Encl.5

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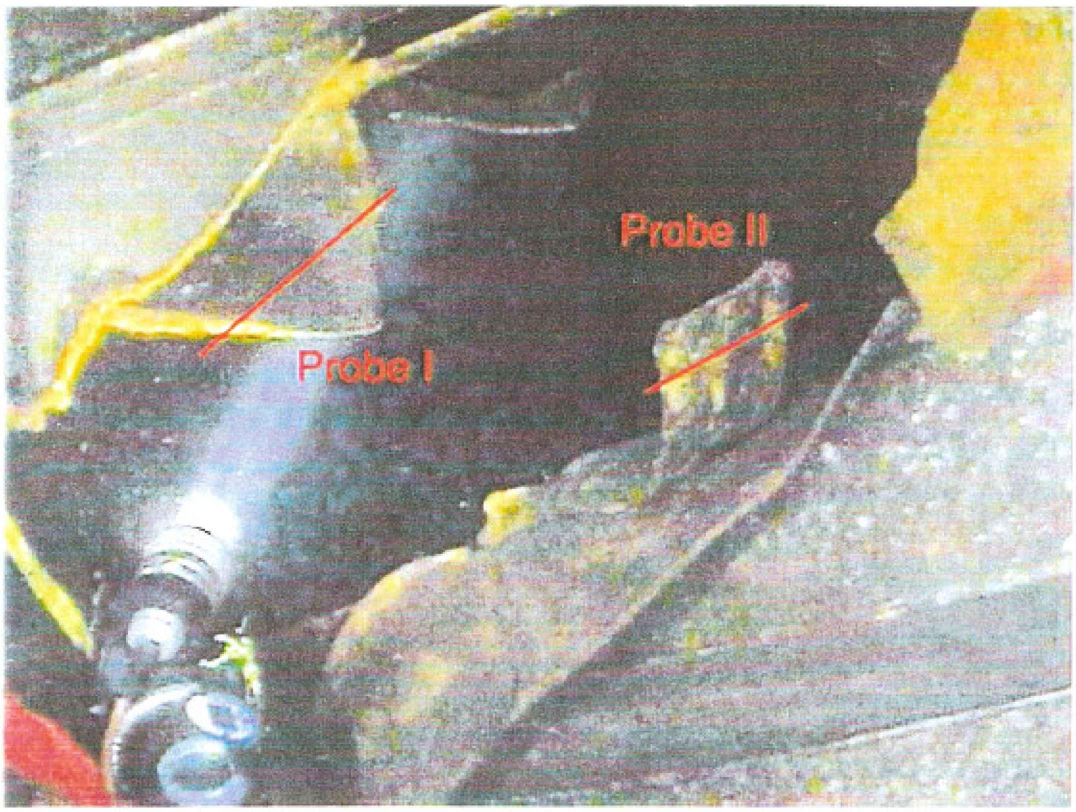
to the German Group of Experts

REPORT ON METAL SAMPLES TAKEN FROM THE ESTONIA

The sinking
of the car/passenger ferry
ESTONIA
in the Baltic Sea
on the 28th September 1994



This report was prepared for the German Group of Experts in September 2001

ESTONIA
REPORT ON METAL SAMPLES TAKEN FROM THE SHIP
by B H L Braidwood, MBIM, MIExpE

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PART 1

INTRODUCTION

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PART 1

INTRODUCTION

1.1 In March and August 1999 I wrote Investigation reports on the sinking of the ESTONIA. At that time, the only part of the ship available for examination on land was the Bow Visor. In the year 2000 an independent diving expedition has recovered two samples of metal from the damaged area near the starboard forward bulkhead above B Deck level. The cover picture of this report shows where the two samples came from. In the picture they are marked Probe I and Probe II. They are referred to in this report as Sample 1 and Sample 2.

1.2 The samples of metal have been subjected to comprehensive tests at separate and independent Material Testing Laboratories in Germany. The laboratories were asked to examine the samples for any evidence of an explosion and produce an account of their test results.

1.3 In this present report, under Background Information in Part 2, I have described how samples taken after an event might be tested to produce evidence of an explosion. This is followed by details of an example taken from my own work on another ship.

1.4 I then comment on the recent technical reports and how their findings provide indisputable proof that the samples were exposed to the effects of an explosion in the ESTONIA.

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PART 2

BACKGROUND

INFORMATION

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PART 2

BACKGROUND INFORMATION

Understanding Technical Reports

2.1 The following pages are intended to allow someone who is not a scientist to understand the findings of Technical Reports on testing samples of metal from the ESTONIA. For simplicity, the reports are referred to by their origins - namely Brandenburg and Clausthal-Zellerfeld. It should be possible to realise the significance of their conclusions without having access to the reports concerned. Nevertheless, access to the reports may permit a better understanding of the work involved.

Evidence of an Explosion

2.2 When an explosion occurs next to metal it affects the metal in several ways. It is possible to detect these effects by testing samples of metal taken from the area and so provide evidence that there was an explosion. This evidence can be divided into four types. These are chemical traces, surface marking, crystalline deformation, and hardening. The extent of each effect depends on how much contamination may have occurred since the explosion, how long after the explosion the samples were taken, and how close the sample was to the centre of the explosion.

Chemical Analysis

2.3 Analysing the chemical composition of traces on a metal sample is only useful if the sample has been constantly protected from any possible contamination since the time of the explosion. Otherwise, all sorts of traces can be detected but it is impossible to determine their origin and so they prove nothing.

Scanning Electron Microscope (SEM)

2.4 The SEM can examine surface marking which is often present in the form of pitting or cracking in a sample close to an explosion. However, it becomes less evident further away. Surface corrosion of a sample, which can occur even in quite a short time, can make it difficult or even impossible to detect this type of evidence.

Metallography

2.5 Metallography is the descriptive science of the internal structure of metals in contrast with metallurgy which is the art of working metals. Metallography can examine crystalline deformation which is one type of evidence that survives both delay and any surface corrosion of the metal which is being examined. The deformation occurs in varying degrees depending on distance from the explosion.

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Crystalline Deformation

2.6 This deformation is caused by the reaction of the crystalline structure to the shock wave of a detonation. The shock wave travels at the Velocity of Detonation (VOD) of the explosive. For a typical high explosive such as Plastic Explosive (PE) used by NATO or Semtex from Eastern Europe, the VOD is about 6,000 to 8,000 metres/second.

Speed of Deformation Forces in Metal and Transmission Loss

2.7 Inside nearby metal, the deformation forces of this shock wave travel more slowly because of transmission loss. The loss of speed depends on whether the explosion is immediately adjacent to the metal, when it will be slight, or separated by an air space or some other material, when there will be a greater reduction. If the speed in the metal is less than about 1,000 metres/second there will not be any deformation. A reaction speed of more than 1,000 metres/second can only be produced by a detonation.

Lamination or Lamellation

2.8 The deformation produces two distinct effects. First, there is a very distinct lamination or lamellation of the structure. To the purist, lamella is the diminutive form of lamina, but the words are virtually synonymous, meaning thin plates, scales, or layers. In its most extreme form, the lamination can make a sheet of steel look as if it was made up of several layers which have started to slide over each other.

