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Nord Stream AG

Offshore pipeline through the Baltic Sea

Memo 4.3A-6
Spreading of viscous mustard gas

September 2008

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1. Introduction

1.1 Spreading of viscous mustard gas

As basis for the environmental impact assessment (EIA) several background memos have been prepared. This memo describes the spreading of lumps of viscous mustard gas.

Viscous mustard gas was dumped in the Baltic Sea after World War II and remains on the seabed. Every year lumps of viscous mustard gas are caught by fishermen. There has been concern that if the pipeline were laid directly on the lumps of viscous mustard gas they could break into smaller pieces and be transported to the coastline by currents. Because the physical appearance of the lumps resembles amber, there is apprehension that people would collect these small pieces on the beach.

This memo analyses the impact from the pipeline on the lumps of viscous mustard gas on the seabed, as well as the likelihood of fragments of the lumps moving towards the coastline. Furthermore, the drifting of lumps of viscous mustard gas is quantified.

2. Summary

After World War II a large amount of chemical warfare agents were dumped in the Baltic Sea. There are two official dumping areas in the Baltic Proper. One area is south-east of Gotland and the other, east of Bornholm. However, chemical munitions have been found in a considerably larger area than the official dumping sites.

Viscous mustard gas is mustard gas to which thickeners have been added. The thickening agents prevent the mustard gas from reacting directly with the sea water; therefore, the viscous mustard gas can exist on the seabed for years.

The mustard gas is in the form of solid lumps, which are degraded by different processes.

Lumps of viscous mustard gas are frequently found in the Baltic Sea, especially in connection with fishing activities. The findings are reported to the Danish Navy at Bornholm (Bornholms Marinedistrikt), and the lumps are either dumped at one of the two emergency dumping sites east and west of Bornholm or brought by the Danish Navy to land, where they are safely destroyed. The lumps that have been brought in vary in size, and the weight of the findings ranges from approximately 0.1 kg to 100 kg.

Movement of the viscous mustard gas may have happened due to:

- relocation by currents
- relocation by fishing activities

However, it is concluded that the primary means of relocation of chemical munitions is via fishing activities; currents are only a minor factor. There have been no incidents in which lumps of viscous mustard gas have washed ashore.

There is a small risk that the pipeline could be laid directly atop a lump of viscous mustard gas. If so, three different situations can occur:

- the lump is buried under the pipe, which is likely to occur in areas where the sediment is very soft
- the lump is pushed aside without breaking
- the lump is broken into smaller pieces

The mobility of a lump would increase only if a lump were broken into smaller pieces. However, the pipeline introduces no new degradation processes, as these processes are already occurring because of weathering and fishing activities. Increased mobility, therefore, only applies to those single lumps that may be broken, and not to the general mobility of the lumps.

The mobility of broken lumps of viscous mustard gas has been analysed at two locations. Based on the size range of lumps that have been found and brought in, a relevant size range of lumps broken due to interaction with the pipelines can be estimated at approximately 25 cm to 0.2 cm in diameter.

The two locations in Table 2.1 below represent points where the pipeline is closest to each of the two dumping sites in the Baltic Sea.

Location	**Area**	**Coordinates**	**Water depth (From MIKE 3 model,** /1/**)**
1	Bornholm Basin (approximately KP 1025)	15.50°E, 55.43°N	90 m
2	Gotland Deep (approximately KP 800)	18.58°E, 56.35°N	64 m

Table 2.1: Locations where pipeline is closest to dumping sites in the Baltic Sea

To evaluate whether the lumps would be moved by current and waves at the two locations, a desktop analysis has been performed.

The critical current velocity for movement of the lumps varies between 0.05-0.62 m/s, dependent on lump size. The critical current velocity is only exceeded at Location 1 (Bornholm Deep), where movements of small lumps (1 cm in diameter) would be possible.

The maximum wave corresponding to the significant wave height at a one year sea state would not move the lumps at Location 1, but it could move very small lumps (0.2 cm in diameter) at Location 2.

The analysis therefore supports the conclusions of the Helsinki Commission (HELCOM) in /2/ that it is very unlikely that lumps of viscous mustard gas would be transported to the shoreline by the current, even in the case of very small lumps.

It is concluded that breaking of the lumps of viscous mustard gas would not pose any threats to the coastal areas of the Baltic Sea.

3. Mustard gas dumped in the Baltic Sea

3.1 Dumping areas

After World War II a large amount of chemical warfare agents were dumped in the Baltic Sea, including approximately 7,635 tonnes of mustard gas, /2/. It is estimated that approximately 20% of the total production of mustard gas in Germany was in the form of viscous mustard gas, /2/.

The viscous mustard gas was used in different kinds of artillery, mostly in bombs and shells. Chemical warfare agents were also put in different kinds of containers, /2/.

There are two official dumping areas in the Baltic Proper. One is located south-east of Gotland, and the other east of Bornholm, cf. Figure 3.1. Both areas are relatively close to the alignment of the pipeline. There is some uncertainty regarding the actual sites where the munitions were dumped, due to several factors, including dumping methods, navigation and the possibility that some of the munitions were dumped en route to the official sites, /2/. Therefore, chemical munitions have been found in an area considerably larger than that of the official dumping sites. The official dumping areas and the areas where there is considered to be a risk of mustard gas on the seabed are shown in Figure 3.1.

