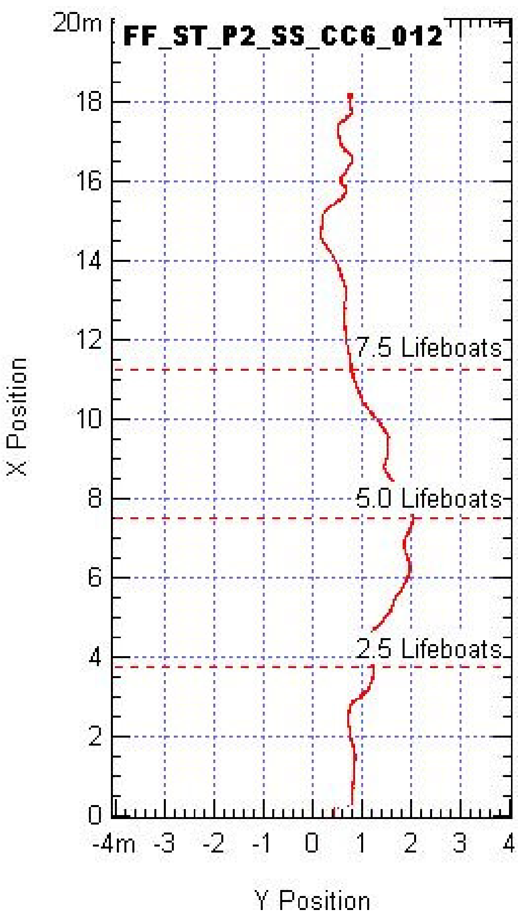
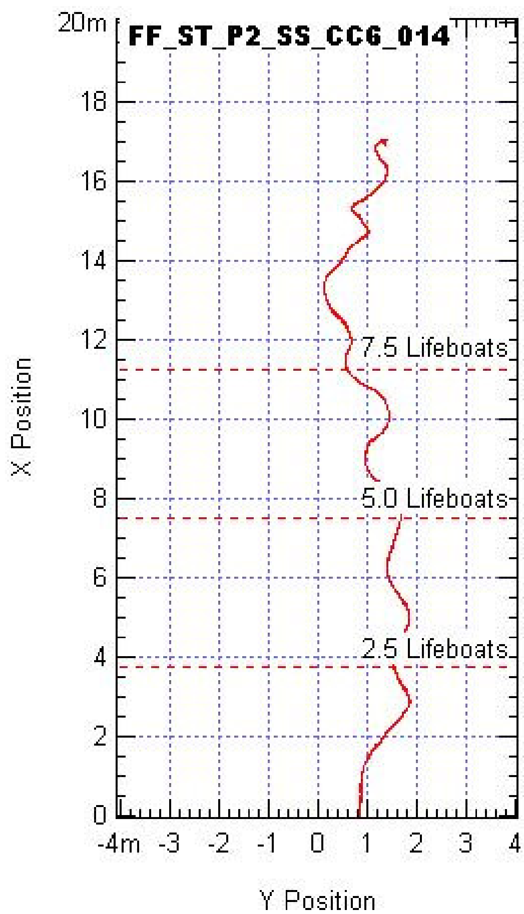
8
6
4
2
0
-4m -3 -2 -1 0 1 2 3 4
X Position
Y Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats


FF_ST_P2_SS_CCG_012
20m
18
16
14
12
10
8
6
4
2
0
X Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
-4m -3 -2 -1 0 1 2 3 4
Y Position


FF_ST_P2_SS_CCG_014
20m
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14
12
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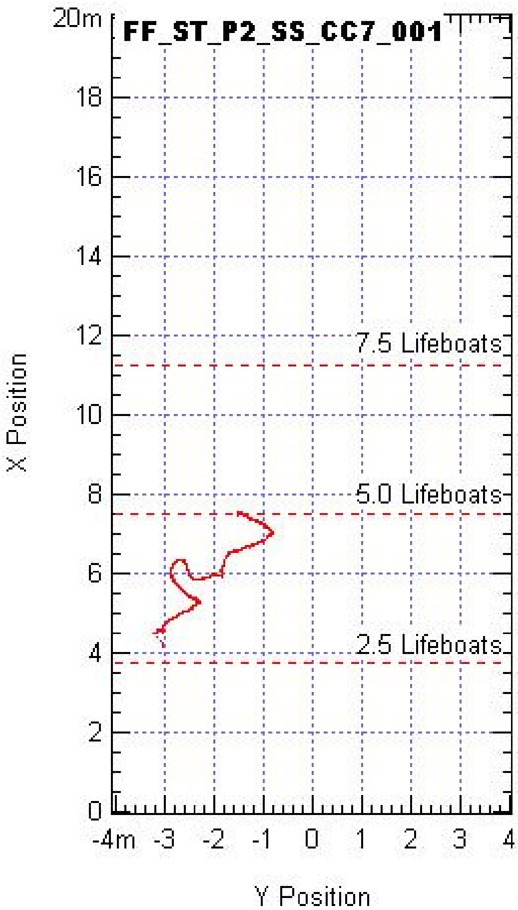
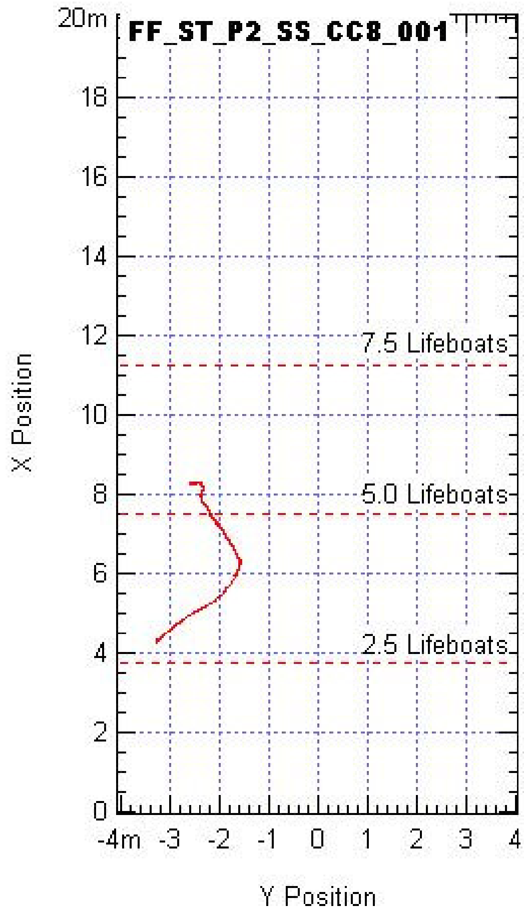
0
X Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
-4m -3 -2 -1 0 1 2 3 4
Y Position



FF_ST_P2_SS_CC7_001
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
X Position
Y Position
20m
18
16
14
12
10
8
6
4
2
0
-4m
-3
-2
-1
0
1
2
3
4



FF_ST_P2_SS_CC8_001
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
X Position
Y Position
20m
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16
14
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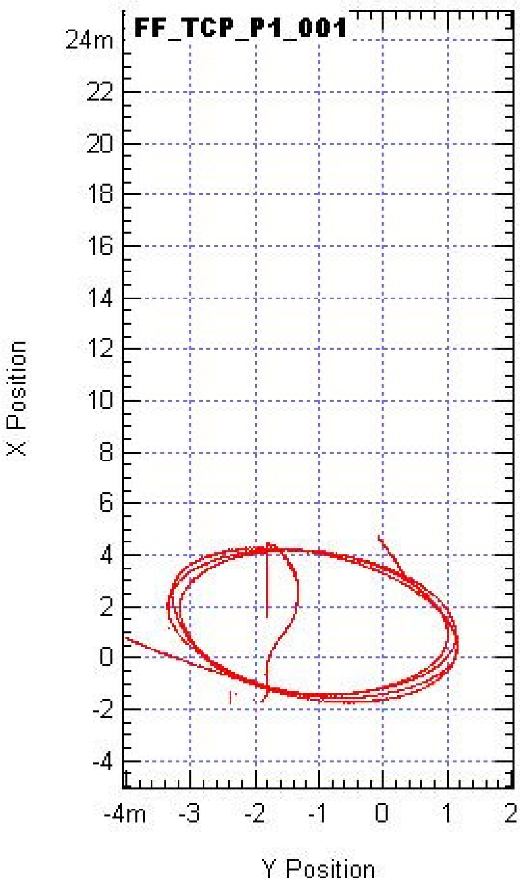
10
8
6
4
2
0
-4m
-3
-2
-1
0
1
2
3
4


FF_TCP_P1_001
24m
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14
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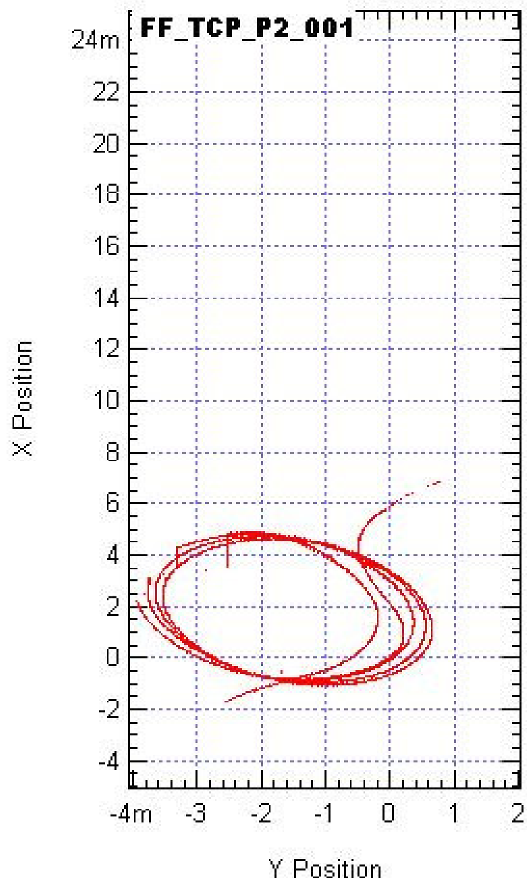
2
0
-2
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position


FF_TCP_P2_001
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14
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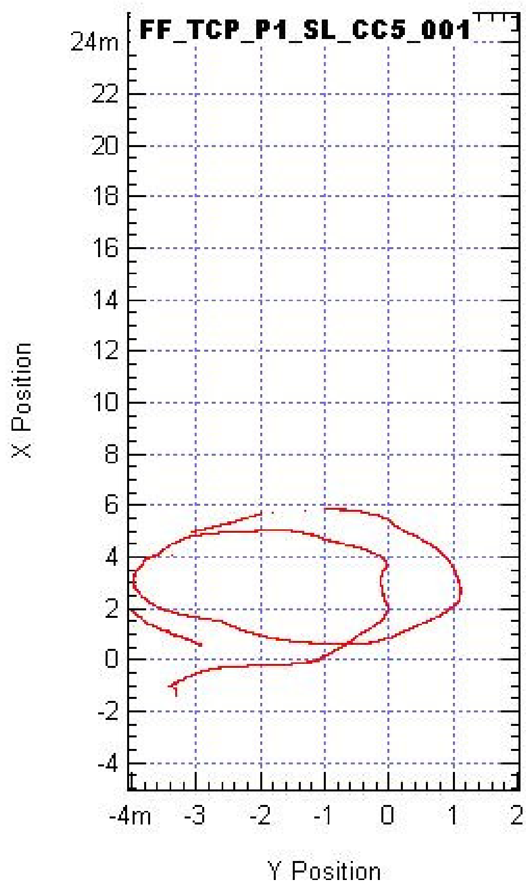
4
2
0
-2
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position