2.9 The effect is shown clearly in the Brandenburg report with the two photos shown below at the same scale. No 21 shows an unaffected granular structure while in 28, the grains have been crushed together into flat layers by the deformation forces in the metal.

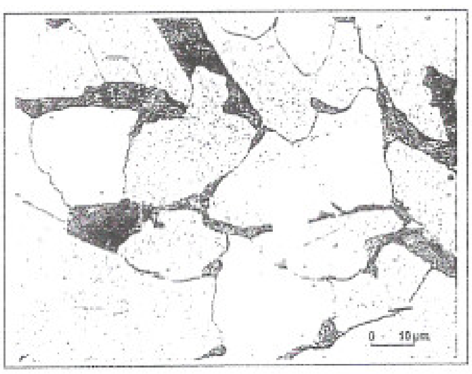

Bild 21 Probe 1.3/00/3664 G01 2

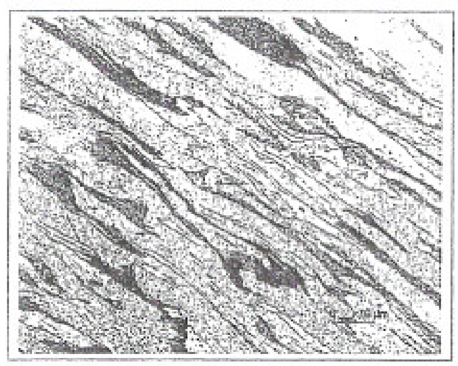

Bild 28 Probe 1.3/00/3664 G02 2

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BACKGROUND INFORMATION

Crystal/Mechanical Twinning or Neumann bands

2.10 This is the second effect found by metallography and caused by deformation following the severe shock wave of a detonation. It is internationally recognised by metallographers and by criminal courts as positive proof of an explosion.

Hardening by Explosives

2.11 Explosive hardening is a technique routinely used by engineers to make use of the fact that metal exposed to explosive shock forces becomes harder. It follows, therefore, that any hardening which can be detected in a metal will have been caused by such forces. The hardening values (HV) of a steel such as ST37-2, used in ship construction, have been established to be in the range of HV105 to HV145. Any significant increase in these values would indicate that the steel had been in the vicinity of an explosion.

Swedish National Defence Research Institute (FOA)
Paper by Dr Åke Persson

2.12 As long ago as 1977, the FOA was making good use of detecting the effects of Crystalline Deformation, Crystal Twinning and Hardening. During that year, at a Symposium on Ballistics at Karlshrue in Germany Dr Åke Persson presented a paper on Fragment Examination as a Tool for Diagnostics of Inbore Premature Firing Accidents. He was able to detect the effects of detonation and deflagration and so establish how the accidents had occurred.

Detonation and Deflagration

2.13 In the Introduction to his paper, he states that:-

a. **Detonation** is a supersonic reaction which means that the reaction front moves through the explosive with supersonic speed (7-8,000 metres/second).

b. **Deflagration** is subsonic and can be anything from low rate burning to a violent reaction with a reaction speed close to the speed of sound.

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Effects on Metal Fragments

2.14 Dr Persson goes on to compare the effects of detonation and deflagration on metal fragments next to an explosion. He states that for detonation these will include:-

Mechanical Twins (i.e. Crystal Twinning)
Large grain deformation
Greatly increased hardness due to shock wave and plastic deformation

He also states that after deflagration there will be:-

No Mechanical Twins
Roughly unchanged grain structure
Small hardness increase

Summary of Dr Persson's Paper

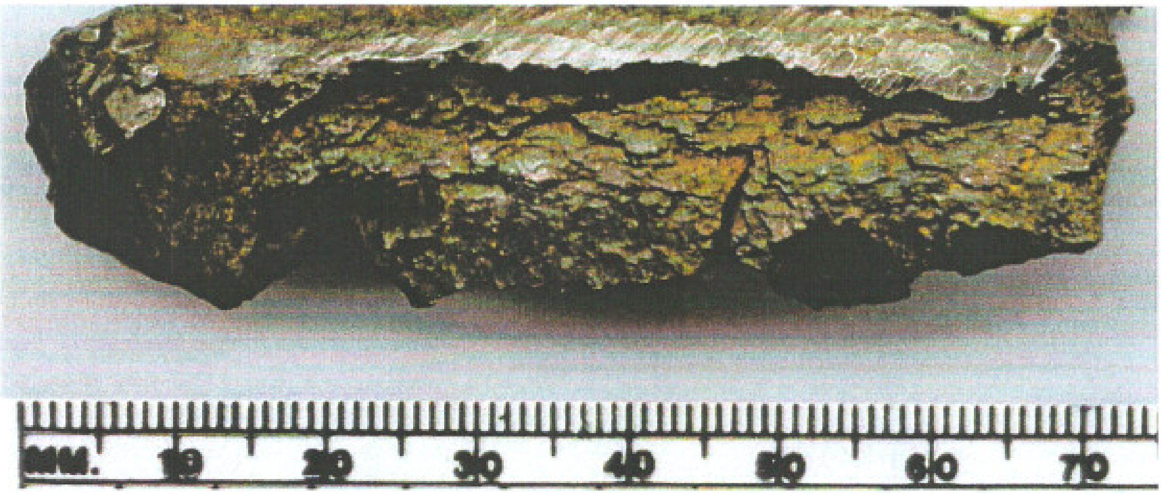
2.15 In summary, the paper describes very clearly the effects of explosions on metals and how these can be used in tests to confirm or deny that an explosion occurred in the vicinity of metal samples being tested. It is exactly these effects of explosions which have been used in testing the samples of metal taken from the ESTONIA.