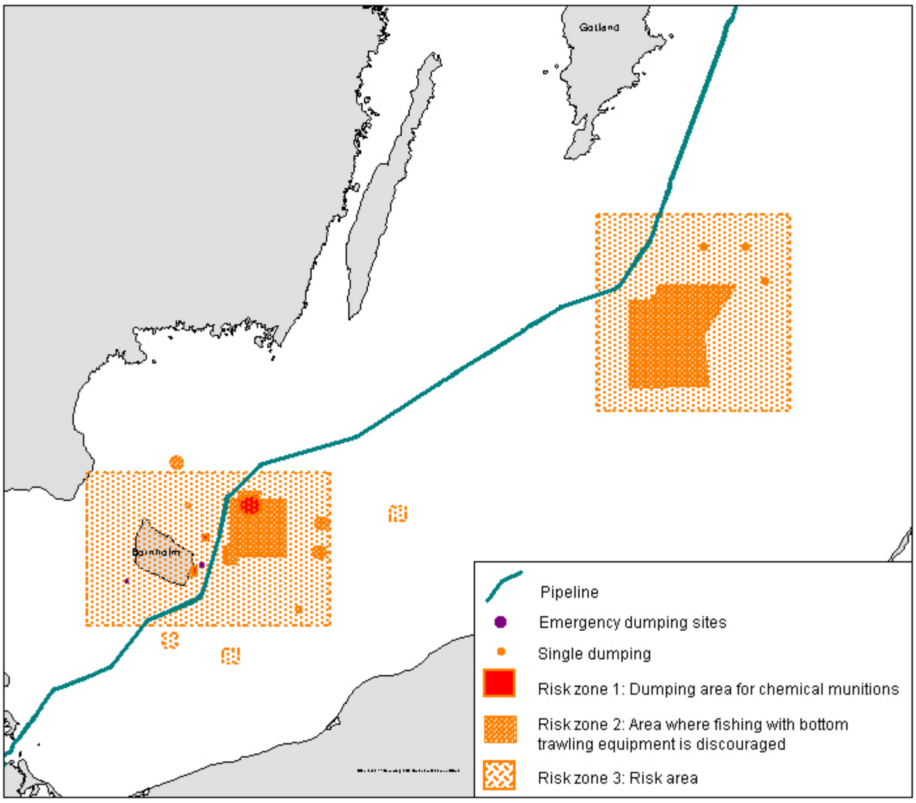

Figure 3.1: Risk zones and dumping areas for chemical munitions

3.2 Properties and degradation of viscous mustard gas

Viscous mustard gas is mustard gas to which thickeners have been added. Because these thickening agents prevent the mustard gas from reacting directly with sea water, the viscous mustard gas can exist in the marine environment for years. The artillery shells used to contain the mustard gas, however, are often corroded, leaving the viscous mustard gas exposed on the seabed.

The viscous mustard gas has the consistency of a thick, beeswax-like paste, and has a density of 1.3–1.5 g/cm^3, /2/. In the water environment, the viscous mustard gas is slowly oxidised and hydrolysed, because the active part of the mustard gas diffuses out of the viscous mustard gas and reacts with the water. The mustard gas is hydrolysed in two stages and ultimately neutralised by the sea water, /2/.

When the viscous mustard gas is oxidised and hydrolysed, the thickening agents remain and form the basis of a solid crust upon which sand and clay can deposit /2/. Therefore, the mustard gas is contained in solid lumps that are only slowly degraded in the sea water, which can be seen from the fact that lumps remain on the bottom of the Baltic Sea, 60 years after being dumped. Small lumps are degraded somewhat faster than large lumps because of the larger surface area per mass unit of the small lumps, /2/.

The hardness of the solid lumps can be compared to hard sandstone, /3/, meaning that it is quite stable but can be broken into smaller pieces by mechanical impact. Because of the intense fishing activity near the dumping area, lumps are therefore broken into smaller pieces when they are hit by trawl boards and anchors, /3/.

In Figure 3.2, a side-scan image shows the tracks from trawl boards in the area where the pipeline will traverse Risk Zone 2 at Bornholm.

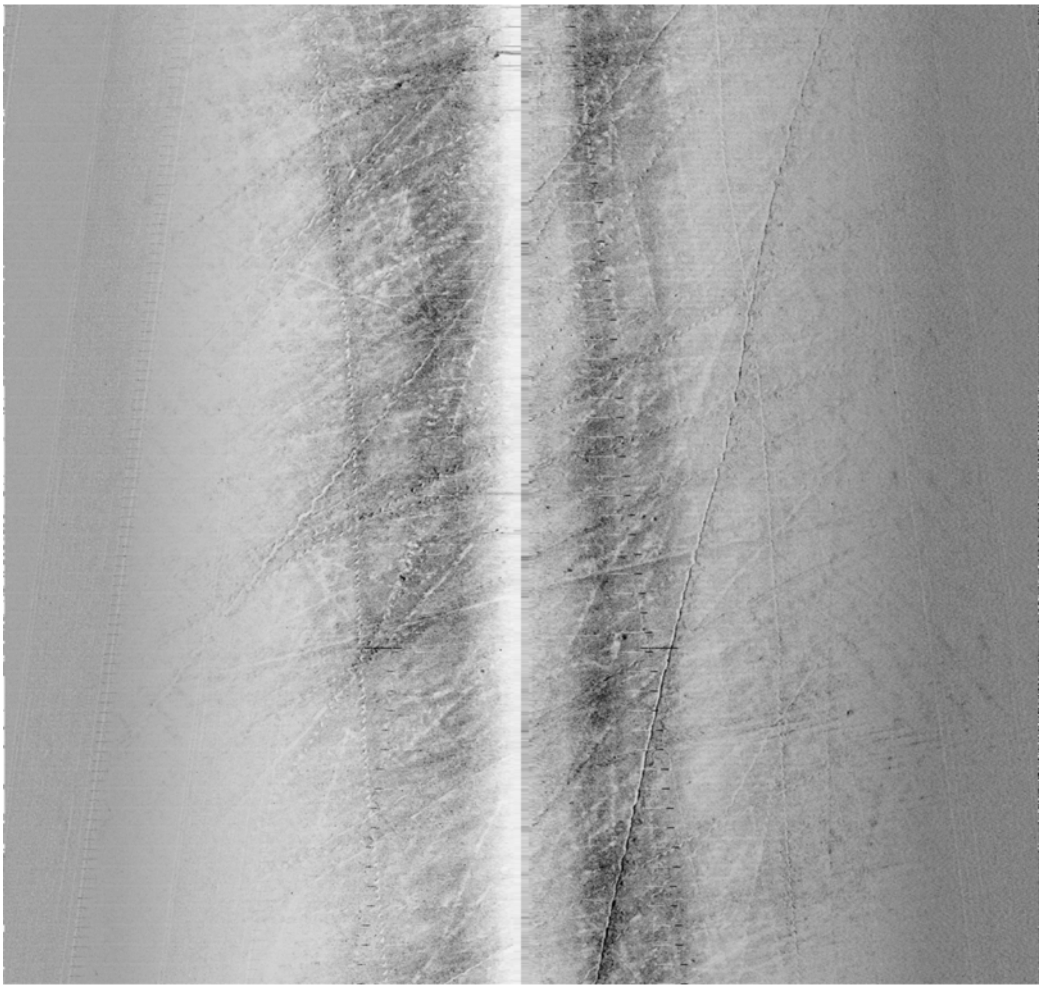

Figure 3.2: Side-scan image of tracks from trawl boards in the area north of Bornholm.

