Annex G – SUPPLEMENTAL INFORMATION ON NECK INJURY ASSESSMENT

G.1 INTRODUCTION

This annex gives general information on neck injuries and injury criteria in support to injury assessment for AV mine testing, and is divided in the 8 following sections:

- Section G.1 – Introduction
- Section G.2 – Neck Injuries
- Section G.3 – Axial Compression Injury Criterion
- Section G.4 – Flexion/Extension Injury Criterion
- Section G.5 – The Neck Injury Criterion (N_{ij})
- Section G.6 – Other Neck Injury Criteria
- Section G.7 – Summary
- Section G.8 – References

G.2 NECK INJURIES

Predicting typical AV mine neck injuries is difficult since the nature and the severity of these injuries will depend on a number of factors. The next paragraphs describe some neck injuries which may occur during AV mine strike. For more information on neck injuries, the reader may be referred to [McElhaney et al. 2002] and [Pike, 2002].

Trauma to the cervical spine has been divided into three main categories [Pike, 2002]:

1) Osseous (bone) injury;
2) Neurological injury; and
3) Soft tissue injury.

Osseous injury refers to vertebral fractures. The severity level of these fractures will depend on: whether or not the fracture resulted in impingement of the neurological structures, and whether or not the fracture is structurally stable. Axial compressive loading of the erect vertebral column produces a characteristic fracture called ***compression or burst fracture*** (see Figure G.1) and can occur from C1 through C5 [Pike, 2002]. Burst fracture fragments can also penetrate further into the spinal canal causing life-threatening complications [McElhaney et al. 2002]. The most serious burst fracture is the one of the atlas (C1) commonly called ***Jefferson fracture*** [Pikes, 2002]. Fatalities and instabilities arising from the *Jefferson fracture* are common and extremely serious. ***Wedge compression fracture*** (see Figure G.1) is a result of a combination of a flexion bending moment and compressive load resulting in a failure of the anterior of the vertebral body [McElhaney et al. 2002]. Compression-extension loadings produce ***posterior elements fractures*** of the cervical spine and they may occur throughout the upper and lower parts. They also occur in conjunction with burst fracture and are frequently multiple. They may also be associated with neurological deficit as a result of impingement of the spinal cord by bony or ligament fragments [McElhaney et al. 2002].

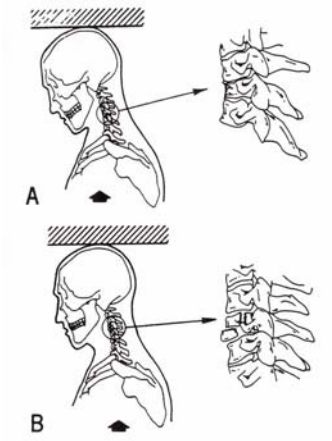

Figure G.1: Illustration of Wedge Fractures (A) and Burst Fracture (B) (from [McElhaney et al. 2002]).

Neurological injury is the most severe class of neck injuries, which may result in paralysis, long-term pain and even death. They generally are the result of primary osseous or soft tissue injuries [Pike, 2002].

Soft tissue injury is the most common type of neck injury in vehicular crash environment. For example, ***neck sprain***, in which the ligaments are stretched beyond their normal limits, is a result of flexion-extension (also called 'whiplash'). Ligamentous injuries are usually minor, but when severe, they can impart severe neurological impairment [Pike, 2002].

G.3 AXIAL COMPRESSION INJURY CRITERION

Mertz et al. undertook a study to develop axial compression neck injury tolerance curves. Impact tests of a spring-loaded tackling block on football helmets [Mertz, 1978] were conducted with a 50th percentile male Hybrid III and then compared them to real accidents of high school aged football players. One player (17 years old, 1.88 m, 101 kg) suffered immediate paralysis of the arms and legs and X-rays showed fractures of C3, C4 and C5. A second 17 year old player (1.82 m, 95 kg) suffered fatal injuries including hemorrhages in the brain stem and pons (white matter nerve fibers) and subarachnoid blood (area of brain containing cerebrospinal fluid, cushioning brain from mechanical shock). In a third incident, a high school player was allegedly struck and rendered quadriplegic by the same tackling block used in Mertz's experiments.

In the tests, the Hybrid III was oriented so that the load was applied to the top of the head, loading the neck structure in compression with minimal head rotation (appropriate figure of the test set-up was not available). The configuration was chosen to produce the maximum value of neck compression force for the impact velocity chosen. The neck compression load measured by the Hybrid III was considered representative of the upper bound of maximum axial compressive load that an equivalent weight human would have experienced for the same impact velocity.

Based on this study, Mertz [Mertz, 1978] derived two injury tolerance curves based on the upper neck axial compression force measured on a 50th percentile male Hybrid III (see Figure G.2). The coordinates of the 'Upper' curve are 0 ms and 6670 N, 35 ms and 1110 N, and greater than 35 ms, 1110 N. The coordinates of the 'Lower' curve are 0 ms and 4000 N, 30 ms and 1110 N, and greater than 30 ms, 1110 N. To evaluate neck load signal, pairs of points (force, duration) are plotted on the graph (shown in Figure G.2) with the two injury assessment curves. The points are connected together by a series of straight lines. If any of the line segments lie above the upper curve (red), the neck axial compression force

is considered to have the potential to produce serious neck injury. If any of the line segments lie above the lower curve (blue), the potential for neck injury from the axial compressive force is considered less likely. If none of the line exceeds the lower curve, the probability of neck injury from axial compressive force is considered remote.

