

TNO Report

TNO | Knowledge for business





Oude Waalsdorperweg 63
P.O. Box 96864
2509 JG The Hague
The Netherlands

www.tno.nl

T +31 70 374 00 00
F +31 70 328 09 61
info-DenV@tno.nl

TNO report

TNO-DV 2007 A598

**Review of published safety thresholds for human
divers exposed to underwater sound**

Date	April 2008
Author(s)	Dr M.A. Ainslie
Classification report	Ongerubriceerd
Classified by	LTZ1 R.P.A. Dekeling
Classification date	3 maart 2008
Title	Ongerubriceerd
Managementuittreksel	Ongerubriceerd
Abstract	Ongerubriceerd
Report text	Ongerubriceerd
Appendices	Ongerubriceerd
Copy no	8
No. of copies	17
Number of pages	14 (excl. RDP & distributionlist)

The classification designation Ongerubriceerd is equivalent to Unclassified, Stg. Confidenciel is equivalent to Confidential and Stg. Geheim is equivalent to Secret.

All rights reserved. No part of this report may be reproduced in any form by print, photoprint, microfilm or any other means without the previous written permission from TNO.

All information which is classified according to Dutch regulations shall be treated by the recipient in the same way as classified information of corresponding value in his own country. No part of this information will be disclosed to any third party.

In case this report was drafted on instructions from the Ministry of Defence the rights and obligations of the principal and TNO are subject to the standard conditions for research and development instructions, established by the Ministry of Defence and TNO, if these conditions are declared applicable, or the relevant agreement concluded between the contracting parties.

© 2007 TNO

AQ F08-12-11058

20080904028



Veilige maximale geluidsniveaus voor duikers - beoordeling van publicaties

Probleemstelling

Blootstelling aan een hoge intensiteit van onderwatergeluid kan schadelijk zijn voor duikers. Ten gevolge van een dergelijke blootstelling kan gehoorschade ontstaan of, direct als gevolg van het geluid of als gevolg van een paniecreactie, schade aan andere organen. Het is derhalve van belang te weten wat het maximale geluidniveau is dat nog veilig is voor duikers.

Beschrijving van de werkzaamheden

In een eerder uitgevoerd intern TNO kennisinvesteringsproject is een overzicht opgesteld van eerder gepubliceerde geluidsniveaus die nog toelaatbaar zijn. In het onderhavige rapport worden de resultaten hiervan gebundeld en overzichtelijk weergegeven, zodat ze voor een breder publiek toegankelijk worden gemaakt. De resultaten worden weergegeven in zogenaamde

'safety thresholds' voor onderwatergeluid voor duikers, in het frequentiebereid van 125 hertz tot 250 kilohertz. Tevens is bekeken waar de diverse publicaties niet met elkaar overeenkomen en is er onderzocht welke publicatie de meest betrouwbare informatie geeft.

Resultaten en conclusies

Er blijken grote verschillen te zijn in de diverse publicaties met betrekking tot maximaal toelaatbare geluidsniveaus onderwater voor duikers. De meest betrouwbare geluidsniveaus van de diverse publicaties zijn in een tabel weergegeven.

Toepasbaarheid

De weergegeven maximale geluidsniveaus zijn relevant voor situaties waar professionele duikers onderwater blootgesteld worden aan onderwatergeluid. Voor recreatieve duikers, die doorgaans

minder goed uitgerust zijn qua uitrusting, zijn de risico's groter en moeten de 'safety thresholds' vermoedelijk voorzichtiger gehanteerd worden. De weergegeven niveaus zijn primair bedoeld voor gebruik in relatie tot militaire sonars, maar zijn ook te gebruiken in vergelijkbare situaties met vergelijkbare sonarbronnen bij oceanografisch onderzoek. De weergegeven niveaus zijn niet geschikt om te gebruiken in situaties waar korte geluidimpulsen voorkomen, zoals bij het gebruik van explosieven, heiwerkzaamheden en zogenaamde air-guns.

