Mine Clearance Vehicles
Crew Safety Standard

The Swedish Defence Material Administration
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Håkan Axelsson
Odd Sundqvist

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1. Introduction

The scoop of this Crew Safety Standard is to specify a simple and inexpensive method to determine the level of injury for the occupants in a mine clearance vehicle when a mine detonates under the vehicle.

When the mine detonates a blast pressure wave in air is generated propagating in all directions with a velocity greater than the speed of sound in air. That blast wave surrounds the occupants' compartment causing the floor, sides and ceiling to oscillate which in turn generates pressure waves inside the compartment. These waves, together with pressure leaking in through holes in the cabin, cause an oscillating pressure-time history inside with duration of hundreds of milliseconds. These waves can be injurious primarily to the unprotected ear and the gas filled organs in the body.

The floor vibrates with amplitude and frequency depending on the blast load strength and the properties of the dampers on the mine clearing device, but also on the physical properties of the floor as thickness, material, construction etc. On the floor the chairs of the occupants are attached with its dampers and springs, which lower the high frequencies from the floor and also lower the load on the occupants. The oscillating floor can lead to acceleration (force) injuries to the foot/ankle complex when having the feet on the floor, but also to the spine of the occupants due to vertical movement of the chair.

2. Conditions

For this standard the following conditions are for the occupants in a mine clearance vehicle exposed to the detonation of a mine:

- the occupants are in the driving compartment and are sitting on their chairs with the feet on the floor
- the mine explodes under the mine clearing device
- the occupants are protected to fragments from the damaged clearing device or from the mine casing
- only blast pressures and accelerations affecting the occupants are considered
- blast pressures will affect only the ear as the injury level of the ear is lower than the levels for other gas filled organs like the lungs and gastrointestinal system
- accelerations will affect the foot/ ankle complex and the spine
- the acceptable injury level to the occupants will be "no injury at all" - implying that after a detonation of a mine the occupants will be able to continue their mission in the vehicle, if undamaged or exit and drive another vehicle

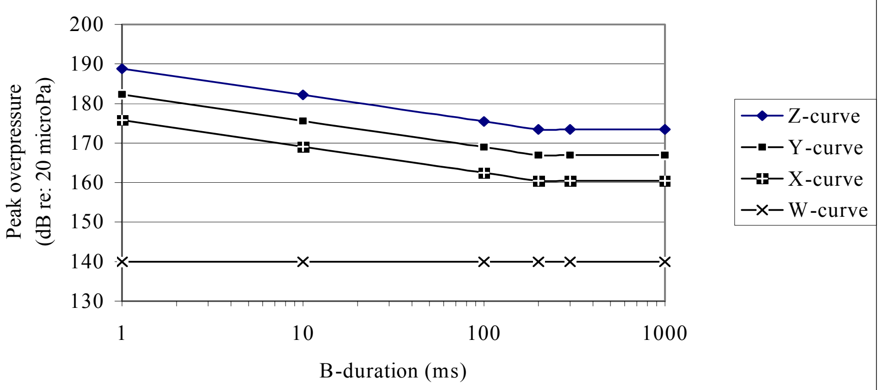
3. Injury criteria

3.1 Ear

3.1.1 Tolerance level

The ear is the most pressure sensitive gas filled organ in the body. For overpressures greater than 200 Pa (=140 dB) hearing protectors must be used as demonstrated in Figure 1 and Table 1 in the US DoD MIL-STD-1474D, 1997 [1]. The number of allowed exposures a day is depending of the peak overpressure, a characteristic time duration (B-duration) in the pressure-time history and the hearing protectors used. The longer B-duration the less peak overpressure can be tolerated (B-dur < 200 msec). Levels higher than the Z-curve are not allowed.

Figure 1: Peak sound pressure levels and B-duration limits for impulse noise [1].