PART 2

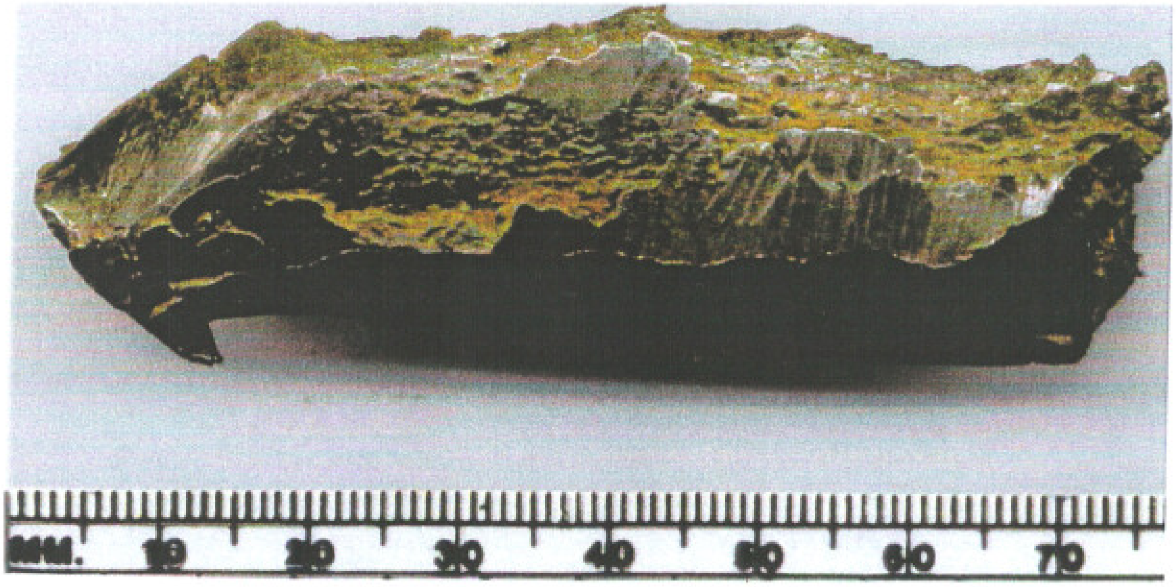
BACKGROUND INFORMATION

Example from a Previous Explosion

2.16 I have a sample of 12 mm mild steel taken from near the centre of an explosion on a ship's structure which I investigated some years ago. I took close-up photos to show the lamination effect. In places the surface appears almost like layers of water flowing over the flat rocks of a waterfall. This effect can be seen in the two photos below.



Lamination effect - View 1



Lamination effect - View 2

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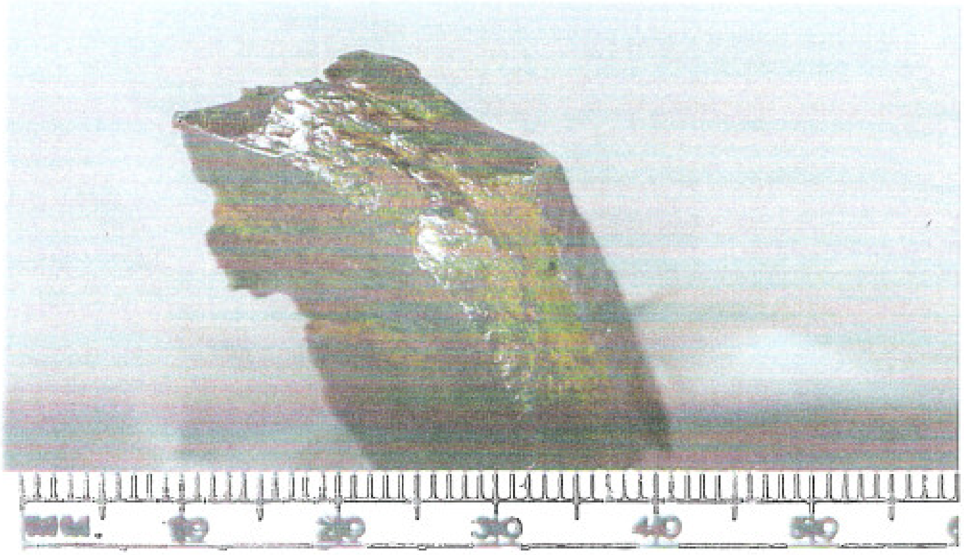
BACKGROUND INFORMATION

Example from a Previous Explosion (Continued)

2.17 The next two photos show one end of the sample. Both photos illustrate the lamination effect again. They may be compared with the larger scale Photos 24 and 25 in the first Technical Report from Brandenburg.



Lamination effect - View 3

Lamination effect - View 4

PART 3

ORIGIN

OF

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PART 3

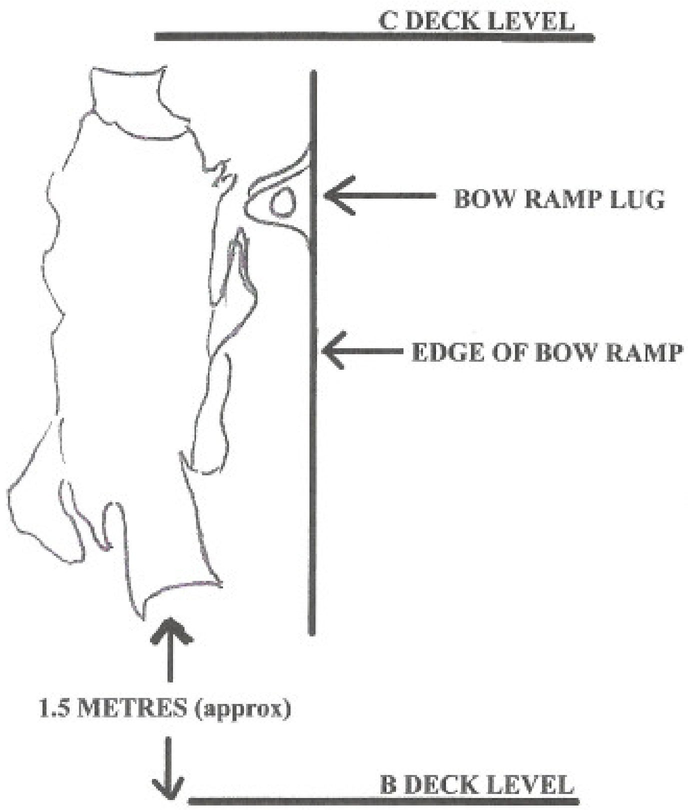
ORIGIN OF RECENT SAMPLES

Recent Samples

3.1 During a diving expedition in August 2000, two samples of metal were recovered from the ESTONIA. They were taken from the damaged area near the starboard forward bulkhead above B Deck level. The area concerned was shown in a drawing and some 1996 pictures in my Supplementary Report. These are reproduced below and on the next page.

FIRST AREA OF STARBOARD SIDE DAMAGE

ABOVE B DECK/UPPER CAR DECK LEVEL



OUTLINE SKETCH OF HOLE IN FORWARD BULKHEAD

BESIDE THE STARBOARD ACTUATOR/CYLINDER

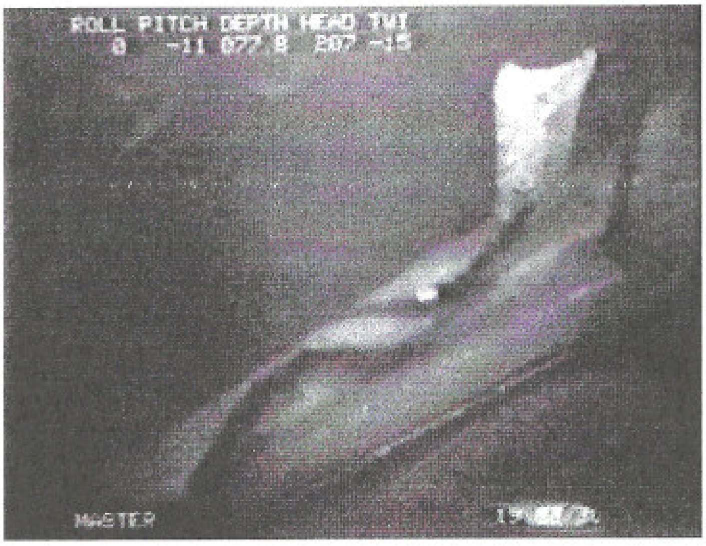
PART 3

ORIGIN OF RECENT SAMPLES

Recent Samples (continued)