3.3 Findings of chemical warfare agents

Chemical warfare agents are frequently found in the Baltic Sea, especially in connection with fishing activities. The findings are reported to the Danish Navy at Bornholm (Bornholms Marinedistrikt) and are either dumped at one of the two emergency dumping sites east and west of Bornholm or brought to the Danish Navy to be safely destroyed. The emergency dumping sites are shown in Figure 3.1. Approximately 80% of the findings of chemical warfare agents are dumped at sea.

The total number of chemical warfare finds reported to Bornholms Marinedistrikt in the period 1979-2006 is shown in Figure 3.5. The number of findings has decreased considerably, except for 2003. This could indicate that the risk of finding chemical warfare agents in the Baltic Sea has decreased.

The findings were mainly mustard gas, but other gasses, such as tear gas and sneeze gas, were found as well.

The chemical warfare agents are found in lumps of different sizes. Intact bombs are very seldom among the more recent findings. Usually, the canisters of artillery shells (approximately 2 mm thick walls) have corroded away and only the warfare agent and some of the explosives remain /4/. An intact bomb containing mustard gas is shown in Figure 3.3. In Figure 3.4 weathered (oxidised and hydrolysed) lumps of viscous mustard gas are shown.

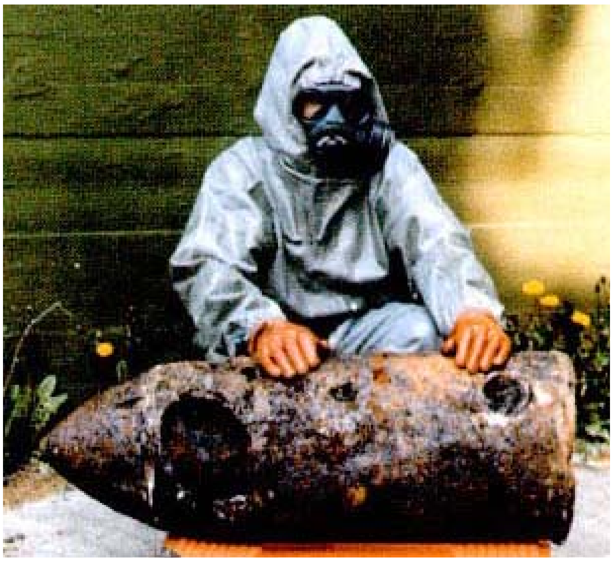

Figure 3.3: Intact bomb containing mustard gas, /4/. (Photo from Bornholms Marinedistrikt)

Intact bombs contain up to 100 kg of warfare agent /4/. The mass of the lumps found in the Baltic Sea is often less than this. The lumps vary greatly in size, and the weight of the findings ranges from approximately 0.1 kg to 100 kg, /3/. Some findings consist of several smaller pieces, and some parts of the lumps may have been crushed. The size of the broken pieces can be as small as a few millimetres in diameter, /3/. This indicates that the lumps of viscous mustard gas on the seabed of the Baltic Sea greatly vary in size; some of them were broken due to fishing activities.

 

Figure 3.4: Weathered lumps of viscous mustard gas, /4/. (Photos from Bornholms Marinedis-trikt)

The types and sizes of findings from the period 2003-2007 are shown in Table 3.1 and Table 3.2.

Type of gas	Number of findings in the period 2003-2007
Mustard gas	31
Sneeze gas	3
Tear gas	2

Table 3.1: Types of gas in findings from 2003-2007, /5/.

Total weight of findings	Total number of findings	Number of findings of one piece	Number of findings of two pieces	Number of findings of more than two pieces
Above 50 kg	14	11	2	1
5 – 50 kg	16	14	1	1
Below 5 kg	6	1	0	5

Table 3.2: Weight and number of lumps in findings from 2003-2007, /5/.

Table 3.1 shows that in the period 2003-2007 mainly viscous mustard gas was found. Table 3.2 shows that the findings typically consisted of one large lump, on many occasions weighing more than 50 kg, but findings of several small lumps are identified as well. In some cases, the findings consist of a large lump that has been broken in two where both pieces have been brought in /5/, /3/.

All recent findings of lumps of viscous mustard gas are weathered solid lumps, /3/, and it must be expected that the lumps of viscous mustard gas on the seabed in the Baltic Sea are solid as well.

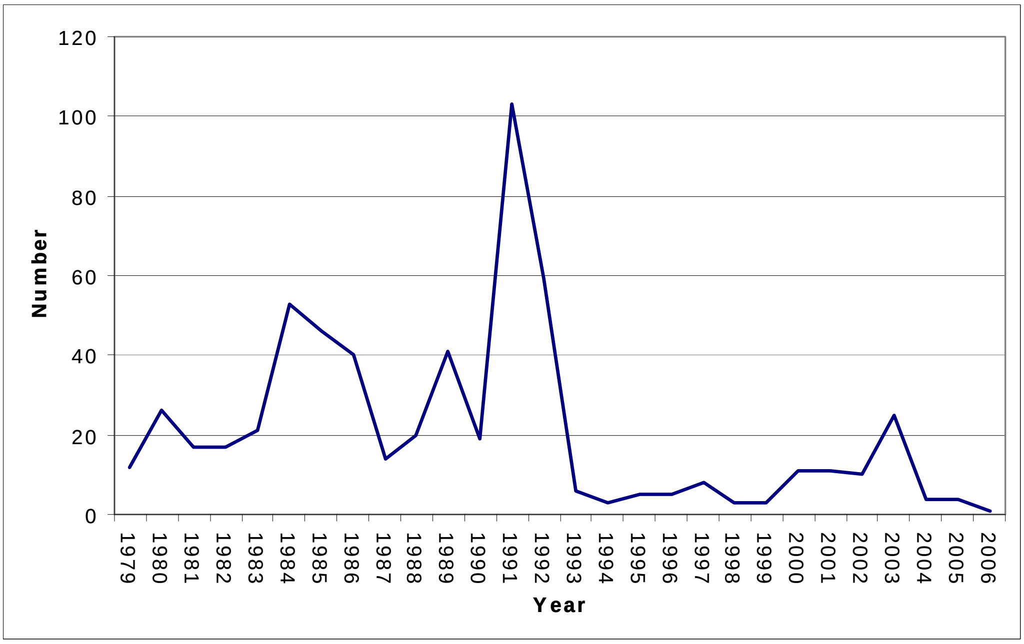

Figure 3.5: Number of chemical warfare finds reported to Bornholms Marinedistrikt /3, 4/.