For an unprotected ear there is a 1% risk to get a minor eardrum rupture [2] and some hearing impairment if the peak overpressure is 19 kPa (=179,6 dB). The injury level for the other gas filled organs, as the lungs and the gastrointestinal system, is higher and the pressure for threshold lung injury is 69 kPa (= 190,8 dB) for long duration pressure waves [3]. For shorter duration the tolerated pressures are even higher.

Table 1: Impulse noise daily exposure limits [1].

Impulse noise limits	Maximum Permissible Number of Exposures/Day		
	No protection	Either plugs or muffs	Both plugs and muffs
Z	0	5	100
Y	0	100	2000
X	0	2000	40000
W	-------- Unlimited exposure ---------		

For this standard we will use as injury level for hearing the Z-curve in the above referred document [1] and not taking into account the injuries to other organs as their injury level is higher than the limiting injury level for the well protected ear. However, a method for predicting these injuries is given in [4]. By using the pressure-time histories from an instrumented cylinder about the size of a human's thorax and applying these histories to a mathematical model of the thorax, the degree of injury can be predicted as a function of a calculated peak chest wall velocity.

3.1.2 Measurement location

Measurement shall be made at the occupants' position with the transducer located at the centre of the occupants' head location. When the occupants must be present the measurements shall be made 15 cm from the ear closest to the noise source.

3.1.3 Instrumentation

A full description of the instrumentation, recording specifications etc is given in [1]. But some of these are highlighted here as follows:

- the transducer mounting will be in a probe having a blunt cylinder shape for measurements below 40 kPa
- the diameter of the sensor's surface shall have a diameter less than 6.4 mm (1/4 inch)
- for other than DC-response, time constants shall be not less than 200 ms
- the transducers shall be positioned with the pressure sensing surface facing upwards, if possible
- if the pressure wave propagation is well defined the transducers should be oriented with the sensing surface perpendicular (side-on pressure) to the wave front
- data shall be analysed through a low-pass 40 kHz filter of the Bessel type (36 dB/octave roll-off)

3.1.4 Determination of peak overpressure and B-duration

The peak overpressure level is the highest instantaneous pressure level reach at any time during the recorded pressure-time history and is exemplified in figure 2. The used unit of pressure is Pa (Pascal). The peak overpressure can also be expressed in dB (decibel) as:

$$\text{Peak overpressure (dB)} = 20 * {}^{10}\log(\text{peak overpressure}/P_0) \text{ with } P_0 = 20\ \mu\text{Pa}$$

A more convenient expression is:

$$\text{Peak overpressure (dB)} = 154 + 20 * {}^{10}\log[\text{peak overpressure (kPa)}]$$

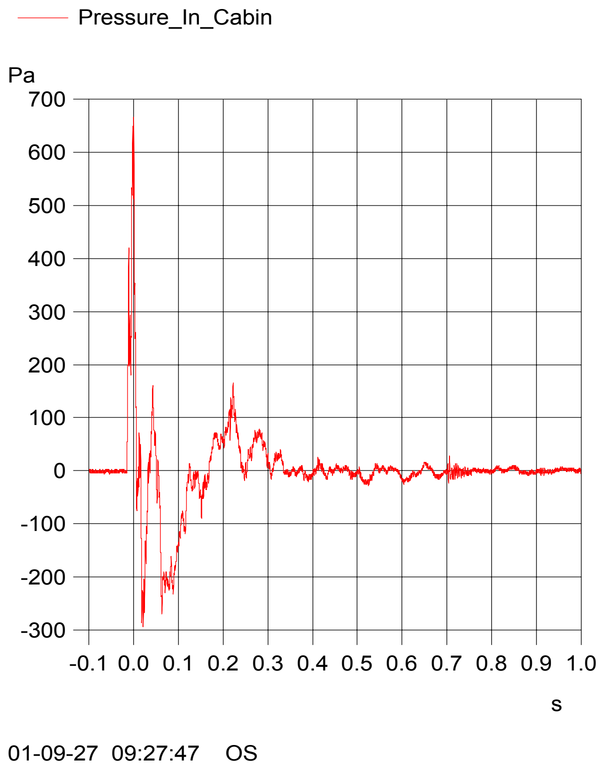


Figure 2: Example of pressure-time history measured in cabin of a Mine Clearance Vehicle.