3.2

FIRST AREA OF STARBOARD SIDE DAMAGE ABOVE B DECK/UPPER CAR DECK LEVEL



1996 Photo 1
Hole in Forward Bulkhead Middle Part and Lower End

3.3

1996 Photo 2
Hole in Forward Bulkhead Lower End - Near B Deck Level

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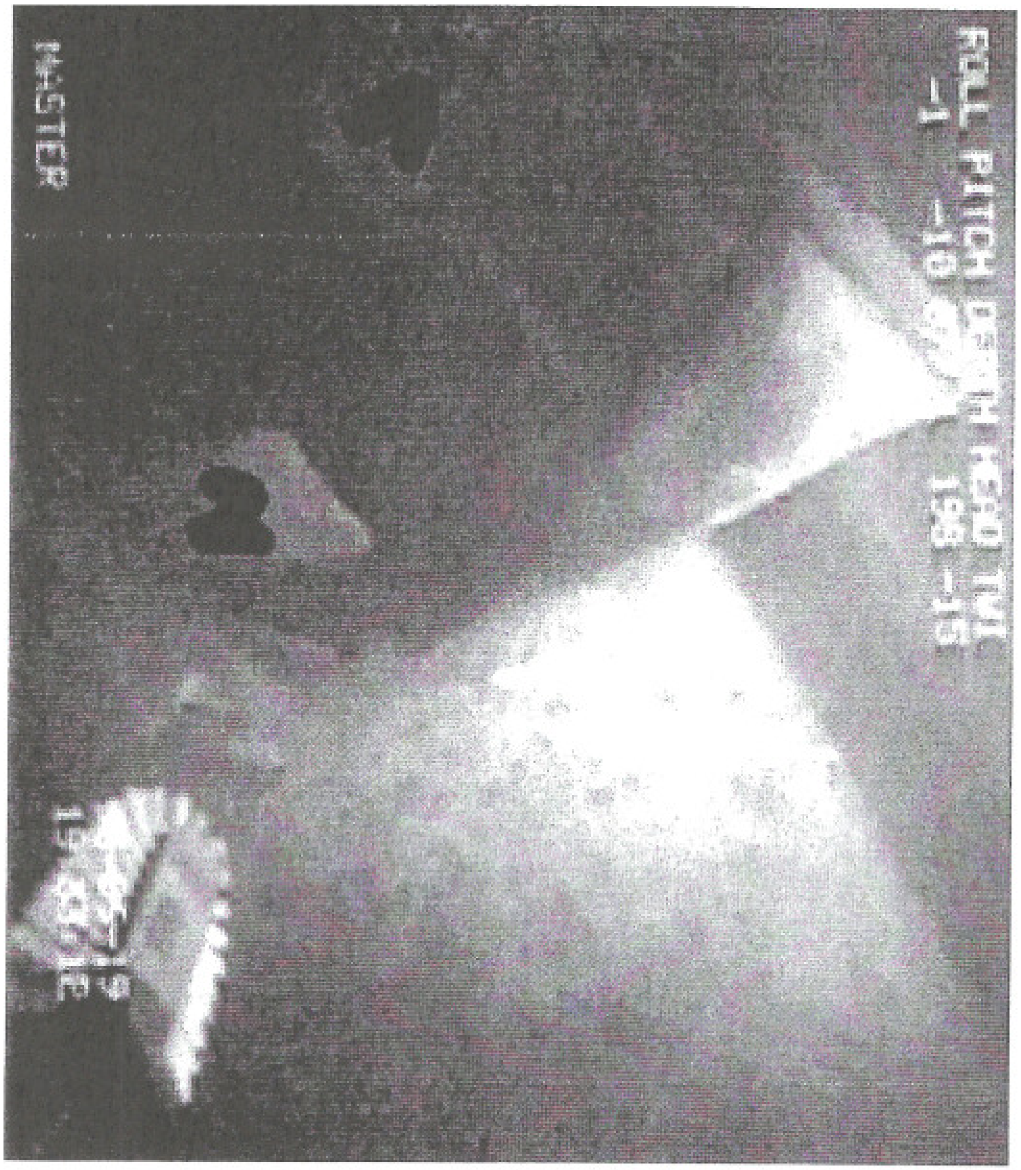
ORIGIN OF RECENT SAMPLES

Clandestine Removal of Evidence

3.4 Another picture of the area taken in 1996 is shown below.



1996 Photo 3

The positions of Sample 1 and Sample 2 are marked with black ink. To the right of Sample 2 is a very large flap of metal bent upwards.

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Clandestine Removal of Evidence (Continued)

3.5 Now compare 1996 Photo 3 on the previous page, with the photo below, taken in August 2000 during the recent diving expedition, and spot the difference!

2000 Photo 1
The positions of Sample 1 and Sample 2 are marked again with black ink. To the right, the "X" shows where the large flap of metal has been cut off.

3.6 It will immediately be obvious that the large flap on the right has been removed. It must be assumed that since 1996, another diving expedition has been to the wreck and removed this evidence without the knowledge of the public in Sweden or anywhere else!

Discrepancy in Photo Quality

3.7 Next, compare the poor quality of the 1996 photos with the excellent quality of the recent one. The underwater visibility is believed to have been the same on both occasions so it seems possible that the 1996 videos must have been altered in some way before being released by the Swedish Government. The recent videos have, of course, remained in the possession of the expedition organisers at all times.

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ORIGIN OF RECENT SAMPLES

Significance of Missing Flap relative to the Visor

3.8 The size and position of this flap as it appears in the videos up to 1996 is of considerable significance. The flap protruded forward of the bulkhead by about 300 to 500 mm. This allows two facts to be deduced. First, when the explosion causing this damage occurred, at about 0100 hours, the visor was at least 300 to 500 mm clear of the bulkhead. Otherwise the flap could not have reached its position as shown in the videos. Second, after the explosion caused the flap to protrude forwards as described, the visor never came back closer than 300 to 500 mm to the bulkhead, or it would have pushed the flap flat again.

Sample 1 and Sample 2

3.9 Sample 2 was an approximate rectangle measuring about 145 by 75 mm. It was supplied direct to the Clausthal-Zellerfeld Institute for testing.

3.10 Sample 1 was triangular in shape and was supplied direct to the State of Brandenburg Material Testing Laboratory.

3.11 Details of the testing are in the next part of this report.

PART 4

PREPARATION

FOR TESTING

OF

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PART 4

PREPARATION FOR TESTING OF RECENT SAMPLES

Sample 1

4.1 This was the triangular piece of metal shown in colour and in black and white on the next page, P-5. The lower edge of the triangle was cut by the flame of a cutting torch. Sides 3 and 4 were fractured by the forces of the explosion. The flat upper surface marked as Side 1 has visible traces of paint. The red/orange was the colour of the Viking Sally line and the white paint was put on when the ship became the ESTONIA.

Sample 2

4.2 Sample 2 was rectangular in shape and measured about 145mm by 75 mm.

Brandenburg Specimen References (taken from Sample 1)

4.3 Sample 1 was supplied to Brandenburg where small cross-section specimens were taken from different positions. In the first Brandenburg report, the specimens were identified as shown in the colour photo on the next page. In the second Brandenburg report a much simpler system was used as shown in the lower black and white photo. The specimens from both reports were numbered consecutively from 1 to 10. When reading the rest of this report reference should be made to the two photos on the next page.