FF_TCP_P1_SL_CC5_001
24m
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20
18
16
14
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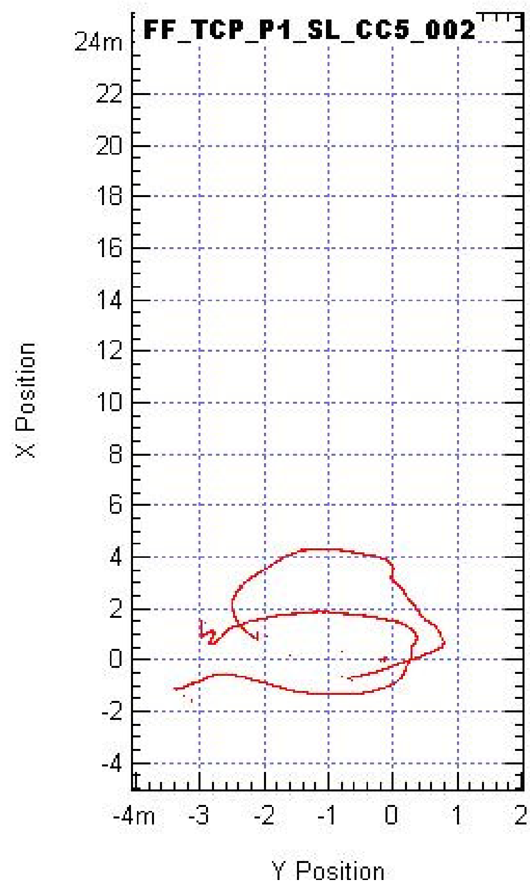
2
0
-2
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position


FF_TCP_P1_SL_CC5_002
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-2
-4
X Position
-4m
-3
-2
-1
0
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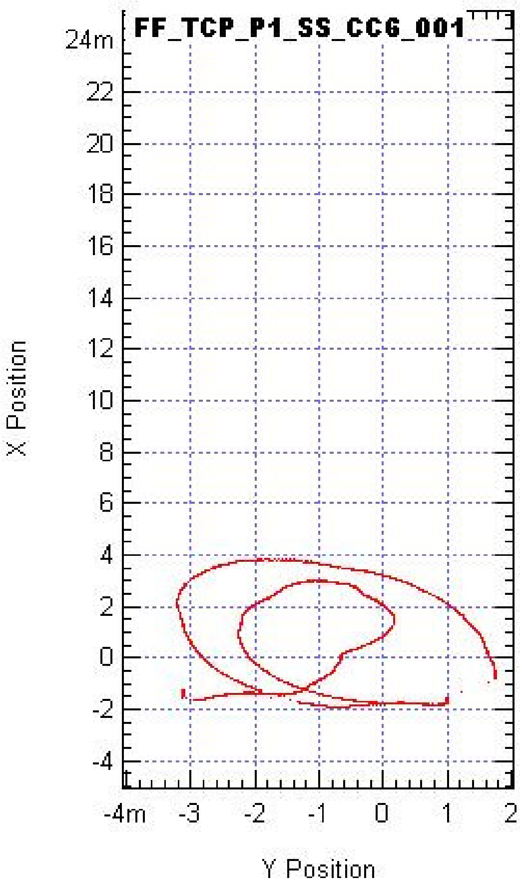
2
Y Position


FF_TCP_P1_SS_CCG_001
X Position
Y Position
24m
22
20
18
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6
4
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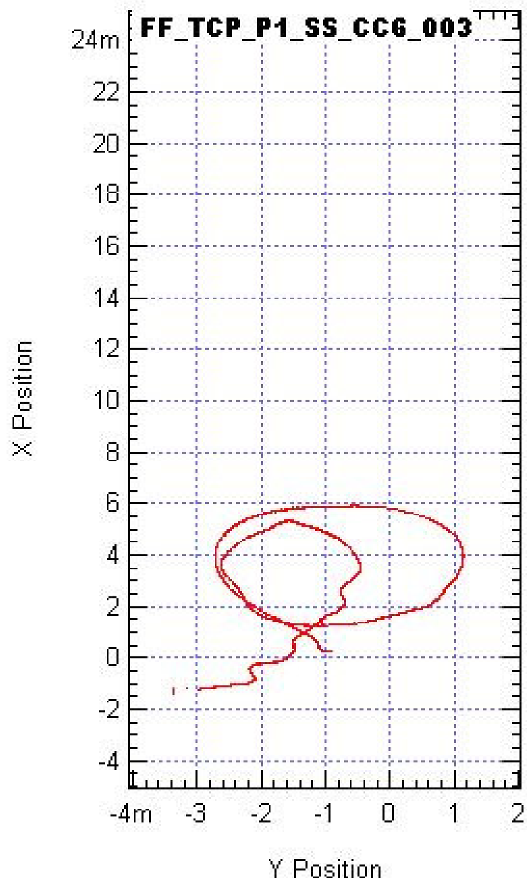
0
-2
-4
-4m
-3
-2
-1
0
1
2


FF_TCP_P1_SS_CCG_003
X Position
Y Position
24m
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-4
-4m
-3
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-1
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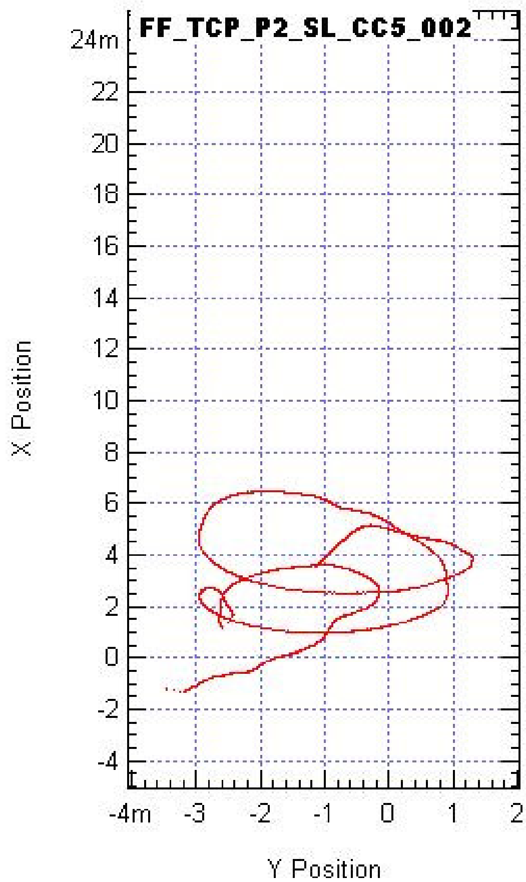
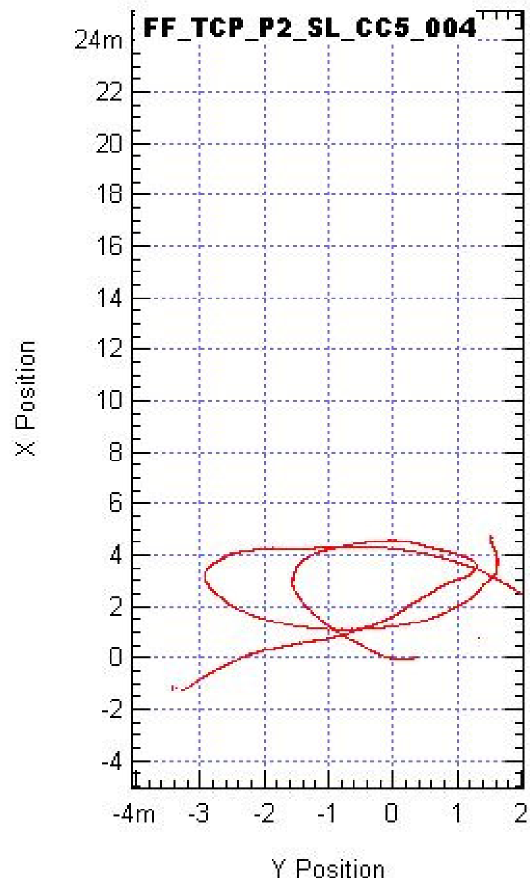
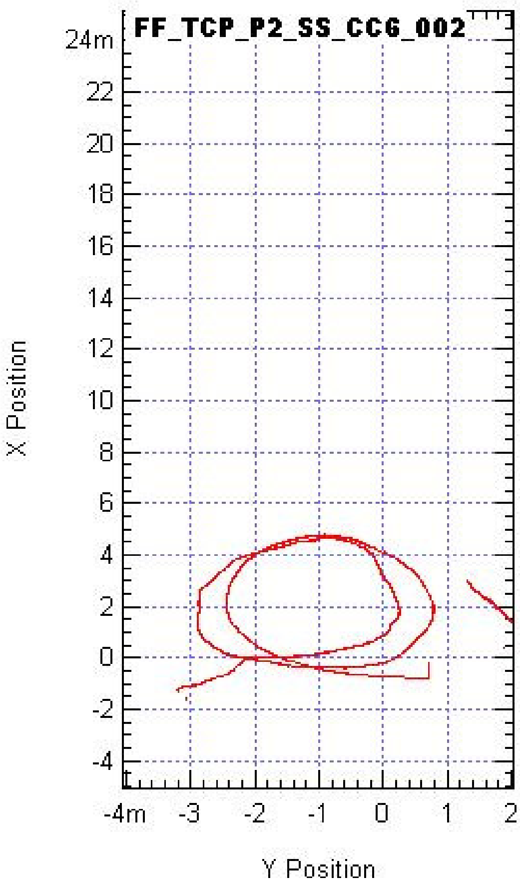
1
2



FF_TCP_P2_SL_CC5_002
X Position
Y Position



FF_TCP_P2_SL_CC5_004
X Position
Y Position


FF_TCP_P2_SS_CCG_002
X Position
24m
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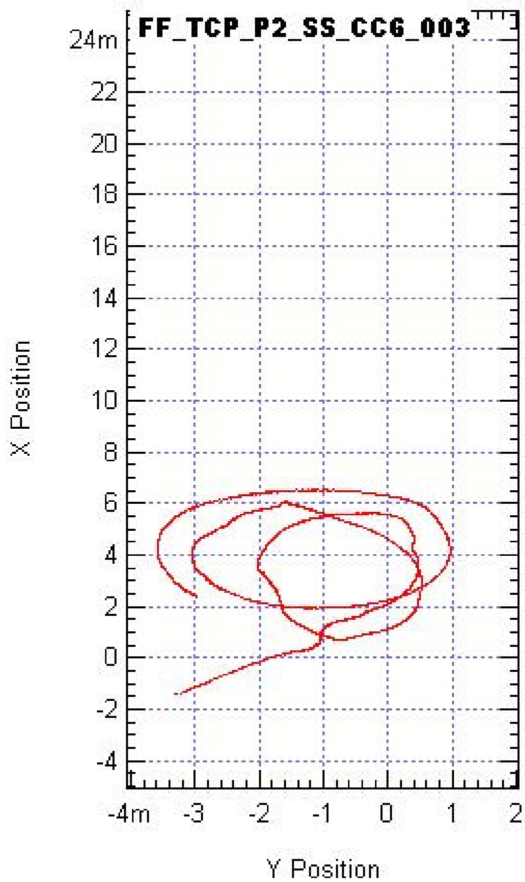
-4
-4m
-3
-2
-1
0
1
2
Y Position