Review of published safety thresholds for human divers exposed to underwater sound

Contact en rapportinformatie

PROGRAMMA	PROJECT
Programmabegeleider -	Projectbegeleider LTZ1 R. Dekeling, DMO, S&WT, OT
Programmaleider -	Projectleider ir. P. Schippers,
Programmatitel -	Projecttitel Sonar Advies
Programmanummer -	Projectnummer 015.34592
Programmaplanning -	Projectplanning Start 1 januari 2005 Gereed 31 december 2007
Frequentie van overleg N.V.T.	Projectteam dr. M.A. Ainslie

Oude Waalsdorperweg 63
Postbus 96864
2509 JG Den Haag

T +31 70 374 00 00
F +31 70 328 09 61

info-DenV@tno.nl

TNO-rapportnummer
TNO-DV 2007 A598

Opdrachtnummer
-

Datum
april 2008

Auteur(s)
dr. M A Ainslie

Rubricering rapport
Ongerubriceerd

Contents

	Managementuittreksel	2
1	Introduction	5
2	Hearing thresholds.....	6
3	Safety thresholds and procedures	7
3.1	NATO guidelines.....	7
3.2	DMAC guidelines	8
3.3	Parvin et al guidelines	8
3.4	Summary	8
4	Discussion and Recommendations	10
4.1	Discussion and Recommended Thresholds	10
4.2	Other Recommendations.....	11
5	References	12
6	Signature	14

1 Introduction

Divers exposed to high levels of underwater sound can suffer from dizziness, hearing damage or other injuries to other sensitive organs, depending on the frequency and intensity of the sound. Even if not the direct cause, a loud sound may cause injury indirectly by startling an unalerted diver, provoking a potentially threatening panic reaction. For these reasons a number of experimental studies have been undertaken, mainly in the UK and US, into maximum safe sound pressure level as a function of frequency.

This note is a spin-off from a self-funded research project at TNO in which the detection of divers was studied [1]. First, thresholds of human hearing in water (underwater audiograms) are summarised in Section 2. In Section 3, the results of high level exposure studies are reviewed, in the context of possible exposure to sonar transmissions. Discussion and recommendations follow in Section 4.

2 Hearing thresholds

Published measurements of human audiograms in water are surprisingly scarce, and the author is aware of just two: one is published by Gerstein [2] in *American Scientist* (Figure 1 below); the other in UDT conference proceedings by Parvin *et al.* [3] (Figure 2). In both figures, the audiograms are in the form of a sound pressure level threshold with a reference pressure of one micropascal ($1 \mu\text{Pa}$), for both air and water¹ (see also section 4.1). Further, no correction is applied for the difference in impedance between air and water. Thus, 80 dB re $1 \mu\text{Pa}$ corresponds to an rms pressure of 10 mPa (10,000 μPa), whether in air or water. Because of the difference in impedance, for the same rms pressure, the sound intensity in water is much lower than in air.

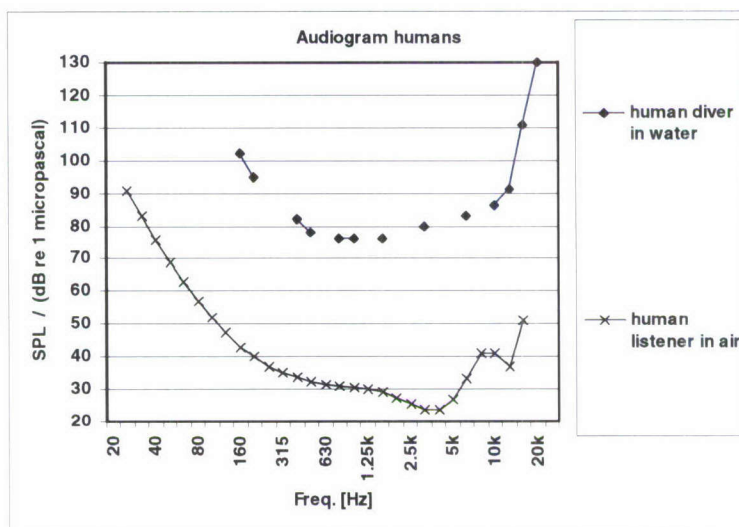


Figure 1 Hearing thresholds from Gerstein.