Samples for Clausthal-Zellerfeld

4.4 Sample 2 measuring about 145mm by 75 mm, was supplied to Clausthal-Zellerfeld for non-destructive testing. This meant that they were not able to take specimens from it but had to test it as a complete piece.

4.5 From Sample 1, Area 3, they were supplied with Specimen GO22 which had been prepared and already tested by Brandenburg.

Samples for BAM

4.6 All the samples described above were later supplied to BAM for testing.

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PART 4

PREPARATION FOR TESTING OF RECENT SAMPLES

Sample 1 - First Brandenburg Report

4.7

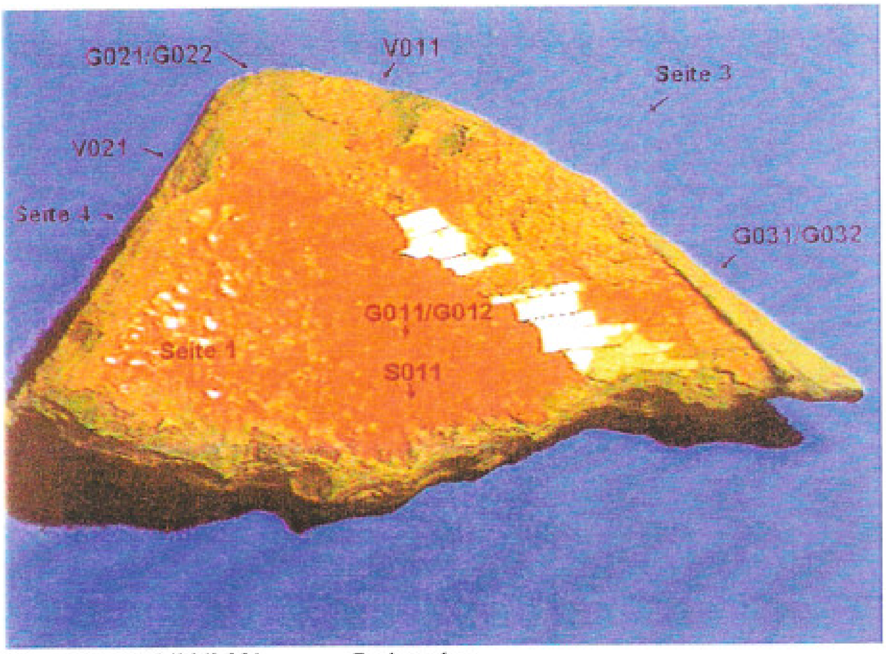
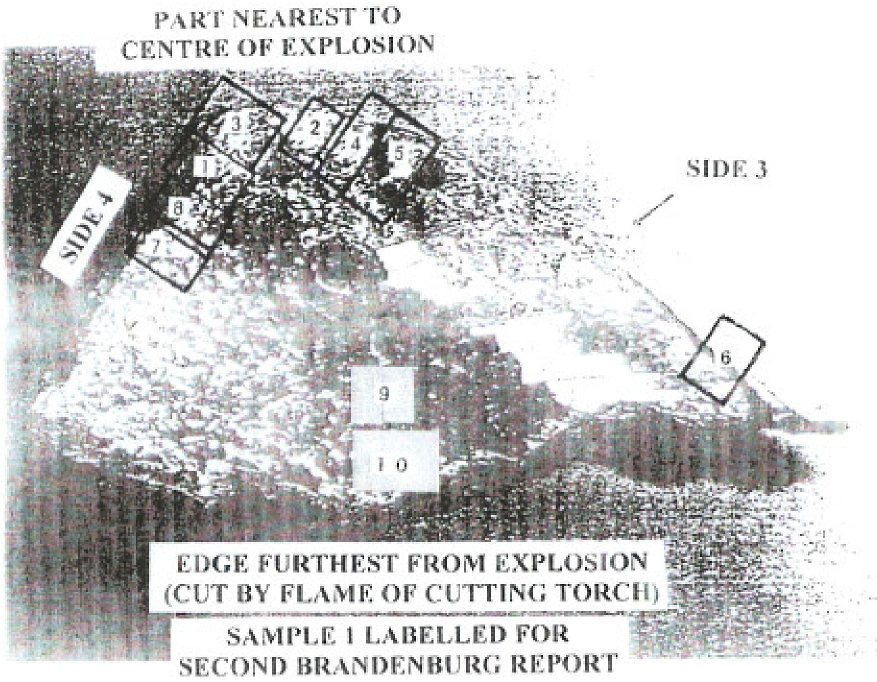


Bild 7 Probe 1 3/00/3664 Probenplan

Sample 1 - Second Brandenburg Report

4.8



PART 5

BRANDENBURG

REPORTS

ON

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PART 5

BRANDENBURG REPORTS ON RECENT SAMPLES

Two Reports to be considered as one

5.1 Brandenburg was supplied with Sample 1 and they produced two reports. The first dealt with test specimens from Areas 3, 6, 9, and 10. These included the area closest to the explosion and the areas furthest from the explosion to look for contrasting results. The second concerned specimens from Areas 4, 5, 7, and 8. This covered the areas where intermediate results might be expected. The tests can best be considered as a whole rather than separating the two reports.

Specimens taken and Tests performed

5.2 Referring back to Page P-5, two specimen cross-sections were taken from Areas 3 (GO2), Area 6 (GO3), and Area 9 (GO1). One cross-section was parallel to the edge and the other perpendicular to the edge. This gave the best chance of metallography detecting any crystalline or granular deformation in all six specimens. The three cross-sections perpendicular to the edge were then subjected to Hardness Testing and on completion, the one from Area 3 was passed on to Clausthal-Zellerfeld. The surface of Area 10 was subjected to Chemical or Piece Analysis.

Surface Examination by Scanning Electron Microscope (SEM)

5.3 This was carried at points VO11 and VO21 in the top photo Page P-5. Despite heavy corrosion some evidence of an explosion was found. This was described in the second report where it stated that the SEM examination showed:-

"areas in which the lamella are either heavily deformed or completely destroyed. The typical rounded grain form of the perlite has been changed beyond recognition."

Chemical Analysis

5.4 This was carried out at point SO11 in Area 10. The presence of numerous substances showed that there had been a lot of contamination since the sinking and no conclusions could be drawn relevant to an explosion.

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BRANDENBURG REPORTS ON RECENT SAMPLES

Micro Hardening Development

5.9 Brandenburg established that the range of Hardness Value (HV) for Steel Type 37-2 (like the sample), is in the range HV 105 to 145, which would give an average figure of HV 125. Multiple measurements were then taken in specimen cross-sections perpendicular to the edge. An average figure was then calculated for each cross-section.