3.4 Observed mobility of dumped material

It is considered that chemical warfare agents were dumped in an area larger than the official dumping area, /2/. Furthermore, spreading of viscous mustard gas may also have happened due to:

- relocation by currents
- relocation by fishing activities

Findings by fishing vessels of viscous mustard gas have been reported in an area much larger than that of the official dumping sites. The reports, however, do not necessarily reflect the distribution of viscous mustard gas on the seabed, as the positions given for findings by vessels are those where trawls were taken onboard, not where the lumps were caught by trawls.

However, there is a possibility that fishing vessels themselves transport lumps from one site to another and drop the lumps before taking them onboard. It is also possible that parts of a lump break off during trawling and are left on the seabed.

On basis of /2/ chemical warfare agents are not found onshore, except for the few incidents described below. From 1952–1954, five bombs were found along the Polish coast, but it is not known if they were chemical or conventional bombs. In 1954, a chemical bomb was found on the German island of Rügen. In all these cases it was concluded that the munitions were thrown overboard close to land, /2/.

In addition to these reports, one newer finding of chemical munitions was reported. In 1992 a mustard gas bomb was found at Dueodde Beach on Bornholm. However, Danish experts concluded that the bomb had not washed ashore, but was placed at the beach on purpose, /2/.

The final conclusion from the HELCOM Working Group on Dumped Chemical Munitions regarding the mobility of the chemical munitions is, /2/: “A relocation by hydrographic conditions is unlikely. Because of intensive fishing activities in or close to the dumping areas relocation of chemical munitions may take place.” Furthermore, /2/: “The Group concludes that a threat to the coastal areas of the Helsinki Convention Area from residues of warfare agents or chemical munitions washed ashore is unlikely.”

These conclusions indicate that although there has been relocation of lumps of viscous mustard gas there have been no incidents where lumps have washed ashore. Furthermore, the relocation of chemical munitions is due primarily to fishing activities; relocation by currents is only a minor factor.

4. Impacts due to pipe-laying

4.1 Degradation of munitions due to pipe-laying

The pipelines will traverse two areas where there is a risk of chemical warfare agents lying on the seabed, as shown in Figure 3.1. There is therefore a small risk that the pipeline will be laid directly atop a lump of viscous mustard gas.

The pipelines will influence only a narrow corridor in the risk areas. In the area around Bornholm, the length of each of the pipelines in the risk area is approximately 105 km. The influenced area is 0.160 km^2, assuming the influence area is equal to the diameter of the pipeline. This corresponds to 1/60,000 of Risk Zone 3 (see Figure 3.1) being influenced by the pipelines. In the area south-east of Gotland, the length of each of the pipelines in the risk area is approximately 50 km. This corresponds to 1/120,000 of Risk Zone 2. A much larger part of the risk area is influenced by fishing activities every year.

During installation, the pipeline will be laid slowly on the seabed, so the mechanical action from the pipeline will be quite small. When laying the pipeline atop a lump of viscous mustard gas, three possible situations can occur:

- the lump is buried under the pipe, which is likely in the areas where the sediment is very soft
- the lump is pushed aside without breaking
- the lump is broken into smaller pieces

Each of the three situations is likely to occur, and it is impossible to estimate which is the most likely, as it will depend on several factors. However, it is certain that there is a risk of lumps breaking.

The influence from the pipeline is not different from the breakdown of the lumps already taking place in connection with weathering processes and fishing activities, but it may very slightly speed up the breakdown if the pipeline hits lumps on the seabed and breaks them to smaller pieces /3/.

If a lump is broken into smaller pieces similar to those caused by trawl boards, the sizes of the broken pieces must be in the same range as the lumps broken due to fishing activities. From the lumps reported to Bornholms Marinedistrikt, the size of the broken pieces may be estimated. The size distribution of these findings cannot be directly used as a size distribution of lumps broken by mechanical action. Large lumps may be caught in trawls more easily, and if small pieces break off when the lumps are moved in the trawls, they may be left behind. Furthermore, many of the lumps that have been found were not broken. However, from the description of the size range of the findings, a relevant size range of lumps broken by mechanical action can be estimated at approximately 0.2-25 cm in diameter.

4.2 Expected mobility due to pipe-laying

Each of the three different situations that could occur if the pipeline were laid directly atop a lump of mustard gas would have a different effect on the mobility of the lumps.

1. If a lump were buried under the pipe, the lump would become totally demobilised.
2. If a lump were pushed aside without breaking, the mobility would be unchanged.
3. If a lump were broken into smaller pieces, the mobility of the lump would increase.

It therefore cannot unambiguously be concluded whether pipe-laying will increase or decrease the mobility of lumps in the corridor of the pipeline.

As the process of degrading and breaking the lumps is ongoing due to weathering and fishing activities, increased mobility would only apply to those single lumps that could be broken, not to the general mobility of the lumps. The pipeline introduces no new degradation processes. This means that the considerations of the mobility of the broken lumps is general and applies to both the breakdown caused by pipe-laying as well as the breakdown caused by decades of fishing activities.

The conclusions from Section 3.4 regarding the observed mobility of dumped chemical munitions, therefore, also apply to viscous mustard gas influenced by pipe-laying.

5. Modelling of spreading

5.1 Scenarios

To further support the conclusions from /2/, that relocation by hydrographic conditions is unlikely, the possibility of the lumps being transported by current and waves has been quantified in the following.

Two locations have been chosen to analyse the mobility of lumps of broken-down viscous mustard gas.

The two locations represent the points where the pipeline is closest to each of the two dumping sites in the Baltic Sea. The locations are shown in Table 5.1.

Location	Area	Coordinates	Water depth (from Mike 3 model, /1/)
1	Bornholm Basin (approximately KP 1025)	15.50°E, 55.43°N	90 m
2	Gotland Deep (approximately KP 800)	18.58°E, 56.35°N	64 m

Table 5.1: Locations where pipeline is closest to dumping sites.