The determination of B-duration is more complex and is given in detail in [1]. In short: the B-duration is the total time that the envelope of the pressure fluctuations, Figure 2, both positive and negative, exceeds a level 20 dB down from the peak overpressure. This 20 dB value represents one tenth of the peak overpressure.

3.2 Foot/ankle

3.2.1 Tolerance level

A.E. Hirsch published in 1967 a model for the tolerance level for the foot/ankle complex and for a stiff-legged standing man when subjected to shock motions aboard ships undergoing underwater attack [5]. He found by analysing data from explosive events that the deck responded in a sudden severe, upward motion which could be represented by a typical velocity-time curve as shown in Figure 3. That information together with tests on volunteers on ship shock motion simulators and theoretical considerations gave a tolerance level curve presented in Figure 4. The tolerance level for short duration pulses (rise time to maximum velocity less than 10 ms) was for a peak velocity change of 3 m/s. For longer duration the tolerance level was for an average acceleration of 20 g.

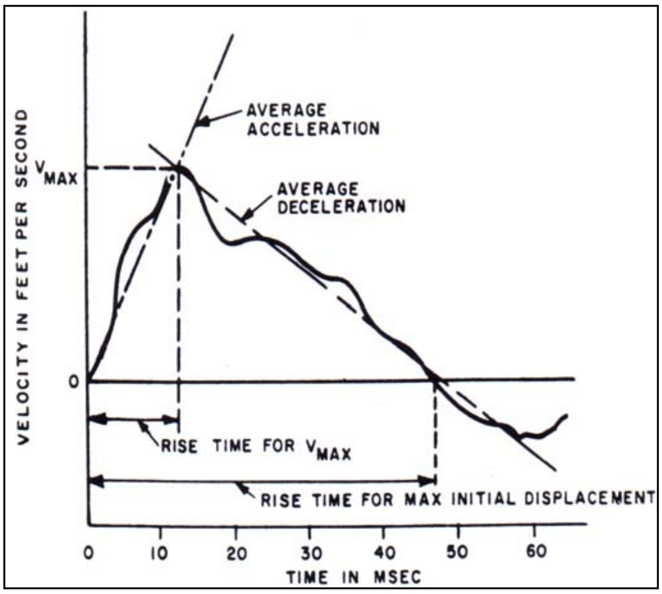


Figure 3: Example of shock-motion terminology [5].

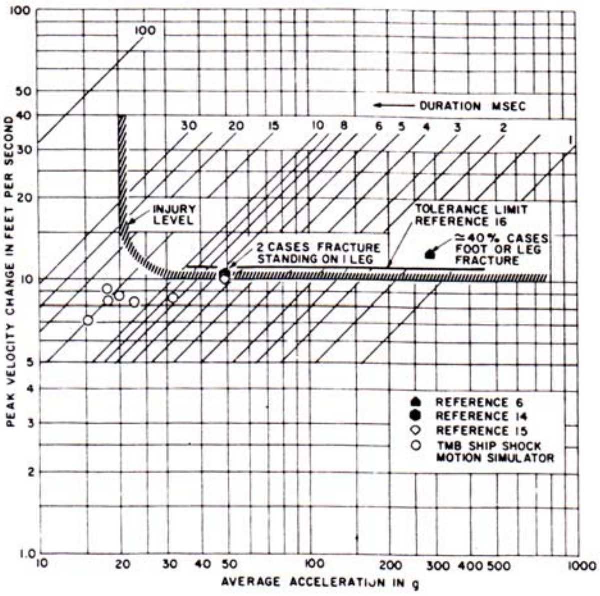


Figure 4: Tolerance of stiff-legged standing man to shock motion of short duration[5].