5.10 The average figures for each area (See Page P-5) were as follows:-

Area	7	8	3	4	5	6	10
Average HV	**417**	**442**	**457**	**445**	**443**	**371**	**306**

Significant Increases in Hardness Values

5.11 These figures show that at the point nearest the explosion the HV showed a 265% increase and even near the opposite edge in Area 9 the increase was about 215%. As the Brandenburg Report stated:-

"The lowest hardening values measured of the specimen are with HV281 substantially higher than the hardening values of an uninfluenced material of this class." and *"the increase in hardness indicates a hardening of the metal which also appears during detonations."*

Summary and Discussion of the Results (First Report).
Metallographic Examination

5.12 Where the strain was greatest, the first report states on page 11 that:-

"The strained metallographic specimen from the fracture area (Area 3) *of the starboard front bulkhead shows extensive destruction of components in the original structure. The plastic deformation within the micro range indicates exposure to extremely heavy shock forces, such as happens from the effects of a substance detonating.*

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Summary and Discussion of the Results (First Report). Metallographic Examination (Continued)

5.13 The report went on to say:-

"The resulting heat, which is created during such a shock, by the internal friction, whilst overcoming the sliding resistance, is responsible for the changes within the structure."

The report explains that sliding does not occur in phases but in a wavy pattern which in turn produces a recognisable wavy pattern in the deformation that is characteristic of an explosion.

"Based on these results it is probable that the main strain area is to be found at another part of the hole."

This acknowledges that the sample was to one side of the explosion's centre which would have been in the middle of the damage area.

Summary of Both Examination Results (Second Report) Metallographic Examination

5.14 Here the report states that:-

"The plastic changes in the micro area, indicating an extremely strong shock effect, such as occurs in detonations, are recognisable in all specimens.

A general characteristic for a detonation is the destruction of the shell type build-up of the perlite. In the pictures taken by the SEM, it is apparent that the cementite of the perlite did not coagulate, which would have indicated the influence of heat alone, but the lamellar structure was changed beyond recognition by mechanical strain."

PART 5

BRANDENBURG REPORTS ON RECENT SAMPLES

Summary of Both Examination Results (Second Report)

5.15 The report ends by stating:-

"In the following, all the examination results which, according to our experience, do occur if there has been a detonation:

the appearance of parallel shear bands (Neumann bands)
(Note: This is also known as Mechanical or Crystal Twinning - see Dr Åke Persson's paper on page 4)

changes causing destruction of the cementite lamella in perlite
(Seen in the SEM examination)

hardness increase

plastic deformation in the micro area (wavy arrangement of the structure parts)."

5.16 The report ends by stating that:-

"The characteristics, determined during the examinations, which are consistent with the effects of a detonation, allow the conclusion, that the deformation velocity in the material must also have been in the detonation range. It is not possible to state the exact speed because it depends on a number of unknown influence factors, as e.g. the extent of transmission losses. (See Transmission Losses on page 3) *The lower limit in the case of a detonation is about 1000 metres/ second.* (See Speed of Reaction Forces on page 3)"

Meeting at Brandenburg Institute to discuss their Reports

5.17 On Monday 26th November, I attended a meeting with the authors of the reports - Dr.-Ing. Helmut Nega and his colleague Dipl,-Ing. (FH) Hannelore Mettel. The meeting was chaired by their Director, Professor Dr.-Ing. habil. Kurt Ziegler. At the end of a very useful meeting, the Professor was able to conclude that the tests completed by his department were "100% consistent with an explosion." This simply summarises the extracts I have quoted in this part of my report!

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BRANDENBURG REPORTS ON RECENT SAMPLES

CONCLUSIONS

5.18 From the Brandenburg reports, I can conclude beyond reasonable doubt that:-

1. The structural deformation of Sample 1 was caused by an explosion.

2. The increase in hardness measured in Sample 1 was caused by an explosion.

3. Overall, the findings of these technical reports are further evidence that there was an explosion in the ESTONIA, in the vicinity of the starboard forward bulkhead from which Sample 1 was taken.

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PART 6

CLAUSTHAL-ZELLERFELD

REPORT

ON

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PART 6

CLAUSTHAL-ZELLERFELD
REPORT ON RECENT SAMPLES

Clausthal-Zellerfeld Report

6.1 Clausthal-Zellerfeld examined, from Area 3 of Sample 1, Specimen GO2 2 after it had been examined by Brandenburg. They also examined Sample 2 referred to in Part 3 of this report.

Specimen GO2 2 Metallographic Examination

6.2 The report states that:-

" At one end of the sample an area of massive deformation is visible, which finally ends in a deformation flap. In addition, a further rather narrow area of high deformation was detected in way of one longitudinal side."

6.3 Tests also established that the deformation must have been caused by high deformation velocities which would have produced a temperature of about 720 degrees C.

6.4 These test results were consistent with those from Brandenburg on the same specimen.

Sample 2 Metallographic Examination

6.5 Tests on Sample 2 were carried out and the report states that:-

"directly at the fracture edge of sample No. 2 areas with extremely massive deformation were found."

The same paragraph goes on to say:-

"....calculations revealed that crystal size in way of the fracture area is smaller by factor x compared to the areas of unaffected material, a clear indication for a very high degree of deformation relating to a very high deformation velocity."

Temperatures of Deformation

6.6 The report explains that the major part of deformation energy from any explosion will be changed into heat and produce very high temperatures in the immediate vicinity of the explosion. In the case of high explosives, the temperatures would be consistent with the figure of 700 degrees C quoted in this report.

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CLAUSTHAL-ZELLERFELD REPORT ON RECENT SAMPLES

Velocities of Detonation and Subsequent Deformation

6.7 The report states that:-

> *"a deformation velocity between 1,000 to 10,000 metres/second must have occurred in this particular case. According to the relevant literature this range of velocities can only be achieved by detonations and/or firing guns."*

The velocity of detonation or VOD of a normal high explosive is about 6,500 m/s. After allowing for possible Transmission Loss, this is consistent with the range of deformation velocities quoted in the report.

Summary of Test Results

6.8 The findings of this technical report are further evidence that the damage to the starboard forward bulkhead in the ESTONIA was caused by the detonation of a high explosive charge.

CONCLUSIONS

6.9 From the Clausthal-Zellerfeld report, I conclude that beyond reasonable doubt:-

1. The massive structural deformation visible in Specimen GO2 2 from Area 3 in Sample 1 was caused by an explosion.

2. The clear indication of a very high degree of structural deformation found in Sample 2 was caused by an explosion.

3. Overall, the findings of this technical report are further evidence that there was an explosion in the ESTONIA, in the vicinity of the starboard forward bulkhead from which Sample 1 and Sample 2 were taken.

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PART 7

BAM

REPORT

ON

RECENT SAMPLES

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PART 7

BAM
REPORT ON RECENT SAMPLES

Samples supplied to BAM for testing

7.1 BAM was instructed by the Spiegel company to establish whether two test pieces supplied to them showed any signs of having been near an explosion or detonation. The first test piece, which BAM named "front bulkhead", was in fact Sample 1, described in Part 3 of this report. By the time it reached BAM it was without some specimen pieces which had been removed by Brandenburg and prepared for testing by them. The second sample, which BAM called "Holland Profile" was in fact Sample 2 as described in Part of this report. When BAM realised that Sample 1 was incomplete, they were supplied with the missing specimens from MPA Brandenburg. They then had access to all the samples, and specimens from samples, which had already been examined and tested by Brandenburg.