The mobility of broken lumps of viscous mustard gas has been analysed for the following sizes in the interval that is assumed to represent the lumps: 0.2 cm, 1 cm, 5 cm and 25 cm in diameter. The pieces are assumed to be spherical to make the modelling possible, although their actual shape is unknown.

On basis of the MIKE 3 Model, /1/, the current conditions in the lower metre of the water column at the sites at the two locations are shown in Figure 5.1 and Figure 5.2 as current roses representing conditions in the year 2005.

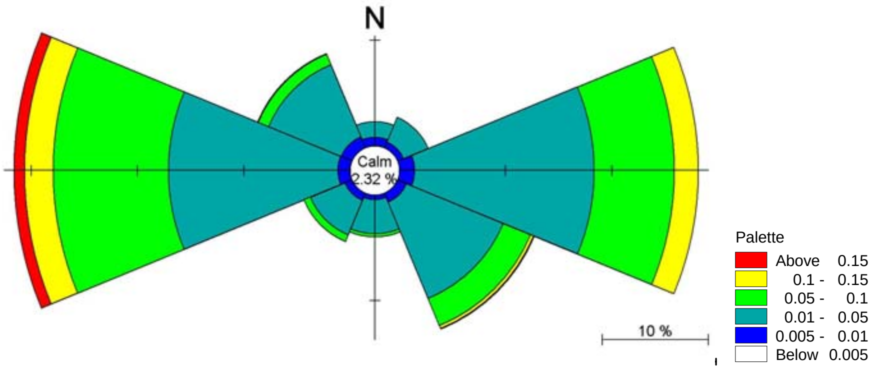

Figure 5.1: Current rose (m/s) representing modelled currents at the sea bottom in 2005 for Location 1 (Bornholm Basin) /1/.

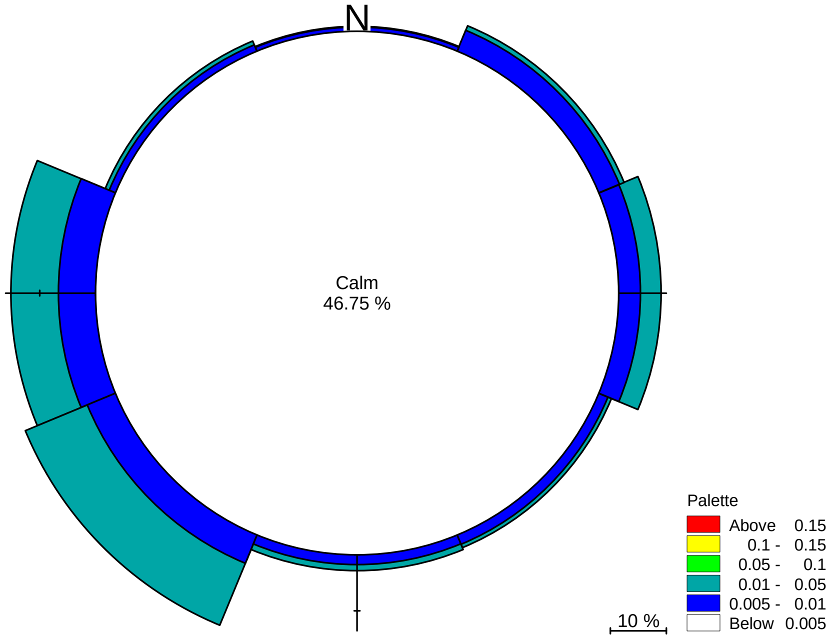

Figure 5.2: Current rose (m/s) representing modelled currents at the sea bottom in 2005 for Location 2 (Gotland Deep) /1/.

5.2 Critical velocity for movement of the lumps

To evaluate whether the lumps will be moved by current and waves, a desktop study has been performed. Movement of the lumps on the seabed is only initiated if the current velocity is above a certain critical velocity for the movement. The critical velocity depends on several factors, but it can be estimated by making some assumptions on the physical parameters governing the movement.

The Morison equation for fixed circular elements has been used to calculate the horizontal current and wave-induced forces on the lumps. Drag and inertia coefficients have been applied dependent on roughness of the lumps (estimated to 1 mm), and the Reynolds number. Three dimensional effects have been taken into account by using reduction factors on drag and inertia coefficients /6/.

The horizontal hydrodynamic Morison force that causes the lump to move has been compared with the friction force that retains lumps on the seabed.

If the Morison force exceeds the friction force, the lumps can be moved by the current or waves on a plain seabed, i.e., where there are no influences due to obstacles like larger rocks, grass, sloping seabed, etc.

The friction force is calculated by the submerged weight of the lumps times a friction coefficient, *f*. The friction coefficient depends on the seabed type and the surface of the lumps. In /7/ conservative values for the longitudinal friction coefficients between the soil and the pipe are given. A friction coefficient of 0.5 is assumed to be representative for sand, and a coefficient of 0.2 is assumed to be representative for clay, till and rock. In the two areas of concern, the seabed is dominated by clay. However, the lumps are considered to be quite irregular, and the friction coefficient between the soil and the lumps is presumably larger than the coefficient between soil and pipe. The friction coefficient between the soil and the lumps of mustard gas in the two areas, therefore, is estimated to be in the interval of 0.2–0.5. Conservatively, a friction coefficient of 0.2 has been used in the analysis.

The critical current velocities for two friction coefficients are estimated by calculating the critical current velocity for friction coefficients, f, of 0.2 and 0.5. The results are shown in Table 5.2.

Lump size	**Critical current velocity Uc (m/s) for *f* = 0.2**	**Critical current velocity Uc (m/s) for *f* = 0.5**
Very small (0.2 cm)	0.05	0.08
Small (1 cm)	0.11	0.16
Medium (10 cm)	0.23	0.36
Large (25 cm)	0.62	0.91

Table 5.2: Critical current velocity for different values of the friction coefficient, *f*.

Thee critical current velocity is seen to increase by approximately 50% when using a friction coefficient of 0.5 in comparison with the current velocity calculated using a friction coefficient of 0.2. Due to precautionary reasons the calculated velocity values for a friction coefficient of 0.2 are applied in the evaluation below.

5.3 Results

The critical current velocity for movement of the lumps, i.e., for which the force criteria just has been fulfilled, has been determined for each location and for different lump sizes.