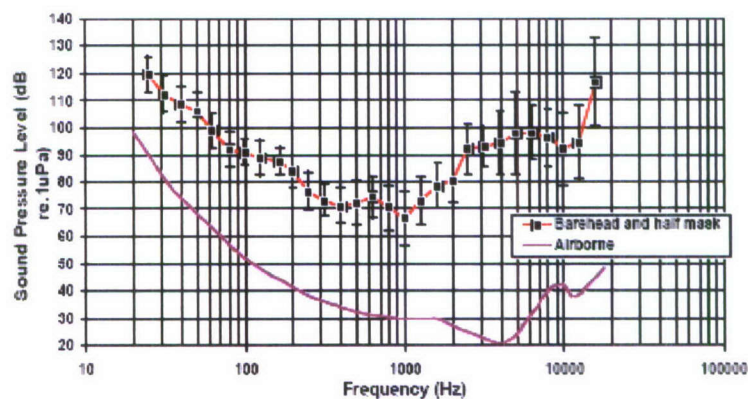


Figure 2. Comparison of Minimum Audible Field airborne and underwater hearing threshold level.

Figure 2 Hearing thresholds from Parvin *et al.*

¹ A more common reference pressure for use in air is $20 \mu\text{Pa}$. The numerical value of sound pressure level, expressed in units of $1 \mu\text{Pa}$, is 26 dB higher than if expressed relative to $20 \mu\text{Pa}$.

3 Safety thresholds and procedures

Three different documents concerning diver safety thresholds are reviewed in this section. In two of the three documents, the terms 'sound level', 'exposure level' and 'sound pressure level' occur repeatedly and in a manner that implies they are interchangeable. However, these terms actually have quite different meanings. According to the Dictionary of Acoustics [4] *sound pressure level* (SPL) is the mean square pressure expressed in decibels, *sound level* in air is the SPL corrected for the frequency-dependence of human hearing (usually A-weighted) and *sound exposure level* is the integral in time of the squared sound pressure. Because these terms are used interchangeably in the reviewed documents, and because there is no mention in any of them of any frequency-weighting to be applied, it is assumed here that in all cases SPL is intended.

3.1 NATO guidelines

Safety guidelines for human divers are published in a NATO Undersea Research Centre (NURC) publication[5]. The NURC safety thresholds, based on three US references [6, 7, 8] are summarised in Table 1. It is stated that these thresholds should not be exceeded for military divers. It is not specified whether the thresholds apply with or without a protective diving suit or hood.

Table 1 received 'sound level' thresholds for alerted NATO or other military divers from NURC guidelines.

frequency range / kHz	threshold / (dB re 1 μ Pa)
0.125 – 4	160
4 – 25	167
25 – 31.5	172
31.5 – 250	177

It is unclear from the text, which reads 'The ceiling values may be verified by using an integrating sound level meter with slow detection and 1/3 octave bands', whether it is sufficient to stay below the thresholds in each third-octave sub-band, or whether there is a further requirement for the total SPL in each of the four main frequency bands to be less than the stated threshold (a more stringent requirement). It is assumed that by 'slow detection' is meant 'slow weighting', implying an averaging period of one second.[4]

For recreational divers, a threshold of 154 dB re 1 μ Pa in the frequency range 600 Hz-2500 Hz is quoted in Section 3.2.3 of the NURC report, referring to further US research. [9].

3.2 DMAC guidelines

The Diving Medical Advisory Committee (DMAC) is an 'independent body, comprising diving medical specialists from across Northern Europe' seeking to 'provide advice about medical and certain safety aspects of commercial diving' [10]. DMAC publishes the following table of sensitivity and tolerance levels [11].