FF_TCP_P2_SS_CCG_003
X Position
24m
22
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-4m
-3
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-1
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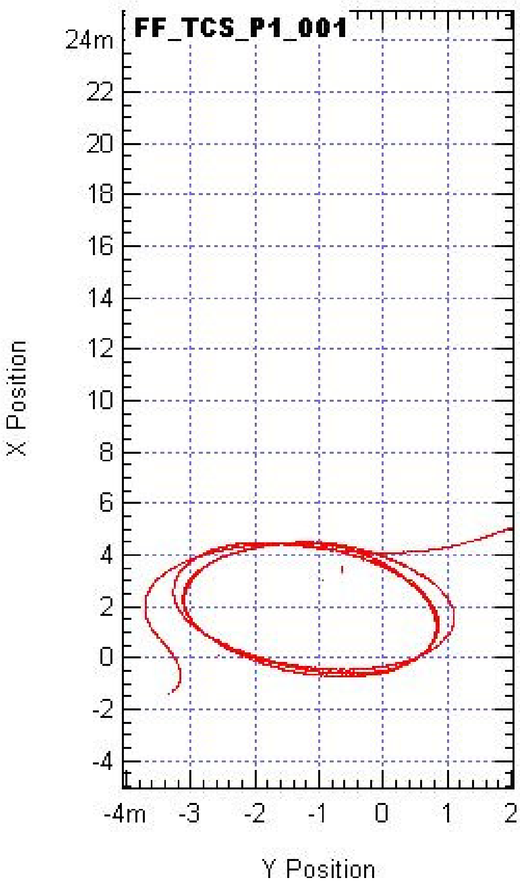
Y Position


FF_TCS_P1_001
24m
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X Position
-4m
-3
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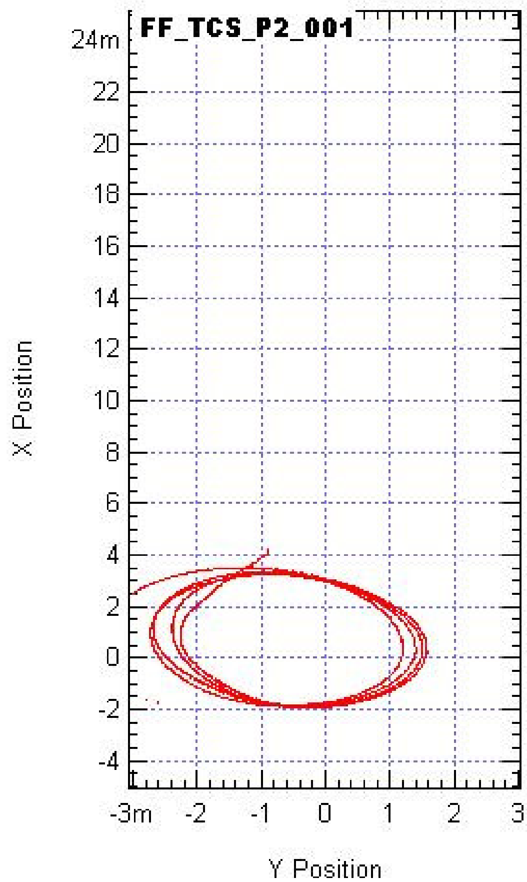
2
Y Position


FF_TCS_P2_001
24m
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-4
X Position
-3m
-2
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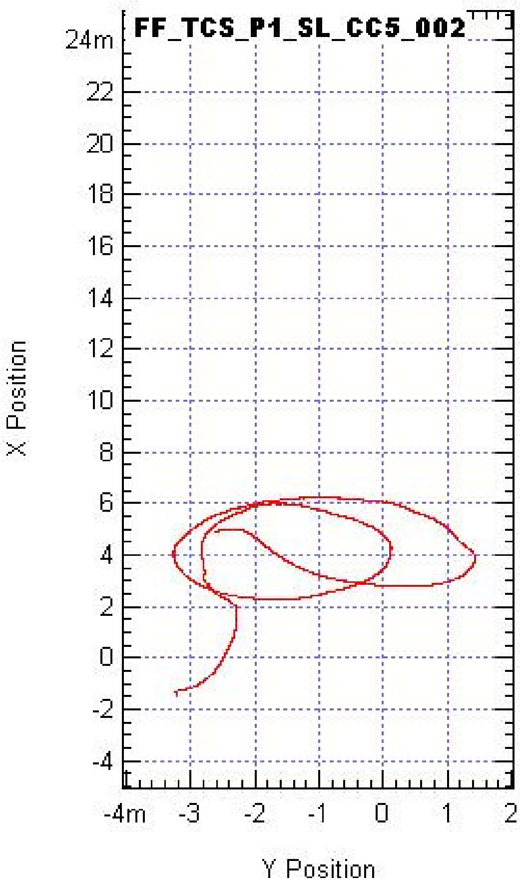
1
2
3
Y Position


FF_TCS_P1_SL_CC5_002
24m
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-4
X Position
-4m
-3
-2
-1
0
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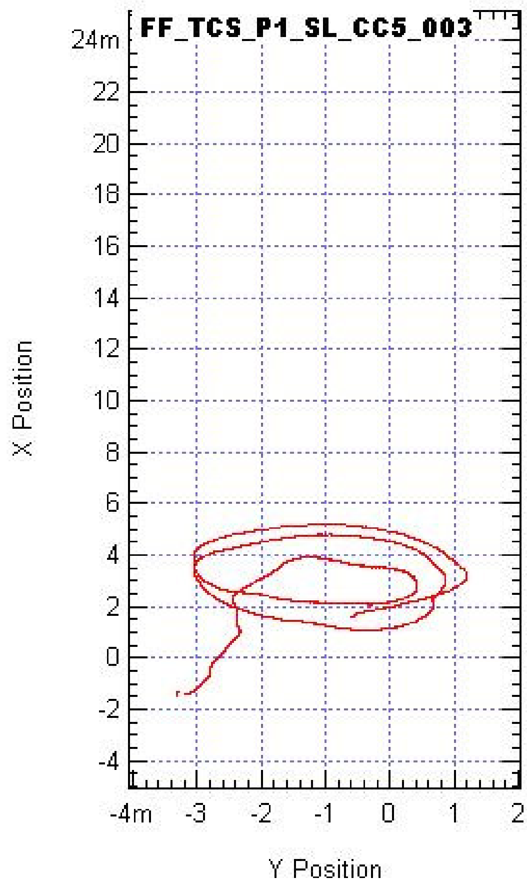
2
Y Position


FF_TCS_P1_SL_CC5_003
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X Position
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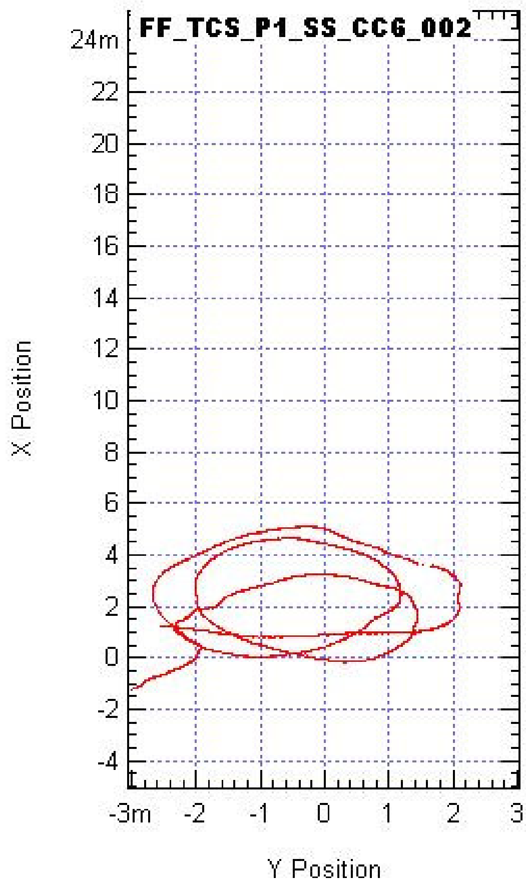
2
Y Position


FF_TCS_P1_SS_CCG_002
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X Position
-3m
-2
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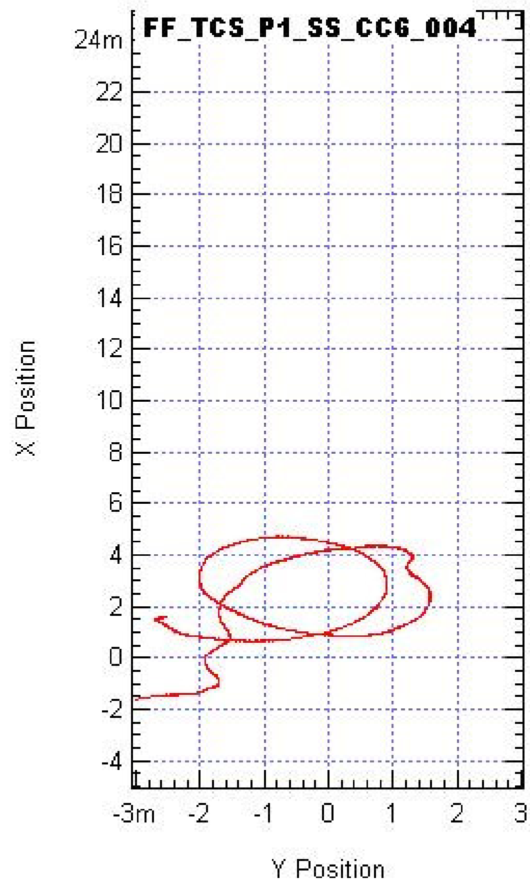
3
Y Position


FF_TCS_P1_SS_CCG_004
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X Position
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1
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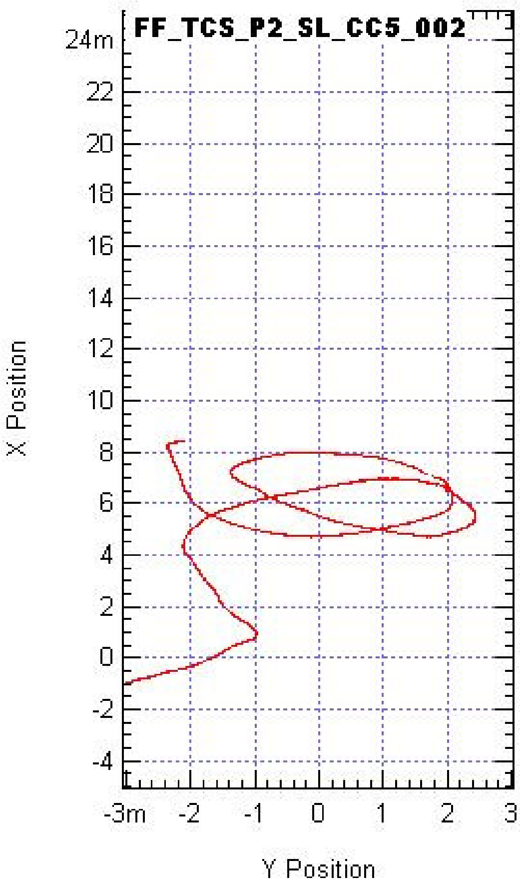
3
Y Position