Fractures to the heel bone and anklebones have been reported. These injuries are very painful and require a long period of convalescence.

No tolerance curve for a sitting man was presented in [5] so in this Crew Safety Standard we will use the model for a standing man also for a sitting man with both his feet on the floor.

Integration of the recorded acceleration-time history will give the velocity–time history where the maximum velocity change and risetime can be deduced and applied to the Hirsch tolerance criteria for a standing man.

3.2.2 Measurement location.

The acceleration will be measured where the occupants have their feet on the floor. Any kind of floor mat will be cut out around the transducer. If some kind of foot-rest with a damping device is used the foot-plate will be loaded with an extra weight of 10 kg simulating the load of the lower legs when driving.

3.2.3 Instrumentation.

Some important parameters are:

- Digital recording. Sampling rate shall be a minimum of 20 kS/s.
- Analog-to-digital converters shall have a 12-bit word size or more.
- Transducer-amplifier-digital recorder shall have DC response.
- Upper frequency limit of transducer-amplifier-digital recorder shall be not less than 5000 Hz.
- Accelerometer mount. Proper care should be taken so that the useful frequency and dynamic ranges are not limited by poor accelerometer mounting. Techniques involved may be screw mount, adhesive mount etc.
- Mechanical filters. These may be used to protect the accelerometer from damaging high level shocks, to avoid zero shift effects and to reduce transverse coupling.

3.3 Spine

3.3.1 Tolerance levels

Hirsch also presented in his report from 1967 [5] a similar model for the injury to the spine for at sitting man in upright position exposed to a driving force foot-to-head. The typical injury is a fracture to vertebrae in the spine. The tolerance level for short duration pulses (rise time to maximum velocity is less than 20 ms) was for a peak velocity change of 4.5 m/s (Figure 5). For longer duration pulses the tolerance level was for an average acceleration of 15g.

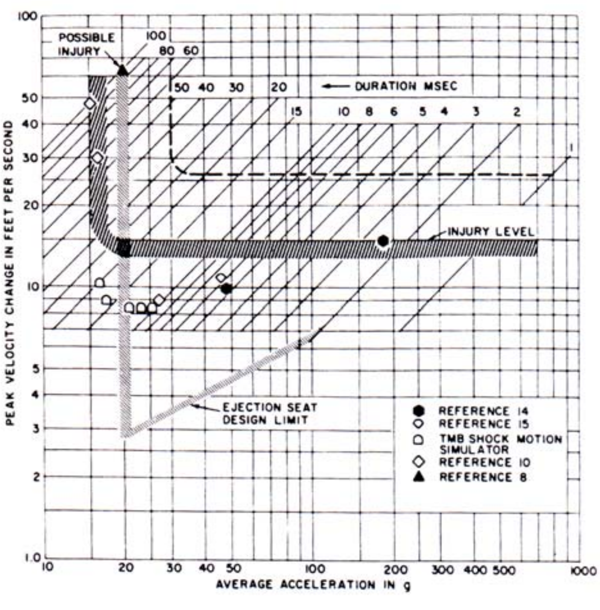


Figure 5: Tolerance of seated man to shock motion of short duration [5].

An alternative method, the DRI concept, is taken from the aircraft industry in their work with ejection seats for pilots [6].

The Dynamic Response Index (DRI) was developed to predict probability of thoracolumbar-spine fracture injury during ejection seat use [7 & 8]. The DRI uses a simple mass-spring-damper system for predicting the gross response of an aircrew member subjected to abrupt vertical acceleration. The equation of motion for this system is:

$$d^2\delta/dt^2 + 2\zeta\omega_n d\delta/dt + (\omega_n)^2\delta = a_c(t)$$

where

δ = the deflection of the system
ζ = the damping ratio
ω_n = the natural frequency
a_c = is the measured critical point acceleration in the vertical direction

The equation of motion can easily be solved with numerical methods.