BAM Report and TV coverage of tests

7.2 The report produced by BAM is long and detailed. An English translation of the Summary from the Spiegel Online internet website has been used to help in writing these comments. The TV coverage of the BAM tests has also been studied.

General Impression

7.3 When any client asks a technical organisation to examine metal samples for signs of an explosion, they can expect that the staff involved will carry out their examination and base their conclusions on past experience.

7.4 The overall impression from the work carried out by BAM is that they lacked the experience necessary to make any valid conclusions. They then set out on a learning exercise to establish the effects of explosions on the many large samples of modern ship-building steel supplied to them. This meant conducting a long and complex series of mechanical and explosive tests which were recorded on video and used as a basis for the Spiegel TV coverage. BAM also examined and reported on some, but not all, of the samples taken from the ESTONIA.

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Shot Peening and Sand Blasting

7.5 Shot peening is the process of bombarding a metal sheet with pellets of lead shot to clean the surface. The lead pellets are collected during the process for re-use. Before this process became available, the technique of sand-blasting was used to produce a similar cleaning effect. In a fax sent from the ship-builders to BAM on 5th December 2000, Meyer Werft said it was almost certain that when the ship was built the plates would have been sand blasted and not shot peened. Both samples taken from the ESTONIA and supplied to BAM would have been subjected to the same cleaning process when the ship was built.

Twinning from BAM Shot Peening tests

7.6 The tests carried out by BAM showed that shot peening can produce some twinning effects and also some hardening, which could equally be produced by an explosion. However, no attempt was made to find out if sand blasting produced similar effects. BAM then ruled out the possibility of an explosion having caused the twinning and hardening effects in the samples.

Twinning Effects in ESTONIA Samples examined by BAM

7.7 BAM emphasise in their report that the twinning they observed from shot peening tests on the new steel samples was only seen close to the surface. They therefore conclude that the twinning they observed close to the surface in the ESTONIA sample they called "front bulkhead" could have been produced by shot peening rather than by an explosion. This completely disregards the fact that the sample they call "Holland profile" would have undergone an identical cleaning process when the ship was built.

7.8 According to BAM, this "Holland profile" *"does not exhibit deformation twins as well as shear localisation nor pearlite, thus, there was no need to involve it for further considerations."* This means that twinning in the "front bulkhead" cannot have been produced by any cleaning process when the ship was built as it does not appear in the "Holland profile". Therefore any twinning in the "front bulkhead" must have been produced by something else, such as an explosion.

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BAM access to other reports

7.9 Before BAM wrote their report they had access to all the reports from Brandenburg, including the Neubert Report, as well as the report from Clausthal-Zellerfeld, and also a brief report from the South West Research Institute. From this report, they should not have been surprised at the lack of any significant twinning or hardening effects in the "Holland Profile" sample from the ESTONIA. In contrast, they would have been able to see that Brandenburg saw very significant twinning and hardening effects near the point of the triangular ESTONIA sample, which would have been nearest the centre of the hole. These effects diminished towards the opposite side of the triangle which was cut by a torch.

BAM failure to test all samples

7.10 When BAM received Sample 1, without the specimens inadvertently retained by Brandenburg, they had the part which was least likely to be affected by an explosion since it was the part furthest from the centre of the hole in the bulkhead. They then concluded that their tests of this incomplete sample showed no signs of an explosion. They then completely ignored any tests of the specimens from Sample 1, later supplied to them by Brandenburg. This extraordinary lapse occurred despite the fact that BAM had access to all the Brandenburg test results. They would therefore have known that these specimens showed far greater signs of the effects of an explosion.

BAM Report shortcomings and false conclusions

7.11 From the above paragraphs, it can be seen that the BAM Report has a number of shortcomings. For example, BAM attempts to discount the possibility of an explosion because the effects they saw in the ESTONIA samples they examined, could have been caused by something else. They say these could have been a result of the original cleaning treatment or some mechanical damage, *"and therefore could not have been caused by an explosion."*

7.12 Despite access to all other relevant test reports and against the instructions of their client, BAM seem to have completely ignored the samples that were likely to show the greatest effects of twinning and hardening.

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CONCLUSIONS

7.13 From the BAM Report I conclude that:-

1. Their report is quite unsatisfactory and inadequate for the reasons explained above.

2. Some of the conclusions reached by BAM are flawed and based on false logic. This may be because of their apparently limited experience in the very specialised field of explosive effects on metals.

PART 8

ROYAL MILITARY COLLEGE OF SCIENCE (RMCS)

COMMENTS ON RECENT SAMPLES REPORTS

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RMCS Background

8.1 RMCS has been a centre of expertise on military aspects of all sciences for many years. Their experience includes an enormous number of trials and experiments involving the effects of explosions on metals during the testing of military hardware. In view of this background they were approached to comment on the reports from German laboratories on the ESTONIA samples.

8.2 Dr Michael Edwards of their Department of Materials and Medical Sciences is a metallurgist with many years experience in the effects of explosions on metals. He was supplied with copies of the Brandenburg Report, the BAM Report, and my own earlier reports on the ESTONIA and copies of the videos taken at the wreck. In the light of his own experience and past trials, he was then asked to comment on the validity and content of the test results and conclusions reached by the laboratories concerned. His comments are listed below.

Old and New Steel Standards

8.3 RMCS noted that the percentage content of Carbon and Manganese in the ESTONIA steel was quite different from that supplied to BAM for their tests. The latter, new steel, has 0.1% C which is exactly half as much as in the old steel. In contrast, the new steel has about twice the Manganese content, 1.1% Mn against 0.5% Mn in the old steel.

8.4 RMCS pointed out that the steels used for ship-building today have been selected by the industry to ensure that there are no cold cracking problems when welded as well as having a lower ductile-brittle transition temperature. By increasing the manganese content and reducing the grain size through control of the hot rolling process, the strength of the steel is retained. ESTONIA was built using the sort of steel normally used by the ship-building industry at that time.

BAM interpretation of Twinning Effects

8.5 Page 5 of the of the BAM Report Summary translation states:-

"A clear indication of a detonation is represented by the formation of deformation twins across the entire thickness of the plate. Specimens of shipbuilding steels exposed to detonation tests always show deformation across the entire plate thickness from about 4mm off the fracture surface onward, Fig 87. Thus the appearance of deformation twins across the entire plate thickness up to several centimetres towards the lateral direction away from the fracture surface is the only criterion a detonation might definitely be provable by."

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Past Test Results from RMCS

8.6 Trials at RMCS have produced results in direct conflict with the BAM statement above. In RMCS tests an explosion in direct contact with metal has produced twinning while a similar explosion separated from the metal by as little as 12 mm of sand or packaging, to absorb the "brisance" or shattering effect, has produced no twinning effect at all, even though the "petalling" effect as seen in the ESTONIA was present in each case.