FF_TCS_P2_SL_CC5_002
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-4
X Position
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-2
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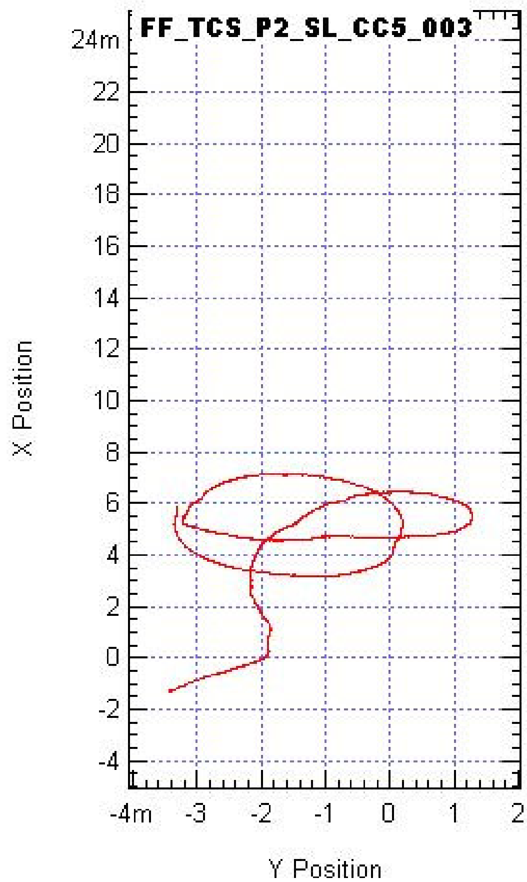
3
Y Position


FF_TCS_P2_SL_CC5_003
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X Position
-4m
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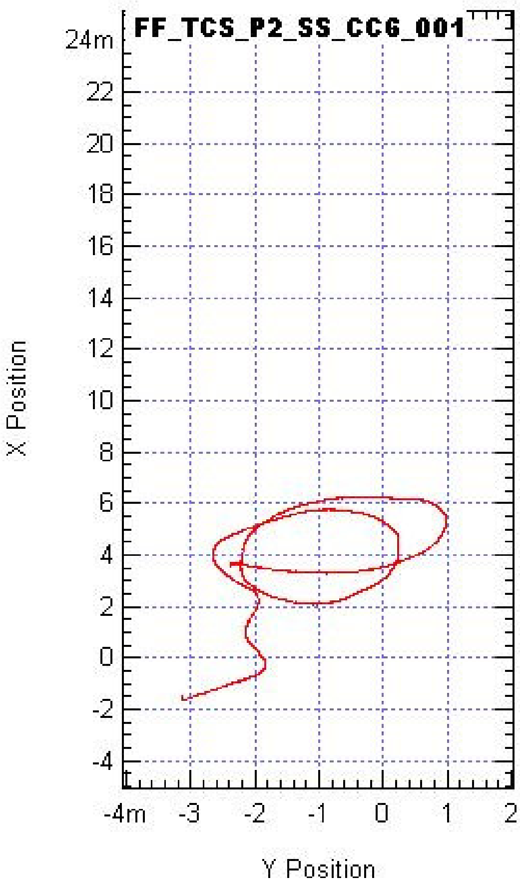
2
Y Position


FF_TCS_P2_SS_CCG_001
24m
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-4
X Position
-4m
-3
-2
-1
0
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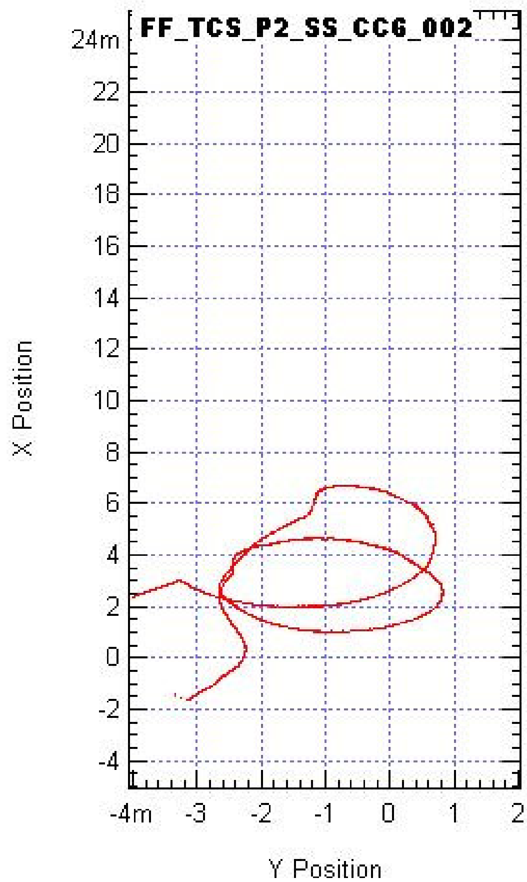
2
Y Position


FF_TCS_P2_SS_CCG_002
24m
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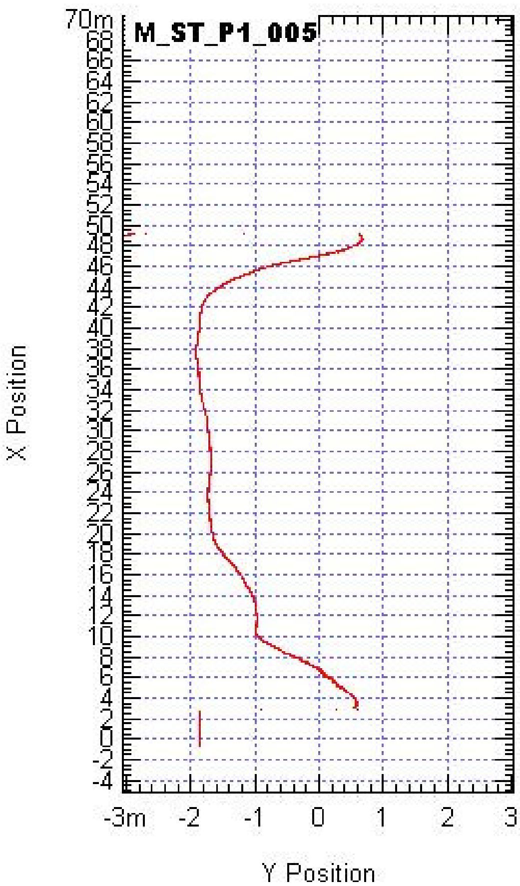
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position


M_ST_P1_005
70m
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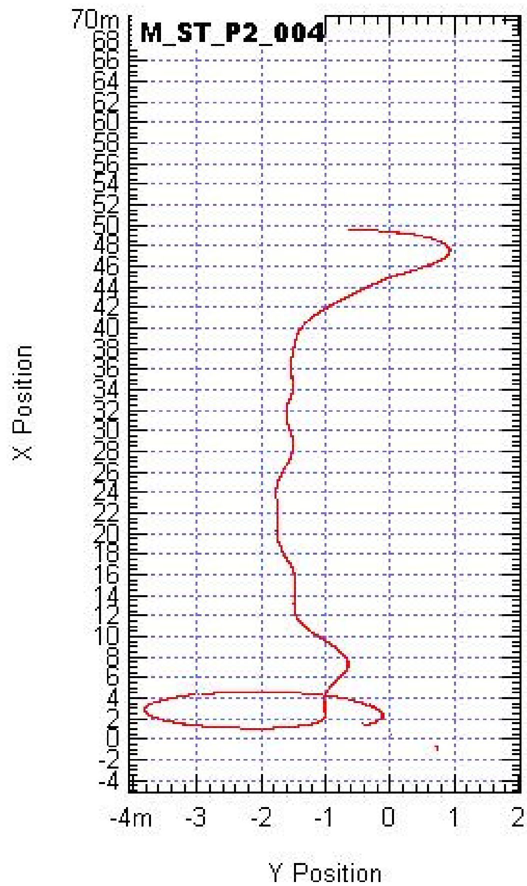
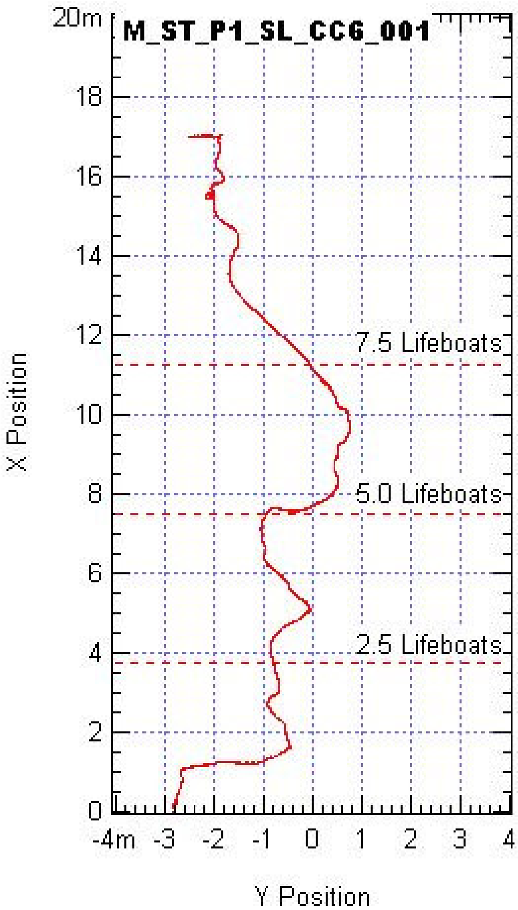
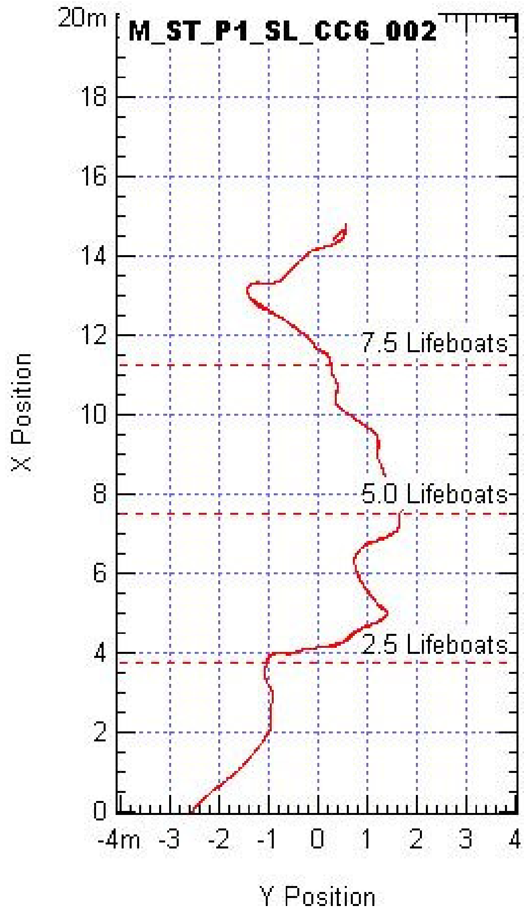
Y Position
-3m -2 -1 0 1 2 3


M_ST_P2_004
70m
X Position
Y Position
-4m -3 -2 -1 0 1 2


M_ST_P1_SL_CCG_001
20m
18
16
14
12
10
8
6
4
2
0
X Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
-4m -3 -2 -1 0 1 2 3 4
Y Position