Table 2 received sound pressure level thresholds for commercial divers, from DMAC guidelines. The asterisks (*) indicate values that are 'unlikely to be attained'.

	hooded		non-hooded	
	dB re 20 μ Pa	dB re 1 μ Pa	dB re 20 μ Pa	dB re 1 μ Pa
threshold of oculo- gyral sensitivity	175	201	165	191
discomfort	180	206	170	196
disorientation	*	*	180	206
intolerance	*	*	192	218

Based on Table 2, the DMAC document specifies recommended maximum sound pressure levels for commercial divers of 201 dB re 1 μ Pa for non-hooded divers and 211 dB re 1 μ Pa for hooded ones. This maximum for a non-hooded diver is half-way between the stated thresholds for 'discomfort' and 'disorientation', with 10 dB added for a diver wearing a neoprene hood. It is stated by DMAC that 'the actual thickness of the hood does not greatly alter the degree of attenuation given'. More information about the properties of such a hood can be found in the DMAC leaflet [11].

3.3 Parvin et al guidelines

Joint UK-US research published by Parvin et al. reports the following findings for sound in the frequency range 500-2500 Hz:

- temporary dizziness and related symptoms for bareheaded divers for 'sound levels' above 176 dB re 1 μ Pa;
- vibration in forearms and thighs at 'sound levels' above 180 dB re 1 μ Pa;
- sounds tolerated up to the maximum used in the trial 191 dB re 1 μ Pa;
- advised threshold 'exposure level' for human divers of 155 dB re μ Pa for use in environmental impact assessment;
- advised threshold 'exposure level', for military divers wearing a diving suit and hood, of 180 dB re μ Pa.

The maximum SPL permitted by the ethical protocol for Parvin's research was 191 dB re μ Pa.

3.4 Summary

Published thresholds for military divers (assumed alerted) are summarised in Table 3, followed by thresholds for commercial or recreational divers (assumed unalerted and unprotected) in Table 4.

Table 3 SPL thresholds suggested by NURC and Parvin for alerted military divers.

originator	type of diver protection	frequency range / kHz	maximum value suggested by originator (dB re 1 μ Pa)
NURC	unspecified	0.125 – 4.0	160
NURC	unspecified	4.0 – 25.0	167
NURC	unspecified	25 – 31.5	172
NURC	unspecified	31.5 – 250	177
Parvin	diving suit and hood	0.5 – 2.5	180

Table 4 SPL thresholds suggested by NURC, DMAC and Parvin for unprotected and unalerted commercial or recreational divers.

originator	frequency range / kHz	maximum value suggested by originator (dB re 1 μ Pa)
NURC	0.6 – 2.5	154
DMAC	Unspecified ²	201
Parvin	0.5 – 2.5	155

² Thought to be based on research carried out for a tone at 1.5 kHz.

4 Discussion and Recommendations

4.1 Discussion and Recommended Thresholds

The DMAC guidelines for a non-hooded diver exceed the threshold recommended by Parvin et al by 46 dB (see Table 4) – a very large discrepancy. To put the difference into perspective, note that **the DMAC discomfort threshold for a hooded diver (206 dB re μPa) is 25 dB higher than the maximum permitted by the ethical protocol for Parvin's research.** The DMAC guidelines appear to be at least partly based on a publication by Montague & Strickland [12]. Using a reference pressure of 0.0002 dyn/cm^2 , this article quotes a figure of 175 dB for 'oculo-gyral effects' and a 'tolerance limit' of 174 dB (quoted in their abstract, and based on their Fig. 6) for non-hooded divers. ³ Converting to modern units these are 201 dB re $1 \mu\text{Pa}$ and 200 dB re $1 \mu\text{Pa}$. The threshold for oculo-gyral sensitivity is precisely the value quoted by DMAC. The origin of the other values in Table 2 is not known.

By comparison with DMAC, the remaining two sources seem more credible and are reasonably consistent with one another. In particular there is independent support for the threshold of 160 dB re $1 \mu\text{Pa}$ for frequencies up to 4 kHz [13].