8.7 The relevant trials were described in :-

(1) The 2000 MSc Thesis of B C Halls (faculty of Military Science, Technology and Management, Cranfield University)

and (2) The 2000 Thesis of D Lord (faculty of Military Science, Technology and Management, Cranfield University)

Drawing conclusions from twinning effects

8.8 In summary, there may be little or no twinning effect produced close to an explosion. This means that the possibility of an explosion should not have been ruled out by BAM because of the effects they found in the samples they examined. In contrast, the presence of significant and deeper widespread twinning as observed by Brandenburg can be considered as positive proof of an explosion as it will not result from any cleaning process or mechanical damage.

8.9 The last sentence of the BAM Report extract quoted above should more correctly read:-

"Thus the appearance of deformation twins across the entire plate thickness up to several centimetres towards the lateral direction away from the fracture surface is A CLEAR (NOT 'the only') criterion a detonation might definitely be provable by."

8.10 In summary, metal close to an explosion may show significant, slight, or even no twinning effects depending on circumstances. Since, slight twinning effects can result from several causes they are not in themselves conclusive evidence for or against an explosion. However, significant or deep twinning effects should be recognised as conclusive proof of an explosion since they cannot result from anything else.

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Videos of the damage area

8.11 Dr Edwards' comment was:-

"I looked over the film and the hole in the starboard side is clearly a petalled hole. This is typical of what happens when a thin plate is subjected to an explosive charge. The charge has not been in direct contact with the ship plate (if this had happened the hole would not have been surrounded by the relatively large petals seen in the film)."

Brandenburg Report and most likely cause of Twinning

8.12 I asked Dr Edwards whether he would be prepared to endorse the following extract from this report:-

From the Brandenburg reports, I can now conclude beyond reasonable doubt that:-

1. *The structural deformation of Sample 1 was caused by an explosion.*

2. *The increase in hardness measured in Sample 1 was caused by an explosion.*

3. *Overall, the findings of these technical reports are further evidence that there was an explosion in the ESTONIA, in the vicinity of the starboard forward bulkhead from which Sample 1 was taken.*

8.13 His response was:-

"I am happy with the conclusions that you have drawn and listed."

8.14 In the same letter, Dr Edwards went on to deal with the three causes of mechanical twinning as follows:-

"The possibility that they were created by an impact is remote. Any impact would have to be at a velocity of kilometres per second - this would have had to come from an explosively driven projectile. Petalled holes of the size seen would have arisen from a projectile several centimetres in diameter. This could not have happened in the context of the ESTONIA.

PART 8

ROYAL MILITARY COLLEGE OF SCIENCE (RMCS) COMMENTS ON TESTS

Brandenburg Report and most likely cause of Twinning (continued)

8.15 *The strain rates required for the production of twins would not have occurred by mechanical deformation at room temperature. They are simply too fast.*

This leaves the final possibility of an explosion taking place close by. This appears to be the most credible explanation for the presence of twins and I have agreed with this earlier."

CONCLUSIONS

8.16 From my discussions and meetings with Dr Edwards and my visits to RMCS, I have concluded that:-

1. He was able to look at the complete circumstances of the ESTONIA sinking as well as just the detailed metallurgical aspects of the samples from the ship. It is in this wider context that he has been able to consider the most likely cause of the twinning and hardening effects identified by the different laboratories.

2. There is little doubt from the paragraphs above that Dr Edwards believes an explosion occurred.

ANNEX A

B H L BRAIDWOOD

CV

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Summary of Naval Service Experience

Thirty-four years in the Royal Navy, leaving in the rank of Lieutenant-Commander. Qualified as a Naval diver in 1957 and spent twenty-five years as an Explosive Ordnance Disposal specialist. This included the Defence of Ships Against Sabotage Attack. Three years commanding the Far East Clearance Diving Team, and Diving School, based in Singapore. Responsible for all Diving and Explosive Ordnance Disposal, both operational and training, East of Suez. Major operations included the disposal of Japanese World War Two ammunition dumps, aircraft salvage, reef blasting, and the clearance of the Navy's bulk oil-tanker ENNERDALE which sank off the Seychelles. Awarded Queen's Commendation for Brave Conduct.

Qualified with the Army in the Disposal of Terrorist Devices. Commanded the UK Joint Service Explosive Ordnance Disposal School for three years. Trained 750 students each year ranging up to Lieutenant Colonel level, from the UK and overseas.

For last thirteen years of service, was the Navy's specialist for new demolition and explosive disposal equipment and techniques. This included testing commercial and military explosives. The work required a close liaison with many military and civilian organisations throughout the world.

Summary of Commercial/Civilian Experience

Qualified Commercial Diver by Health and Safety Executive. Qualified BSAC Advanced Diver (CMAS*** equivalent). Medically in-date for diving. Forty four years total diving experience.

Have given expert opinion for insurance litigation of shipping casualties. Clients include Clifford Chance, Hill Taylor Dickinson, Norton Rose, Clyde & Co., Holman Fenwick & Willan, Thomas Miller P&I, Hellenic P&I, and the North of England P&I. Investigated and reported on ships lost or damaged by explosive charges. Made underwater videos for underwriters to illustrate the damage sustained by sunk ships. Worked for the New Zealand Government investigating the bombing and sinking of the Greenpeace vessel RAINBOW WARRIOR. Worked on the investigation of the car ferry ESTONIA sinking in the Baltic with the loss of 852 lives.

Worked on commercial explosives applications including decommissioning offshore structures and oilwell blowout control. Assisted civilian and defence manufacturers with product development, trials and testing programmes.Advised on planning underwater explosives test areas. Helped write "Guidelines for the safe use of explosives underwater", sponsored by the Maritime Technology Directorate Ltd.

Lectured on security matters to HM Government training courses. Presented papers to international conferences at home and abroad, including Oceanology International at Brighton and the FBI Academy.

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PART 5

BRANDENBURG REPORTS ON RECENT SAMPLES

Metallographic Examinations (First Report)

5.5 Five areas of the sample were examined and they revealed differing levels of stress and strain. As expected the area nearest the explosion, Area 3 (GO2), was most affected and the other two areas much less. Concerning the cross-section parallel to the fracture edge, the report states:-

> *"Specimen GO2 2 shows significant changes in way of the fracture edge area (pictures 26-33). The plastic deformation within the micro range indicates exposure to extremely heavy shock forces, such as happens from the effects of a substance detonating. The strained metallographic specimen from the fracture area of the starboard front bulkhead shows extensive destruction of components in the original structure."*

5.6 On page 9, the report states that:-

> *"Destruction of the lamellae has occurred which cannot have resulted from any equivalent mechanical technical influence. The processes of explosive treatments of metallic materials as for example explosive hardening and explosive cladding have to be excluded. These processes show comparable effects in areas near a surface."*

5.7 In their second report concerned with the areas 4, 5, 7, and 8, Brandenburg conclude from their metallographic examinations that :-

> *"There must have been strong mechanical strain at a very high deformation velocity, which is typical from detonations."*

5.8 In summary, the above extracts mean that the *"significant changes"* were not consistent with mechanical damage. The sample had not undergone any explosive hardening or explosive cladding process. Nevertheless, the effects were consistent with these explosive processes. It follows, therefore, that the effects must have been caused by an explosion.