M_ST_P1_SL_CCG_002
20m
18
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14
12
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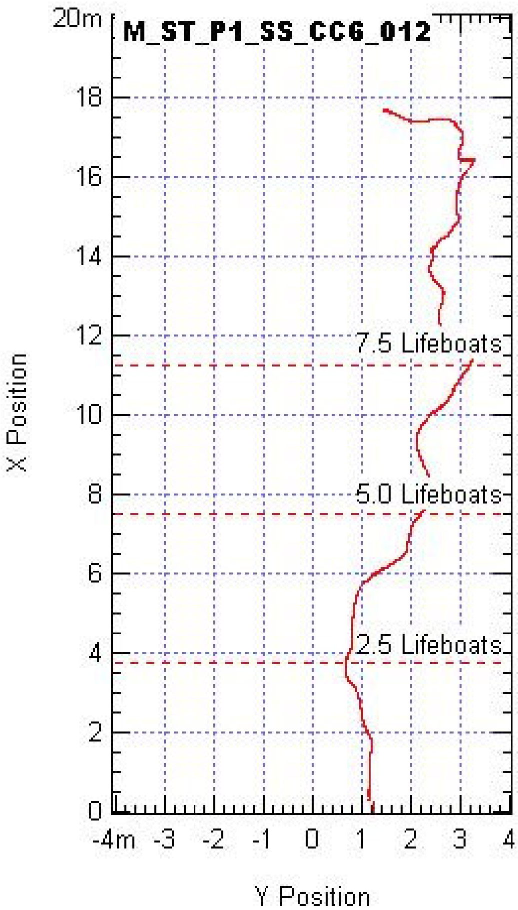
4
2
0
X Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
-4m -3 -2 -1 0 1 2 3 4
Y Position


M_ST_P1_SS_CC6_012
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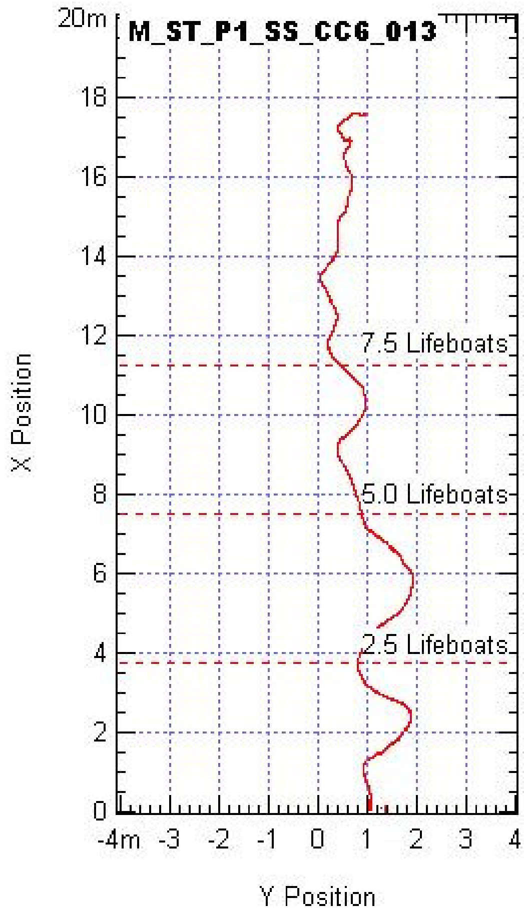
14
12
10
8
6
4
2
0
X Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
-4m -3 -2 -1 0 1 2 3 4
Y Position


M_ST_P1_SS_CC6_013
20m
18
16
14
12
10
8
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4
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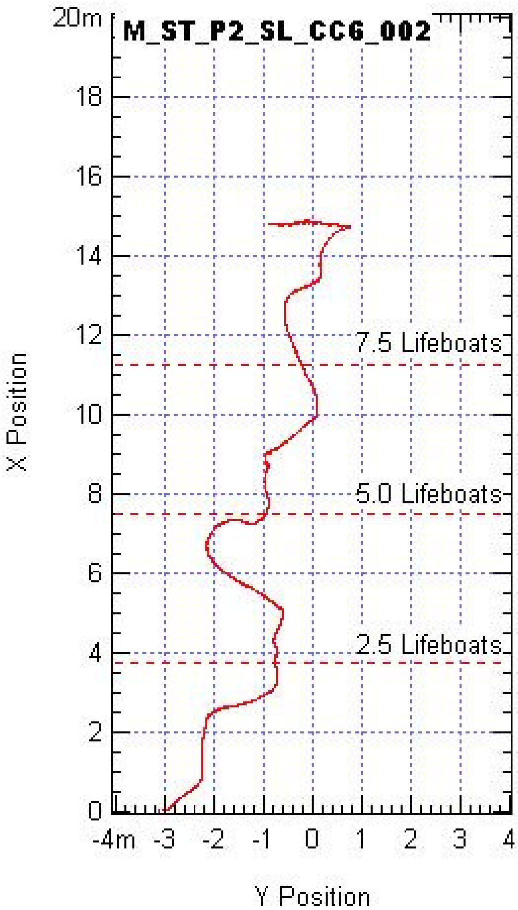
X Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
-4m -3 -2 -1 0 1 2 3 4
Y Position


M_ST_P2_SL_CCG_002
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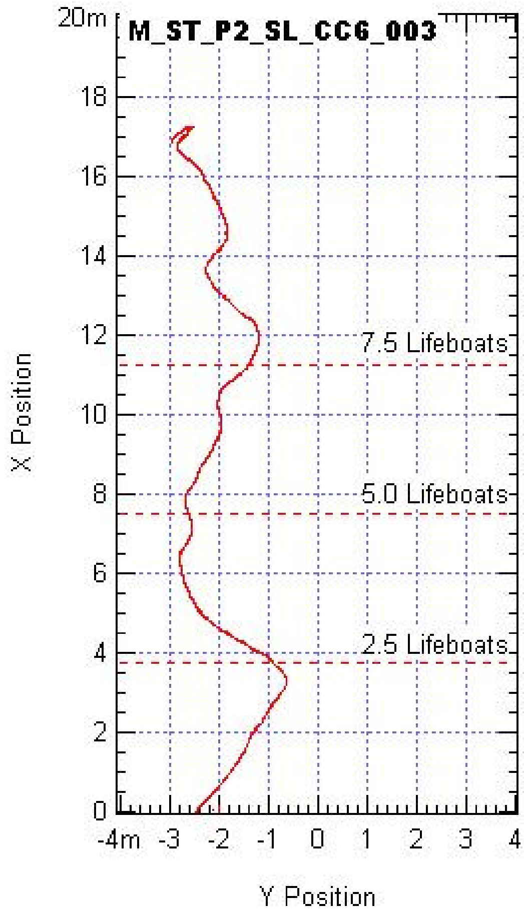
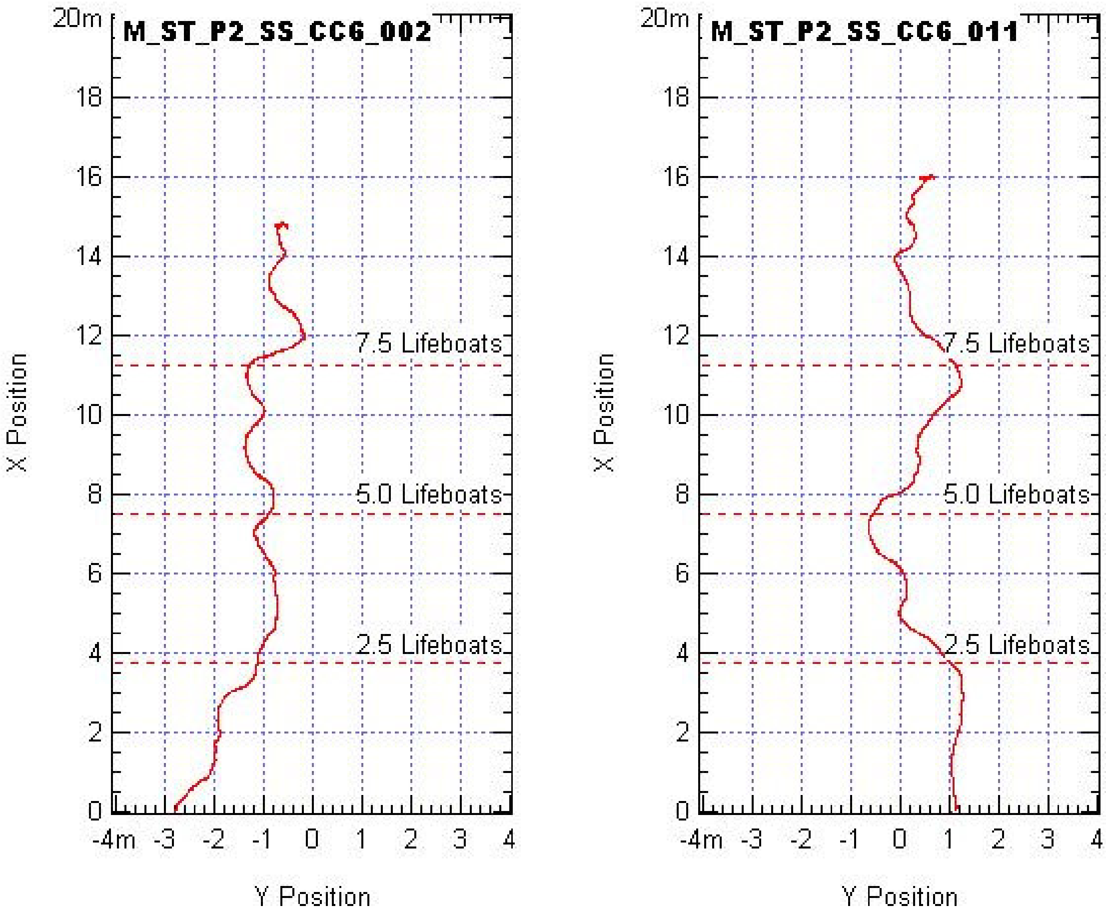
18
16
14
12
10
8
6
4
2
0
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
X Position
-4m
-3
-2
-1
0
1
2
3
4
Y Position