The NURC thresholds are assumed to apply to alerted but unprotected divers. It is understood [3, 14] that the use of a neoprene suit and hood affords significant protection, potentially resulting in higher thresholds for a suited diver, but it is not known by how much; documentation from the UK-US research [14] is required before the thresholds can be safely increased.

The NURC thresholds do not specify whether the protection afforded by a neoprene suit and hood is assumed (see Sections 2.1 and 3.3). A conservative interpretation results in the thresholds recommended in Table 5 below. Thus, until this point can be clarified, sound pressure levels for alerted and hooded navy divers should not exceed the indicated thresholds. The risks for recreational divers may be greater, requiring lower thresholds. The recommended thresholds are intended for use in the context of Navy sonar, although they are also relevant to comparable equipment used in acoustic communications or oceanographic survey applications. They are not suitable for use with short impulsive sounds such as explosions, pile driving or air guns.

³ The dyne is a CGS unit of force equal to $10 \mu\text{N}$, and therefore $0.0002 \text{ dyn/cm}^2 = 0.002 \times 10^{-5} / 10^{-4} \text{ N/m}^2 = 20 \mu\text{Pa}$. The conversion to a reference pressure of $1 \mu\text{Pa}$ is effected by adding $10\log_{10}(20^2) = 26.0 \text{ dB}$.

Table 5 Recommended SPL thresholds for alerted and hooded navy divers exposed to sonar transmissions longer than 125 ms. An averaging time of 125 ms is recommended, corresponding to fast sound level weighting. No advice is offered for transmissions shorter than 125 ms.

frequency range / kHz	maximum recommended value (dB re 1 µPa)
0.125 – 4.0	160
4.0 – 25.0	167
25 – 31.5	172
31.5 – 250	177

The risk of injury caused by accidental exposure of divers to high levels of underwater sound **can be reduced by updating the DMAC guidelines** with advice from research more recent than that of Montague & Strickland (1961) [7].

4.2 Other Recommendations

In matters affecting human safety, it is considered imperative to minimise the risk of error resulting from incorrect or ambiguous terminology. The terms ‘sound level’ and ‘exposure level’ are defined by Morfey’s Dictionary of Acoustics [15] only for airborne sound.

- For underwater sound we propose that ‘sound exposure level’ be defined as the variable L_E in the following expression in decibels[15].

$$L_E \equiv 10 \log_{10} \frac{E}{p_{\text{ref}}^2 t_{\text{ref}}}$$

where E is the time-integral of instantaneous pressure squared

$$E \equiv \int p_w(t)^2 dt ,$$

and the W subscript indicates that the pressure is to be weighted according to hearing sensitivity. For airborne sound, by default the pressure would be A-weighted. In water, it is not obvious what weighting to use, and sometimes it may be appropriate not to use any weighting. Thus, the weighting used should be stated explicitly.

- It is recommended that the term ‘sound level’ be avoided for use in water, except in the context of a *specified* animal or group of animals, with corresponding (specified) weighting curves.