The DRI is the square of the natural frequency of the system, ω_n multiplied by the maximal compressive deflection, δ_{max} that results from a +Z (foot-to-head) driving force or acceleration, and divided by the acceleration of gravity, G:

$$DRI = (\omega_n)^2\, \delta_{max}/G$$

In the calculation of DRI

ω_n = 52.9 radians/s (= 8.4 Hz)
ζ = 0.224

The DRI has been correlated to spinal injury data from laboratory and operational experience. Figure 6 shows the rate of spinal injury as a function of DRI. a_c is the acceleration sensed on the behind of the occupants. A typical acceleration-time history is exemplified in Figure 7.

For the no injury level DRI = 16 has been chosen corresponding to a 1% risk of a detectable fracture to the spine based on operational experience.

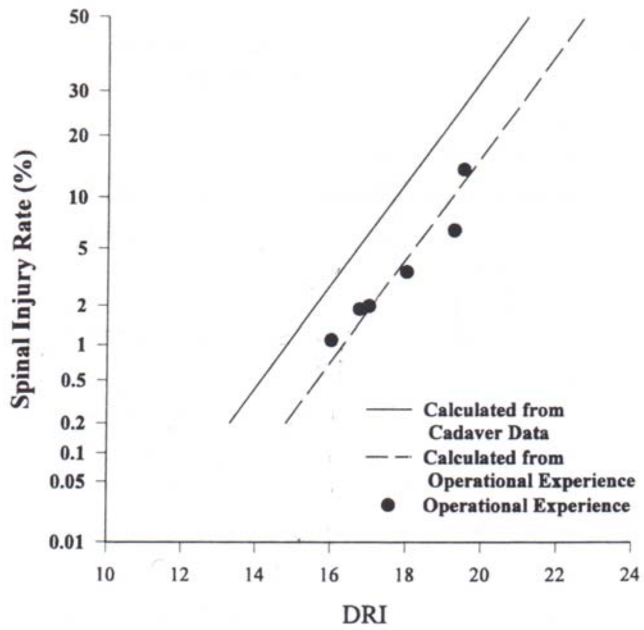


Figure 6: Probability of Spinal Injury Estimated from Laboratory Data Compared to Operational Experience [8].

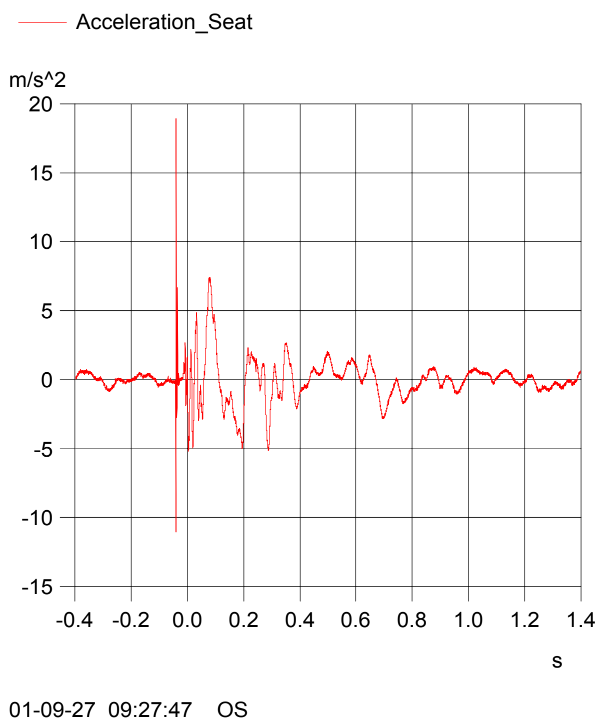


Figure 7: A typical acceleration-time history measured in drivers seat in a Mine Clearance Vehicle.