M_ST_P2_SL_CCG_003
20m
18
16
14
12
10
8
6
4
2
0
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
X Position
-4m
-3
-2
-1
0
1
2
3
4
Y Position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M_ST_P2_SS_CCG_011
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14
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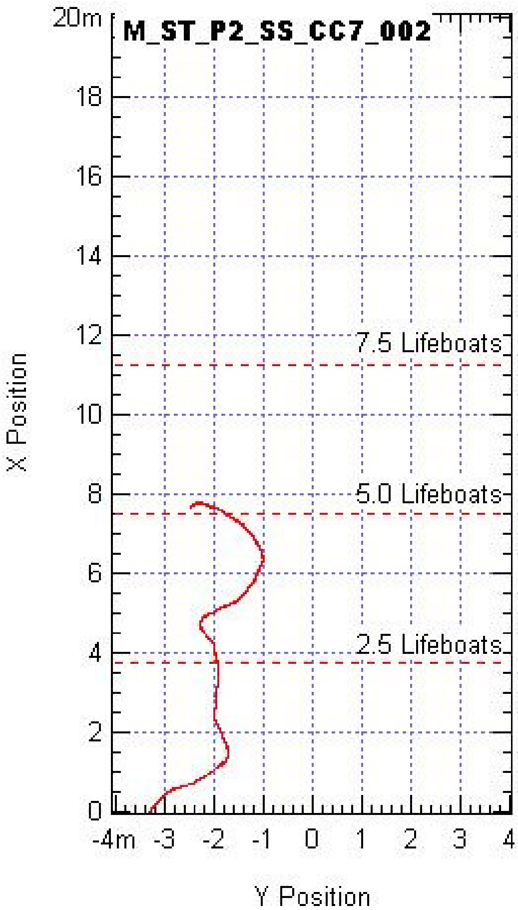
X Position
7.5 Lifeboats
5.0 Lifeboats
2.5 Lifeboats
-4m -3 -2 -1 0 1 2 3 4
Y Position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14
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10
8
6
4
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X Position
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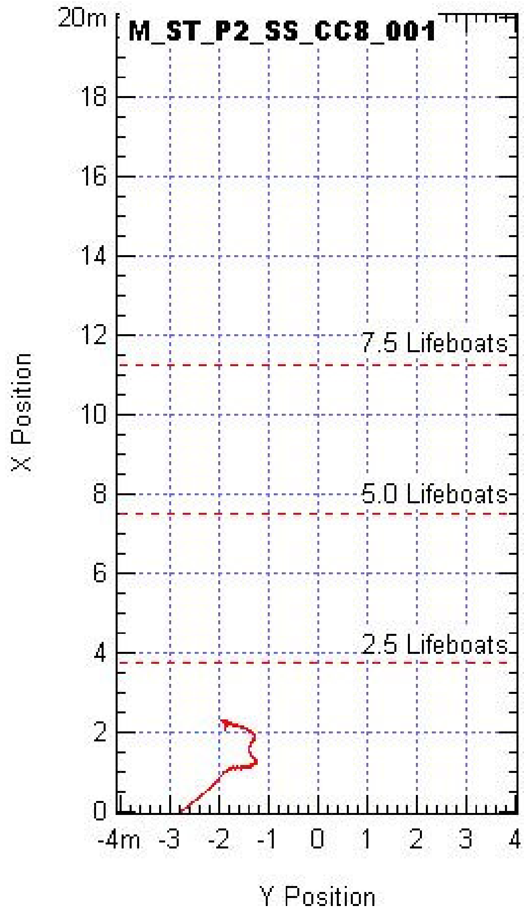
5.0 Lifeboats
2.5 Lifeboats
-4m
-3
-2
-1
0
1
2
3
4
Y Position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14
12
10
8
6
4
2
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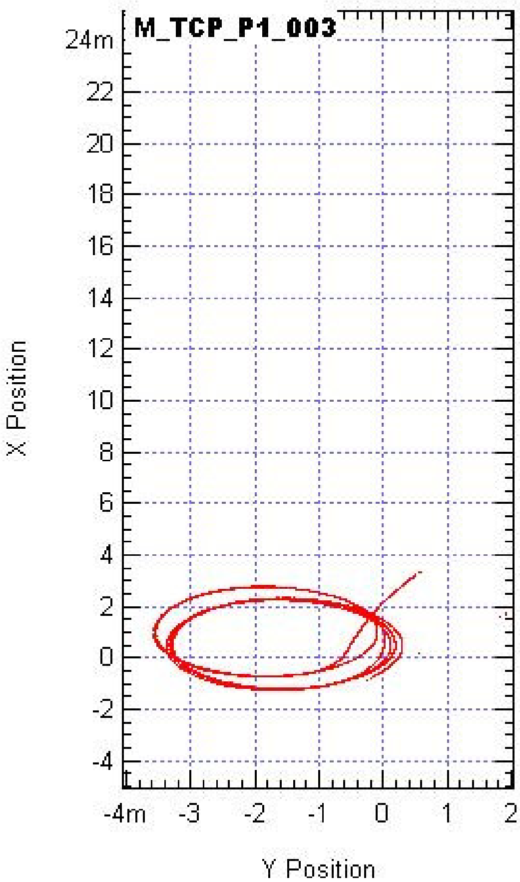
5.0 Lifeboats
2.5 Lifeboats
-4m
-3
-2
-1
0
1
2
3
4
Y Position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22
20
18
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14
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10
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6
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2
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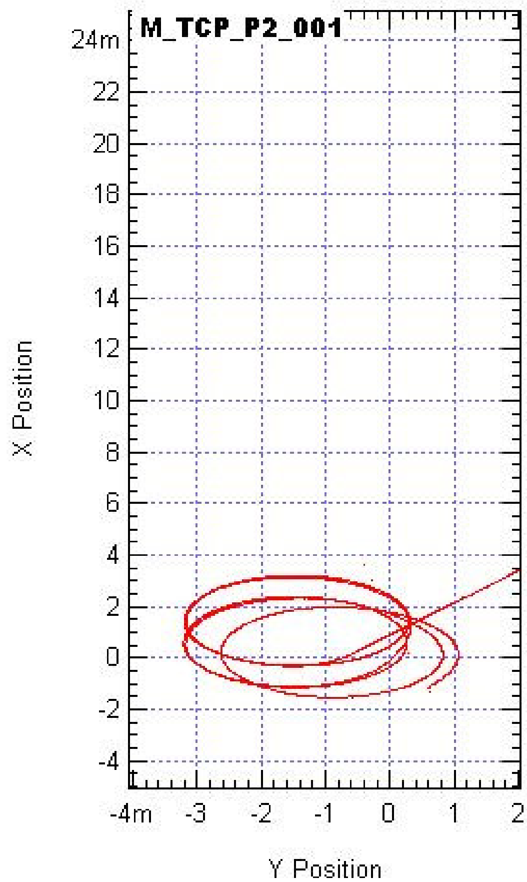
-2
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position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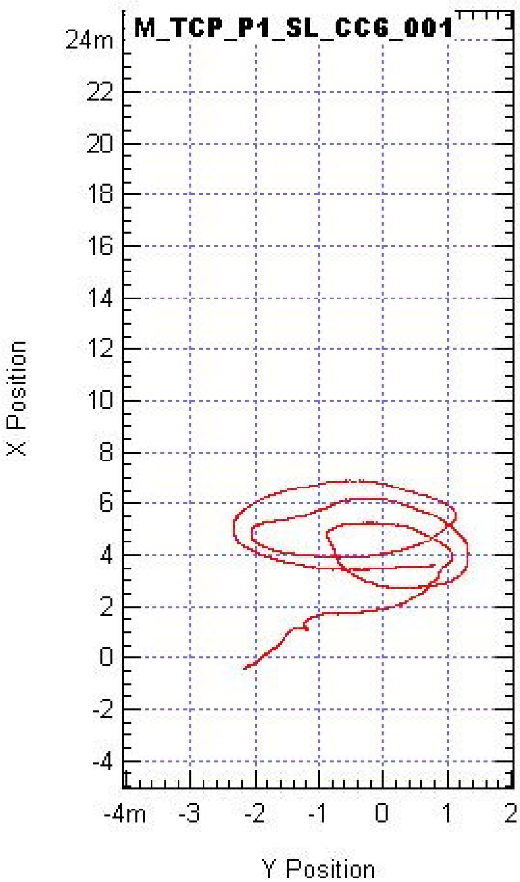
X Position
-4m
-3
-2
-1
0
1
2
Y Position