5 References

- [1] M. Colin, S.P. Beerens & M.A. Ainslie,
Diver detection in Harbours, TNO report in preperation.
- [2] E.R. Gerstein,
Manatees, bioacoustics and boats,
American Scientist **90** (2), 154 (2002).
- [3] Parvin et al., S.J. Parvin, E.A Cudahy & D.M Fothergill,
Guidance for diver exposure to underwater sound in the frequency range
500 to 2500 Hz, *Underwater Defence Technology* (2002).
- [4] C.L Morfey,
Dictionary of Acoustics (Academic,. San Diego, 2001).
- [5] *NATO Undersea Research Centre Human Diver and Marine Mammal Risk
Mitigation Rules and Procedures*, NURC-SP-2006-008, September 2006.
- [6] *Effects of Intense Water-Borne Sound on Divers*. Prepared by Naval Submarine
Medical Research Laboratory, Groton, CT, Department of the Navy, 1996.
- [7] U.S. Department of Labor, OSHA Technical Manual, Section III, Chapter 5.
- [8] Naval Submarine Medical laboratory, Report No. 1223, 13 June 2002.
- [9] Naval Submarine Medical Research Laboratory,
Report No. 1203, 30 September 1996.
- [10] <http://www.dmac-diving.org/>
- [11] *The effect of sonar transmission on commercial diving activities*,
The Diving Medical Advisory Committee, Recommendations DMAC
06 – March 1981, from <http://www.dmac-diving.org/guidance/DMAC06.pdf>
- [12] W.E. Montague & J. F. Strickland,
Sensitivity of the water-immersed ear to high- and low-level tones,
J. Acoust. Soc. Am. **33**, 1376-1381 (1961).
- [13] see Undersea & Hyperbaric Medicine, 1996, vol 23, supplement, Session D,
Exposure to low frequency waterborne sound (39-44).
the following remarks are particularly relevant:

Clark et al. 'No prolonged adverse vestibular aftereffects were detected in divers exposed to 15 min cumulative (vice continuous) 240-320 Hz U/W sound at 160 dB (re 1 μ P) after 10-14 exposures.'

Steevens et al. 'For acute exposures, underwater sound at levels less than 160 dB re μ Pa appear to be well tolerated for frequencies between 125 and 6000 Hz.'

Schlichting et al. 'Acute exposures to low frequency sound [order 100 Hz] as intense as 160 dB re 1 μ Pa were well tolerated by subjects'.

Parvin & Nedwell.

'it is felt that an uninformed diver ... may be disturbed by ... waterborne sound [for SPL up to 160 dB re μ Pa²] at frequencies 300 Hz and below'.

Steevens et al. 'At SPLs of 160 dB and higher both auditory and non-auditory effects may prove intolerable to working divers'.

- [14] S.J. Parvin & S.L. Searle (1998) Underwater sound perception by divers and the protection from waterborne noise provided by a neoprene hood, DERA/CHS/PP5/TR980078/1.0.

Parvin et al. (1994)

Effects of low frequency sonar transmissions on divers and ichthyofauna; Hyperbaric and open water diver studies and noise exposure of species of fish. DRA/awt/cr94101/v1.0.

- [15] Ainslie (2005),
'*A compendium of definitions for sonar performance measurements and modelling,*'
edited by M. A. Ainslie, Version 1, TNO Booklet No. AOG-v9, 2005.

6 Signature

The Hague, April 2008

TNO Defence, Safety and Security

A handwritten signature in blue ink, consisting of a large, stylized 'S' followed by a long, sweeping horizontal stroke that extends to the right.

F.P.G. Driessen, MSc
Head of department

A handwritten signature in black ink, featuring several sharp, vertical strokes followed by a horizontal line.

Dr M. A. Ainslie
Author

ONGERUBRICEERD
REPORT DOCUMENTATION PAGE
(MOD-NL)