The current conditions in the lower metre of the water column, as described in the section above, have been analysed, and the maximum current velocity has been determined for each location and shown in Table 5.3. Assuming that the maximum current is valid one metre above the seabed, a current profile of the power of 1/7 has been applied for calculating the maximum current velocity at the level of one lump diameter above the seabed. The maximum current velocity has then been compared with the critical current velocity in order to evaluate whether the lump can be moved by the current.

Location	**Max velocity, U_{max}, in the Lower 1 metre (m/s)**	**Significant wave height, H_s, in one year sea state (m)**
1 (Bornholm Basin)	0.23	4.5
2 (Gotland Deep)	0.05	5.5

Table 5.3: Modelled maximum velocity from /1/ and *Hs* in one year sea state from /7/

The probability of movement of the lumps by waves has been evaluated by calculating the Morison force using wave-induced particle velocity and acceleration in the level of the lumps. The maximum wave within the sea state of one year, $H_{s,1\ year}$ has been considered in the analysis using linear wave transformation. Wave heights from /7/ have been used in the analysis as shown in Table 5.3.

In Table 5.4, the main results of the calculations are presented. In Appendix A the calculations are described in detail.

The critical current velocity for movement of the lumps varies between 0.05-0.62 m/s, depending on lump size. The critical current velocity is only exceeded at Location 1 (Bornholm Basin) where movements of very small lumps would be possible.

The maximum wave corresponding to $H_{s,1\ year}$ will not move the lumps at Location 1 for a water depth of 90 m. However, the influence from waves depends greatly on water depth. The very small lumps would only be moved by the maximum wave in depths of less than 50 m.

At Location 2 the maximum wave corresponding to $H_{s,1\ year}$ would move the very small lumps, even at a water depth of 64 m. Small-sized lumps would be moved at depths of 50 m and medium-sized lumps would be moved at depths of 40 m.

Location	**Lump size**	**Max velocity U_{max} at level of the lump (m/s)**	**Critical current velocity Uc (m/s)**	**Will the max current move the lumps?**	**Will the max wave in a one year sea state move the lumps?**
1 (Bornholm Basin, water depth of 90 m)	Very small (0.2 cm)	0.09	0.05	Yes	No
	Small (1 cm)	0.12	0.11	Yes[1]	No
	Medium (10 cm)	0.15	0.23	No	No
	Large (25 cm)	0.19	0.62	No	No
2 (Gotland Deep, water depth of 64m)	Very small (0.2 cm)	0.02	0.05	No	Yes
	Small (1 cm)	0.03	0.11	No	No
	Medium (10 cm)	0.03	0.23	No	No
	Large (25 cm)	0.04	0.62	No	No

Table 5.4: Possible movement of lumps.

[1] Not exceeded for f=0.5, see Table 5.2

According to this analysis, the maximum current velocity at Location 1 (Bornholm Basin) could move the very small and small lumps. The maximum wave in a one year sea state at Location 2 (Gotland Deep) could move the very small lumps. The maximum current velocity is estimated by the MIKE 3 model for the year 2005 using a time step of 6 hours. Assuming that the lumps at Location 1 are moved with a velocity corresponding to the maximum current velocity for a period of six hours, the lumps would be moved around 2600 m (on a plain seabed not taking the movement on a sloping seabed closer to the shore into account). Likewise, for Location 2 the maximum wave in a one year sea state (with a time period of around 10 seconds) is only able to move the lumps at a limited distance.

The results in Table 5.4 are given for the maximum current velocities. From Figure 5.1 it can be seen that the current velocities in general are lower than the maximum current velocity.

6. Conclusion

Analysis shows that under very rough conditions the waves and currents could be able to move small lumps of viscous mustard gas. However, due to the short duration during which the lumps could be moved, they would not be transported very far. Furthermore, the lumps would have to travel up a slope from 60-90 m of depth to the surface, which decreases the possibility the lumps moving towards the shoreline.

The analysis therefore supports the conclusions from /2/ that it is very unlikely that lumps of viscous mustard gas would be transported to the shoreline by the current, even in the case of small lumps.

The weathering and natural degradation of viscous mustard gas is more rapid for very small lumps than for large lumps. Therefore, it must be expected that the very small fragments with a diameter of 10 mm would not be preserved on the seabed as long as the large lumps that are found in the Baltic Sea.

It can be concluded that breaking of the lumps of viscous mustard gas would not cause increased threats to the coastal areas of the Baltic Sea.

7. References

/1/ Nord Stream AG and Ramboll, **2007**, "Memo 4.3a-1 - Hydrodynamical model setup for the Baltic Sea", Nord Stream AG, Zug, Switzerland.

/2/ HELCOM, **1994,** "Report on Chemical Munitions Dumped in the Baltic Sea - Report to the 15th meeting of Helsinki Commission 8-11 March 1994, Danish Environmental Protection Agency", http://www.helcom.fi/stc/files/Publications/OtherPublications/1994Report-ChemicalMunitionsDumpedInTheBalticSea.pdf , Date accessed: 2008-8-14.

/3/ Ramboll, **2007-9, "**Conversations with Bornholms Marinedistrikt (the Danish Navy at Bornholm)**",** Received by Jesper Aarosiin Hansen.

/4/ HELCOM, **2002**, "Response Manual, Vol. 2 Chapter 6 - Amendment No. 27/02/03".

/5/ Bornholms Marinedistrikt, **2007**, "Opgørelse over minørsager vedr. gas i 2003-2007 under Bornholms Marinedistrikt (In Danish)".

/6/ Dansk Standard DS 449, **1983**, "Dansk ingeniørforenings norm for pælefunderede offshore stålkonstruktioner (in Danish)", Teknisk forlag.

/7/ Snamprogetti, **25-1-2008**, "Re-routing at Bornholm - LA-E-70624".