M_TCP_P1_SL_CCG_001
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18
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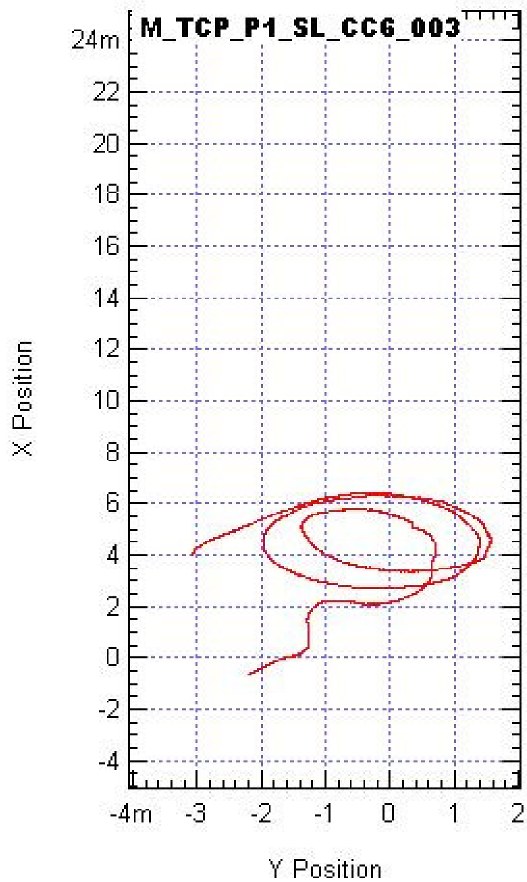
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position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X Position
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-1
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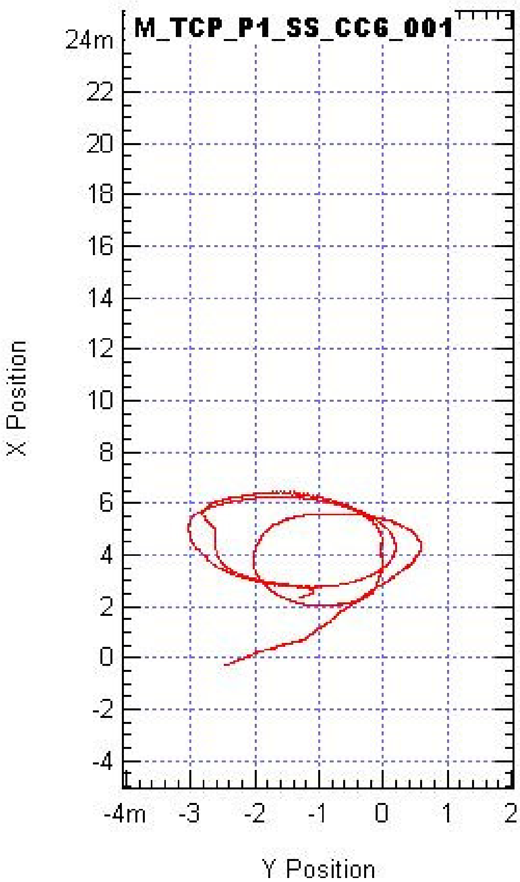
Y Position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18
16
14
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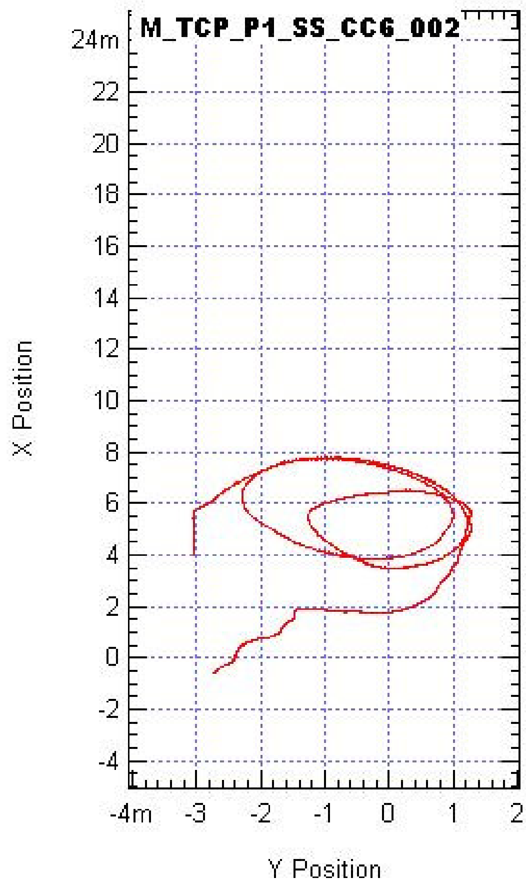
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position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0
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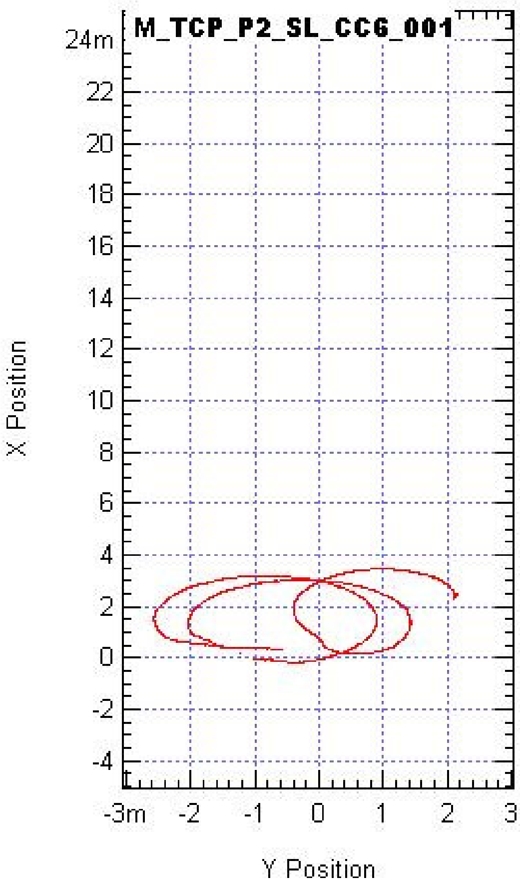
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position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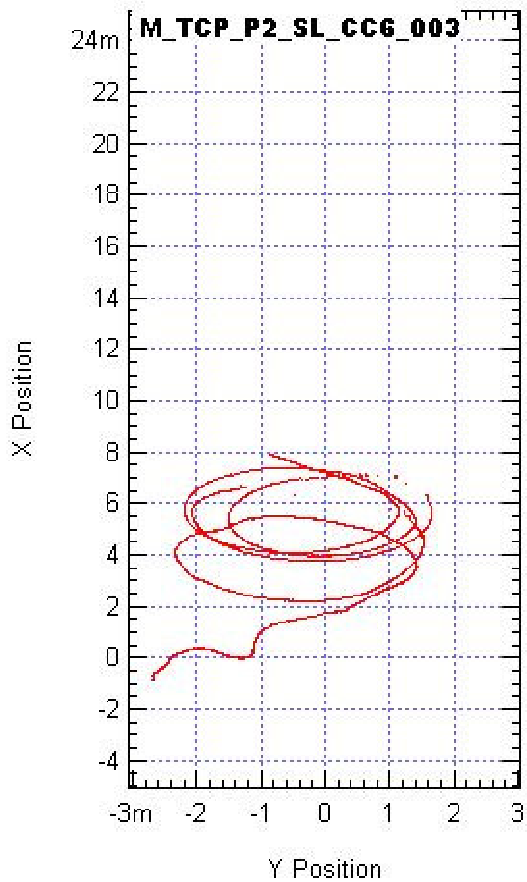
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
X Position
-3m
-2
-1
0
1
2
3
Y Position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16
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8
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4
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0
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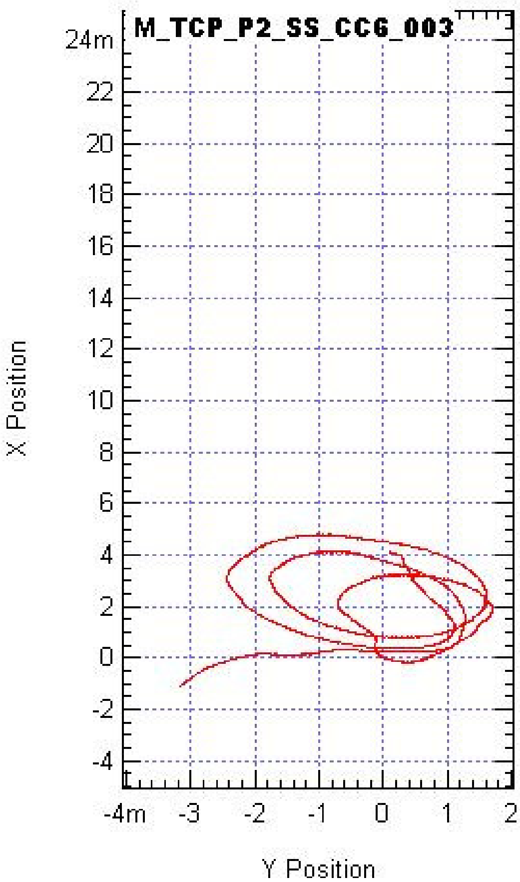
-4
X Position
-3m
-2
-1
0
1
2
3
Y Position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20
18
16
14
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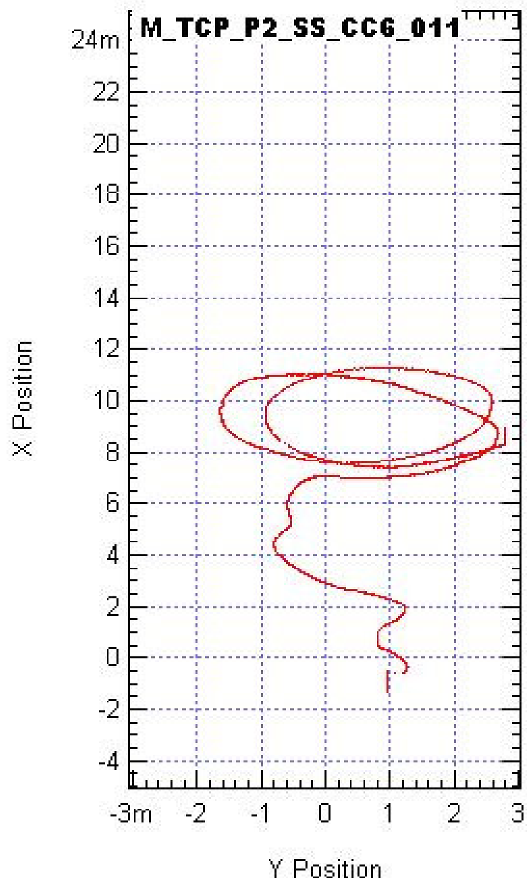
10
8
6
4
2
0
-2
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position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20
18
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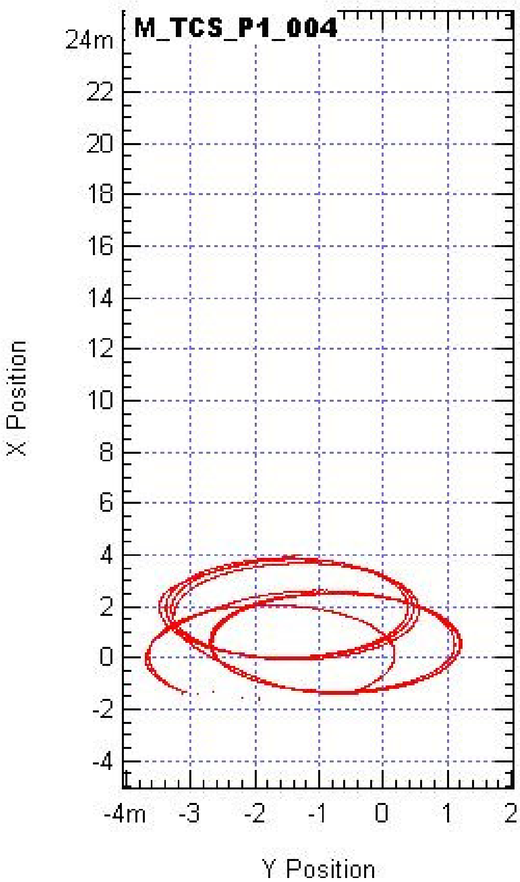
0
-2
-4
X Position
-3m
-2
-1
0
1
2
3
Y Position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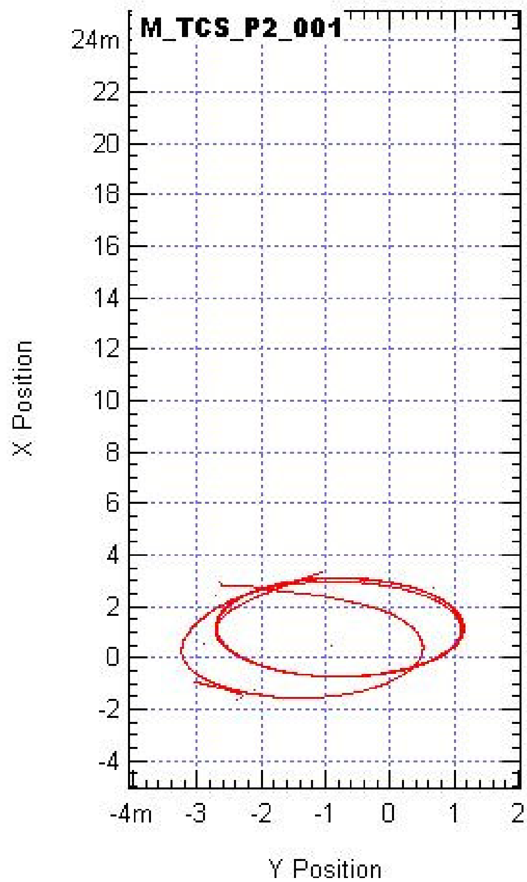
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position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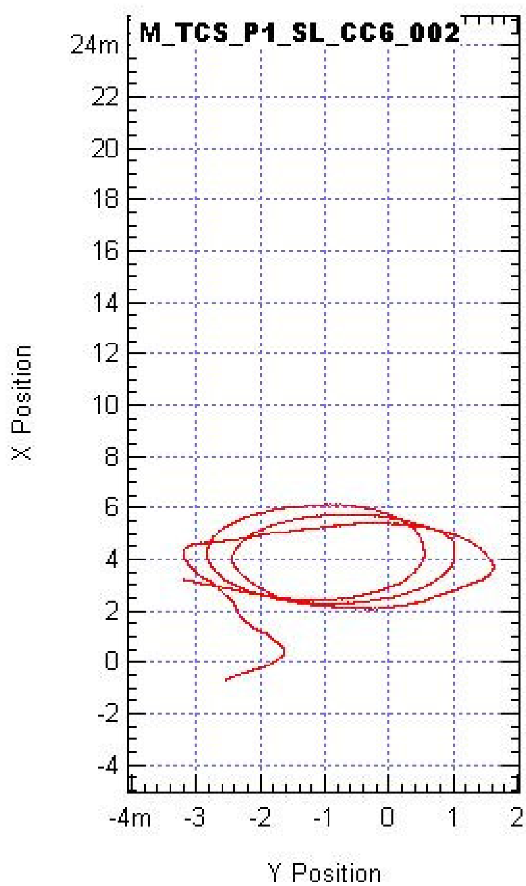
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position