1. DEFENCE REPORT NO (MOD-NL) TD 2007-0276	2. RECIPIENT'S ACCESSION NO -	3. PERFORMING ORGANIZATION REPORT NO TNO-DV 2007 A598
4. PROJECT/TASK/WORK UNIT NO 015.34592	5. CONTRACT NO -	6. REPORT DATE April 2008
7. NUMBER OF PAGES 14 (excl RDP & distribution list)	8. NUMBER OF REFERENCES 15	9. TYPE OF REPORT AND DATES COVERED Final
10. TITLE AND SUBTITLE Review of published safety thresholds for human divers exposed to underwater sound		
11. AUTHOR(S) Dr M. A. Ainslie		
12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) TNO Defence, Security and Safety, P.O. Box 96864, 2509 JG The Hague, Oude Waalsdorperweg 63, 2509 JG The Hague, The Netherlands		
13. SPONSORING AGENCY NAME(S) AND ADDRESS(ES) Koninklijke Marine		
14. SUPPLEMENTARY NOTES The classification designation Ongerubriceerd is equivalent to Unclassified, Stg. Confidentieel is equivalent to Confidential and Stg. Geheim is equivalent to Secret.		
15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE)) High levels of underwater sound can be harmful to human divers, as they can result in hearing damage or damage to other organs, either directly, or indirectly by causing a panic reaction. Published recommendations for the maximum safe underwater sound level are reviewed. The results of the review are presented in the form of safety thresholds of underwater sound for divers, in the frequency range 125 hertz to 250 kilohertz.		
16. DESCRIPTORS active sonar low frequency high frequency underwater acoustics underwater sound		IDENTIFIERS diver safety human divers underwater sound hearing thresholds safety thresholds
17a. SECURITY CLASSIFICATION (OF REPORT) Ongerubriceerd	17b. SECURITY CLASSIFICATION (OF PAGE) Ongerubriceerd	17c. SECURITY CLASSIFICATION (OF ABSTRACT) Ongerubriceerd
18. DISTRIBUTION AVAILABILITY STATEMENT Unlimited Distribution		17d. SECURITY CLASSIFICATION (OF TITLES) Ongerubriceerd

ONGERUBRICEERD

Distributielijst

Onderstaande instanties/personen ontvangen een volledig exemplaar van het rapport.

- | | |
|------|--|
| 1 | DMO/SC-DR&D
standaard inclusief digitale versie bijgeleverd op cd-rom |
| 2/3 | DMO/DR&D/Kennistransfer |
| 4 | LTZ1 R. Dekeling,
DMO, DWA&B, RZS&B, SWT |
| 5 | KLTZAR Dr R.A. van Hulst,
Hoofd Duik Medisch Centrum
DMAC |
| 6/8 | Bibliotheek KMA |
| 9/17 | TNO Defensie en Veiligheid, vestiging Den Haag,
Business Unit Waarnemingssystemen,
dr. M.A. Ainslie
dr. ir. G. Blacquiere
M Colin
ir. F.P.G. Driessen
dr. F. P.A. Lam
M.K. Sheldon-Robert
dr. S. P. Beerens
ir. P. Schippers
dr. P.A. van Walree |

**Onderstaande instanties/personen ontvangen het managementuittreksel
en de distributielijst van het rapport.**

4 ex.	DMO/SC-DR&D
1 ex.	DMO/ressort Zeesystemen
1 ex.	DMO/ressort Landsystemen
1 ex.	DMO/ressort Luchtsystemen
2 ex.	BS/DS/DOBBP/SCOB
1 ex.	MIVD/AAR/BMT
1 ex.	Staf CZSK
1 ex.	Staf CLAS
1 ex.	Staf CLSK
1 ex.	Staf KMar
1 ex.	TNO Defensie en Veiligheid, Algemeen Directeur, ir. P.A.O.G. Korting
1 ex.	TNO Defensie en Veiligheid, Directie Directeur Operaties, ir. C. Eberwijn
1 ex.	TNO Defensie en Veiligheid, Directie Directeur Kennis, prof. dr. P. Werkhoven
1 ex.	TNO Defensie en Veiligheid, Directie Directeur Markt, G.D. Klein Baltink
1 ex.	TNO Defensie en Veiligheid, vestiging Den Haag, Manager Waarnemingssystemen, (operaties), ir. B. Dunnebier
1 ex.	TNO Defensie en Veiligheid, vestiging Den Haag, Manager Informatie en Operaties (operaties), ir. P. Schulein
1 ex.	TNO Defensie en Veiligheid, vestiging Rijswijk, daarna reserve Manager Bescherming, Munitie en Wapens (operaties), ir. P.J.M. Elands
1 ex.	TNO Defensie en Veiligheid, vestiging Rijswijk, Manager BC Bescherming (operaties), ir. R.J.A. Kersten
1 ex.	TNO Defensie en Veiligheid, vestiging Soesterberg, Manager Human Factors (operaties), drs. H.J. Vink