Appendix A: Evaluation of critical currents

NordStream; Evaluation of mustard gas lumps

Date: 071008 Last update 28/09/2009
Prepared by: PFS LGG

Wave parameters based on report 'LA-E-70624 Re-routing at Bornholm', by Snamprogetti
- Hmax calculated by Hs, using Hmax=Hs*sqrt(0.5* ln(N)), where N is number of waves in a 3-hour seastate
- Tz calculated by Tp, using Tp=1.56 Tz for a Pierson-Moskowitz wave spectra

Assumptions:

Water depth: KP 1000 - KP 1050 (area NE of Bornholm): 50 - 80 m
KP 800 (dumping area Gotland): 40 - 60 m

- Hydraulic roughness k= 0.001 m
- Density of sea water ρ = 1025 kg/m3
- Density of sediment ρs = 1400 kg/m3
- Kinematic viscosity ν = 1.30E-06 m2/s
- Friction coefficient f = 0.5 for sand, at KP 800
  0.2 for clay,till and rock, at KP 1000-1050
- Reduction factor on CD due to 3D, κ = 0.58 for current for subcritical Re area (Re< 10^5)
  0.80 for current for supercritical Re area (Re> 10^6)

Model:

Morison equation: F=FM+FD, where — for fixed construction element
FM= ρs*V*Aw*(1+Cm)
FD= 0.5*rs*CD*(Uw+Uc)[Uw+Uc]*A
Cm= =0,5 for a sphere in current, =1,0 for cylinder in waves
CD= depends on k/D and Re for current, depends on Re for waves
Possible Movement: when (FM+FD)>f*Mass