3.3.2 Measurement location

The critical point acceleration (a_c) in the vertical direction (z) is here defined as the interface between the behind of the occupant and the seat cushion of the chair. The chair will be loaded with a 70-kg weight, which can consist of a 60-kg sandbag sitting on a 10-kg wooden block; both strapped together but also strapped to the chair. In the wooden block an accelerometer shall be mounted. If the driver must be present in the cabin for operation of the system during the test he will be sitting on the 10 kg wooden block. One example of the wooden block is illustrated in Figure 8.

Figure 8: 10 kg wooden block with accelerometer mount.

The recorded acceleration-time history $a_c(t)$ will serve, as an input to the equation in Chapter 3.3.1 for calculating the DRI. Integration will give the velocity-time history from where the maximum velocity change and rise time can be deduced and applied to the Hirsch tolerance level for a seated man.

3.3.3 Instrumentation

Some important parameters are:

- Digital recording. Sampling rate shall be a minimum of 4 kS/s.
- Analog-to-digital converters shall have a 12-bit word size or more.
- Transducer-amplifier-digital recorder shall have DC response.
- Upper frequency limit of transducer-amplifier-digital recorder shall be not less than 1000 Hz.

4. Conclusions

The acceptable injury level for the occupants is set to “no injury at all” implying that after a detonation of a mine under the clearing device the occupants will be able to continue their mission in the vehicle, if undamaged or exit and operate another vehicle. The injury levels accepted are given in Table 2 below for the two dominant types of injury, pressure effects on the ear and shock/acceleration effects on the foot/ankle and the spine.

Table 2: No injury levels for the ear, foot/ankle and spine.

Physical effect	Body part	Level
Pressure	Ear	<W-curve (140 dB), no protectors required
		>W-curve but < Z-curve, protectors required. > Z-curve is not allowed
Shock/acceleration	Foot/ankle	Average acceleration < 20 g or max velocity change < 3 m/s
	Spine	Average acceleration < 15 g or max velocity change < 4.5 m/s
		DRI ≤ 16

5. References

[1]	Department of Defense. *Design Criteria Standard. Noise Limits*. MIL-STD-1474D, 12 February 1997.
[2]	James, D.J. & Picette, V.C. & Burdette, K.J. et al: *The Response of the Human Ear to Blast. Part 1: The Effect on the Eardrum of a Short Duration, Fast Rising Pressure Wave.* 1982; joint AWRE/CDE report no.04/82, Atomic Weapons Research Establishment, Aldermaston, Berkshire, England.
[3]	Bowen, I.G. & Fletcher, E.R. & Richmond, D.R.: *Estimate of Man's Tolerance to the Direct Effects of Airblast.* 1968; technical progress report, DASA-2113, Defense Atomic Support Agency, Washington, DC, USA.
[4]	Axelsson, H. & Yelverton, J.T.: *Chest Wall Velocity as a Predictor of Nonauditory Blast Injury in a Complex Wave Environment*. Journal of Trauma, Infection and Critical Care. Vol.40, No.3, 1996.
[5]	Hirsch, A.H.: *Man's Response to Shock Motions*. January 1964, Report 1797. David Taylor Model Basin, Structural Mechanics Laboratory, Washington D.C.
[6]	*Anthropomorphic Dummies for Crash and Escape System Testing*. AGARD Advisory Report 330, 1996.
[7]	Stech, E.L. and Payne, P.R.: *Dynamic Models of the Human Body.* AMRL-TR-66-157, Wright-Patterson AFB, Ohio, November 1969.
[8]	Brinkley, J.W. and Shaffer, J.T.: *Dynamic Simulation Techniques for the Design of Escape Systems: Current applications and Future Air Force Requirements.* AMRL Symposium on Biodynamic Models and Their Applications, Report No. AMRL-TR-71-29, Wright-Patterson AFB, Ohio, October 1970.