M_TCS_P1_SL_CCG_002
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14
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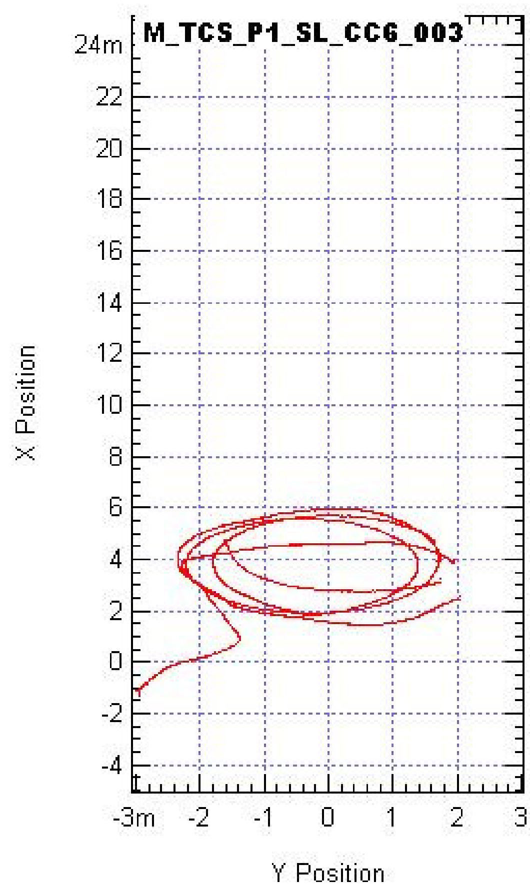
-2
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position



M_TCS_P1_SL_CCG_003
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18
16
14
12
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8
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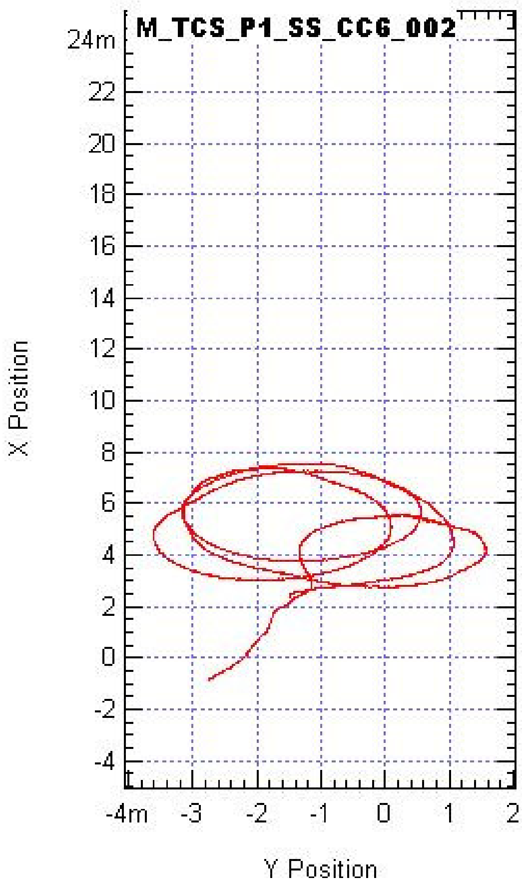
4
2
0
-2
-4
X Position
-3m
-2
-1
0
1
2
3
Y Position


M_TCS_P1_SS_CCG_002
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-4
X Position
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-1
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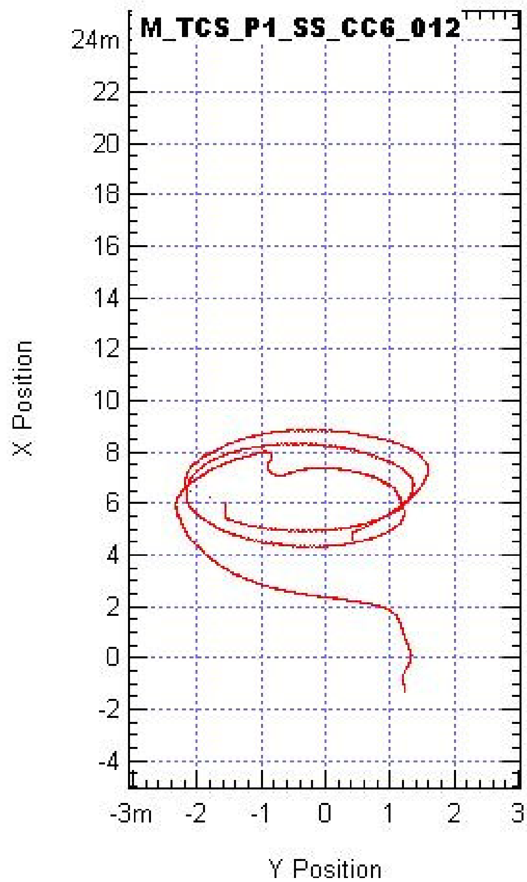
2
Y Position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-4
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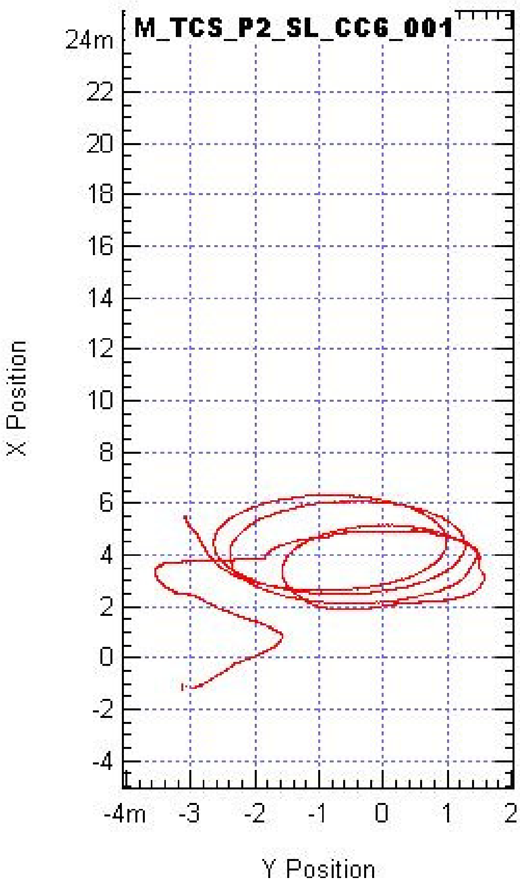
-1
0
1
2
3
Y Position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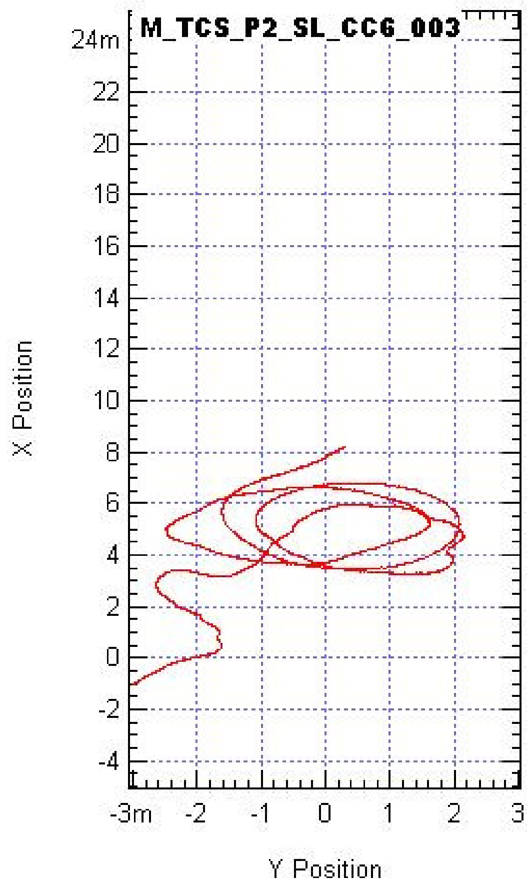
0
-2
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position


M_TCS_P2_SL_CCG_003
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0
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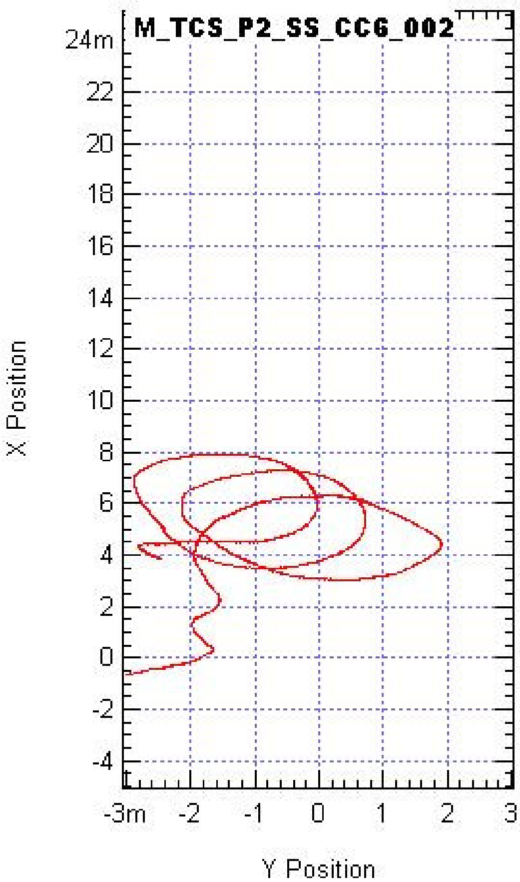
-4
X Position
-3m
-2
-1
0
1
2
3
Y Position


M_TCS_P2_SS_CCG_002
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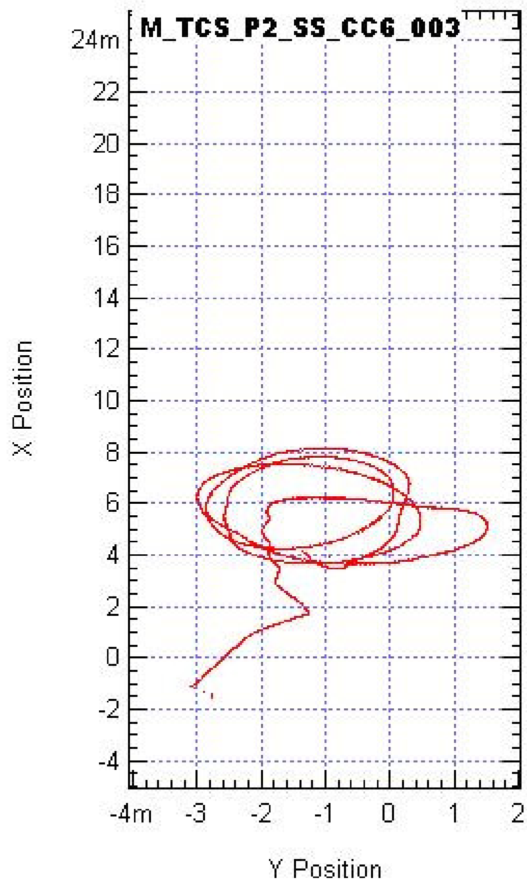
-2
-4
X Position
-3m
-2
-1
0
1
2
3
Y Position


M_TCS_P2_SS_CCG_003
24m
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
X Position
-4m
-3
-2
-1
0
1
2
Y Position

Appendix B

Sample video records from the coxswain position video camera