Location	Lump Type	Current or wave	D	A	V	Depth	Hs	Tp	Hmax	Tz	Lo	L1	L2	error	c	Uw	Aw	Uc	KC	Re	k/D	Cm	CD	Reduction factor	FM	FD	Mass	Friction coefficient f	Possible Movement
			[m]	[m2]	[m3]	[m]	[m]	[m/s]	[m]	[s]	(m)	(m)	(m)	(m)	(m/s)	[m/s]	(m/s2)	[m/s]	=Uw*Tz/D	=Utot*D/ny				on CD due to 3D	[N]	[N]	[N]		Is (FM+FD)>f*Mass
KP 800	Very small lump	Current	0.002	3.14E-06	4.19E-09	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.05	0.00	7.69E+01	0.500	0.5	1.2	0.58	0.00E+00	3.67E-06	1.54E-05	0.2	Yes
			0.002	3.14E-06	4.19E-09	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.04	0.00	6.15E+01	0.500	0.5	1.2	0.58	0.00E+00	2.45E-06	1.54E-05	0.2	No
		1-yr wave	0.002	3.14E-06	4.19E-09	40.0	5.5	11.2	10.519	7.179	80.6	80.3	80.3	0.0	11.2	0.40	0.35	0.00	1445.10	6.19E+02	0.500	1.0	1.2	0.58	3.03E-06	1.82E-04	1.54E-05	0.2	Yes
			0.002	3.14E-06	4.19E-09	50.0	5.5	11.2	10.5	7.2	80.6	80.5	80.5	0.0	11.2	0.19	0.16	0.00	667.29	2.86E+02	0.500	1.0	1.2	0.58	1.40E-06	3.87E-05	1.54E-05	0.2	Yes
			0.002	3.14E-06	4.19E-09	60.0	5.5	11.2	10.5	7.2	80.6	80.5	80.5	0.0	11.2	0.09	0.07	0.00	306.54	1.31E+02	0.500	1.0	1.2	0.58	6.42E-07	8.17E-06	1.54E-05	0.2	Yes
	Small lump	Current	0.010	7.85E-05	5.24E-07	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.11	0.00	8.46E+02	0.100	0.5	1.2	0.58	0.00E+00	4.63E-04	1.93E-03	0.2	Yes
			0.010	7.85E-05	5.24E-07	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.10	0.00	7.69E+02	0.100	0.5	1.2	0.58	0.00E+00	3.83E-04	1.93E-03	0.2	No
		1-yr wave	0.010	7.85E-05	5.24E-07	40.0	5.5	11.2	10.5	7.2	80.6	80.3	80.3	0.0	11.2	0.40	0.35	0.00	289.02	3.10E+03	0.100	1.0	1.2	0.58	3.78E-04	4.54E-03	1.93E-03	0.2	Yes
			0.010	7.85E-05	5.24E-07	50.0	5.5	11.2	10.5	7.2	80.6	80.5	80.5	0.0	11.2	0.19	0.16	0.00	133.46	1.43E+03	0.100	1.0	1.2	0.58	1.75E-04	9.68E-04	1.93E-03	0.2	Yes
			0.010	7.85E-05	5.24E-07	60.0	5.5	11.2	10.5	7.2	80.6	80.5	80.5	0.0	11.2	0.09	0.07	0.00	61.31	6.57E+02	0.100	1.0	1.2	0.58	8.02E-05	2.04E-04	1.93E-03	0.2	No
	Medium lump	Current	0.050	1.96E-03	6.54E-05	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.23	0.00	8.85E+03	0.020	0.5	1.2	0.58	0.00E+00	5.06E-02	2.41E-01	0.2	Yes
			0.050	1.96E-03	6.54E-05	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.22	0.00	8.46E+03	0.020	0.5	1.2	0.58	0.00E+00	4.63E-02	2.41E-01	0.2	No
		1-yr wave	0.050	1.96E-03	6.54E-05	40.0	5.5	11.2	10.5	7.2	80.6	80.3	80.3	0.0	11.2	0.40	0.35	0.00	57.80	1.55E+04	0.020	1.0	1.2	0.58	4.73E-02	1.14E-01	2.41E-01	0.2	Yes
			0.050	1.96E-03	6.54E-05	50.0	5.5	11.2	10.5	7.2	80.6	80.5	80.5	0.0	11.2	0.19	0.16	0.00	26.69	7.15E+03	0.020	1.0	1.2	0.58	2.18E-02	2.42E-02	2.41E-01	0.2	No
			0.050	1.96E-03	6.54E-05	60.0	5.5	11.2	10.5	7.2	80.6	80.5	80.5	0.0	11.2	0.09	0.07	0.00	12.26	3.28E+03	0.020	1.0	1.2	0.58	1.00E-02	5.11E-03	2.41E-01	0.2	No
	Large lump	Current	0.250	4.91E-02	8.18E-03	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.62	0.00	1.19E+05	0.004	0.5	0.8	0.58	0.00E+00	6.18E+00	3.01E+01	0.2	Yes
			0.250	4.91E-02	8.18E-03	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.61	0.00	1.17E+05	0.004	0.5	0.8	0.58	0.00E+00	5.98E+00	3.01E+01	0.2	No
		1-yr wave	0.250	4.91E-02	8.18E-03	40.0	5.5	11.2	10.5	7.2	80.6	80.3	80.3	0.0	11.2	0.40	0.35	0.00	11.56	7.74E+04	0.004	1.0	1.2	0.58	5.91E+00	2.84E+00	3.01E+01	0.2	Yes
			0.250	4.91E-02	8.18E-03	50.0	5.5	11.2	10.5	7.2	80.6	80.5	80.5	0.0	11.2	0.19	0.16	0.00	5.34	3.58E+04	0.004	1.0	1.2	0.58	2.73E+00	6.05E-01	3.01E+01	0.2	No
			0.250	4.91E-02	8.18E-03	60.0	5.5	11.2	10.5	7.2	80.6	80.5	80.5	0.0	11.2	0.09	0.07	0.00	2.45	1.64E+04	0.004	1.0	1.2	0.58	1.25E+00	1.28E-01	3.01E+01	0.2	No
KP 1000-1050	Very small lump	Current	0.002	3.14E-06	4.19E-09	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.05	0.00	7.69E+01	0.500	0.5	1.2	0.58	0.00E+00	3.67E-06	1.54E-05	0.2	Yes
			0.002	3.14E-06	4.19E-09	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.04	0.00	6.15E+01	0.500	0.5	1.2	0.58	0.00E+00	2.45E-06	1.54E-05	0.2	No
		1-yr wave	0.002	3.14E-06	4.19E-09	50.0	4.5	10.2	8.7	6.5	66.8	66.8	66.8	0.0	10.2	0.08	0.07	0.00	246.87	1.16E+02	0.500	1.0	1.2	0.58	6.23E-07	6.39E-06	1.54E-05	0.2	Yes
			0.002	3.14E-06	4.19E-09	65.0	4.5	10.2	8.7	6.5	66.8	66.8	66.8	0.0	10.2	0.02	0.02	0.00	60.28	2.84E+01	0.500	1.0	1.2	0.58	1.52E-07	3.81E-07	1.54E-05	0.2	No
			0.002	3.14E-06	4.19E-09	80.0	4.5	10.2	8.7	6.5	66.8	66.8	66.8	0.0	10.2	0.00	0.00	0.00	14.71	6.92E+00	0.500	1.0	1.2	0.58	3.71E-08	2.27E-08	1.54E-05	0.2	No
	Small lump	Current	0.010	7.85E-05	5.24E-07	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.11	0.00	8.46E+02	0.100	0.5	1.2	0.58	0.00E+00	4.63E-04	1.93E-03	0.2	Yes
			0.010	7.85E-05	5.24E-07	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.10	0.00	7.69E+02	0.100	0.5	1.2	0.58	0.00E+00	3.83E-04	1.93E-03	0.2	No
		1-yr wave	0.010	7.85E-05	5.24E-07	50.0	4.5	10.2	8.7	6.5	66.8	66.8	66.8	0.0	10.2	0.08	0.07	0.00	49.37	5.81E+02	0.100	1.0	1.2	0.58	7.79E-05	1.60E-04	1.93E-03	0.2	No
			0.010	7.85E-05	5.24E-07	65.0	4.5	10.2	8.7	6.5	66.8	66.8	66.8	0.0	10.2	0.02	0.02	0.00	12.06	1.42E+02	0.100	1.0	1.2	0.58	1.90E-05	9.52E-06	1.93E-03	0.2	No
			0.010	7.85E-05	5.24E-07	80.0	4.5	10.2	8.7	6.5	66.8	66.8	66.8	0.0	10.2	0.00	0.00	0.00	2.94	3.46E+01	0.100	1.0	1.2	0.58	4.64E-06	5.67E-07	1.93E-03	0.2	No
	Medium lump	Current	0.050	1.96E-03	6.54E-05	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.23	0.00	8.85E+03	0.020	0.5	1.2	0.58	0.00E+00	5.06E-02	2.41E-01	0.2	Yes
			0.050	1.96E-03	6.54E-05	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.22	0.00	8.46E+03	0.020	0.5	1.2	0.58	0.00E+00	4.63E-02	2.41E-01	0.2	No
		1-yr wave	0.050	1.96E-03	6.54E-05	50.0	4.5	10.2	8.7	6.5	66.8	66.8	66.8	0.0	10.2	0.08	0.07	0.00	9.87	2.90E+03	0.020	1.0	1.2	0.58	9.74E-03	3.99E-03	2.41E-01	0.2	No
			0.050	1.96E-03	6.54E-05	65.0	4.5	10.2	8.7	6.5	66.8	66.8	66.8	0.0	10.2	0.02	0.02	0.00	2.41	7.09E+02	0.020	1.0	1.2	0.58	2.38E-03	2.38E-04	2.41E-01	0.2	No
			0.050	1.96E-03	6.54E-05	80.0	4.5	10.2	8.7	6.5	66.8	66.8	66.8	0.0	10.2	0.00	0.00	0.00	0.59	1.73E+02	0.020	1.0	1.2	0.58	5.80E-04	1.42E-05	2.41E-01	0.2	No
	Large lump	Current	0.250	4.91E-02	8.18E-03	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.62	0.00	1.19E+05	0.004	0.5	0.8	0.58	0.00E+00	6.18E+00	3.01E+01	0.2	Yes
			0.250	4.91E-02	8.18E-03	-	-	-	-	0.0	-	-	-	-	-	0.00	0.00	0.61	0.00	1.17E+05	0.004	0.5	0.8	0.58	0.00E+00	5.98E+00	3.01E+01	0.2	No
		1-yr wave	0.250	4.91E-02	8.18E-03	50.0	4.5	10.2	8.7	6.5	66.8	66.8	66.8	0.0	10.2	0.08	0.07	0.00	1.98	1.45E+04	0.004	1.0	1.2	0.58	1.22E+00	9.99E-02	3.01E+01	0.2	No
			0.250	4.91E-02	8.18E-03	65.0	4.5	10.2	8.7	6.5	66.8	66.8	66.8	0.0	10.2	0.02	0.02	0.00	0.48	3.55E+03	0.004	1.0	1.2	0.58	2.97E-01	5.96E-03	3.01E+01	0.2	No
			0.250	4.91E-02	8.18E-03	80.0	4.5	10.2	8.7	6.5	66.8	66.8	66.8	0.0	10.2	0.00	0.00	0.00	0.12	8.65E+02	0.004	1.0	1.2	0.58	7.25E-02	3.55E-04	3.01E+01	0.2	No