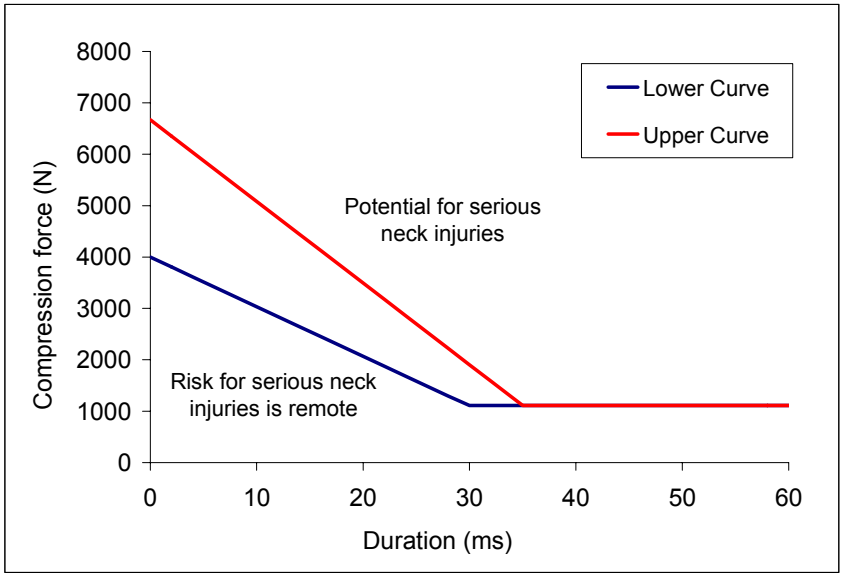

Figure G.2: Injury Tolerance Curves for Axial Neck Compression Force when Using a Hybrid III 50th Percentile Male ATD [Mertz, 1978].

These levels were proposed for an adult population that was considerably older (exact age range not known) and much less conditioned than a high school football athlete. The time durations were determined from the loading times observed during the experiment, which were on the order of 30-40 ms.

G.4 FLEXION/EXTENSION INJURY CRITERIA

Mertz and Patrick [Mertz, 1971] as well as Patrick and Chou [Patrick, 1976] conducted tests on volunteers and PMHSs to determine neck reaction on the head under dynamic conditions. Human volunteers were subjected to static and dynamic tests to produce non-injurious response for neck flexion and extension. PMHSs were used to extend the data into the injury region. Their analysis of the data indicated that equivalent moment at the occipital condyles (protusions on the back of the skull which articulate with the cervical vertebra) was the critical injury parameter in flexion (forward) and extension (backward).

The dynamic tests were conducted with one human volunteer and four PMHS. The subjects were restrained in a rigid chair mounted on an impact sled (appropriate figure of the test set-up was not available). The sled was accelerated pneumatically over a distance of 2 meters to a prescribed velocity. A headrest was used to maintain the head in the upright position. After reaching the prescribed velocity the sled was stopped with a hydraulic cylinder, which produced a repeatable stroke. The occupant was restrained with a lap belt and two shoulder harnesses, which crisscrossed at the sternum. The human volunteer was subjected to 46 sled runs of various degrees of severity for four configurations of head weight. The subject attempted to achieve two different degrees of muscle tenseness, relaxed and tensed. With muscles tensed the volunteer was subjected to sled decelerations of 1.9-6.8 g. With weight placed above the center of mass of the head the volunteer was subjected to a 9.6 g deceleration. This particular run resulted in neck and back pain that lasted several days. The PMHS were similarly fixed so as to obtain comparisons of responses to the same sled deceleration pulses for the various configurations and head

weights, and then subjected to more severe conditions. A total of 132 PMHS runs were completed using four subjects.

The volunteer withstood a static flexion moment about his occipital condyles of 35 Nm. This was without contribution from chin contact to the chest. A dynamic tolerance level for the flexion moment about the occipital condyles for the initiation of pain occurred with the maximum equivalent resisting moment of 59 Nm. The maximum dynamic flexion moment generated by the volunteer was measured to be 88 Nm. This level produced a sharp pain in the neck and upper back region with soreness persisting for several days. It was considered non-injurious, but close to the injury threshold. The PMHS were exposed too much greater decelerations. Based on the PMHS data, it was observed that the 50th percentile human could withstand equivalent flexion moments of 190 Nm without suffering ligamentous injury (AIS 1 or 2) or bone injury (AIS 2 to 6). However, it is expected that muscle injuries (AIS 1) would occur at a lower value of the flexion moment. Based on these results Mertz [Mertz, 1978] proposed an injury tolerance level of 190 Nm for neck flexion moments measured with a 50th percentile male Hybrid III. Similarly from the aforementioned study, corridors for extension were proposed with an injury tolerance level of 57 Nm [Mertz, 1978]. This level was associated with ligamentous damage (AIS 1 or 2), to a PMHS.

G.5 THE NECK INJURY CRITERION (N_{ij})

The N_{ij} (Neck Injury Criterion) was developed to assess performance of frontal airbags during car crashes. The idea of the N_{ij} came from studies of [Mertz and Weber, 1982] and [Prasad et Daniel, 1984], which lead to the conclusion that linear combination of tensile loads and extension could form the basis for an injury prediction function [Shewchenko, 2001]. This was expanded to include flexion and compression resulting if the four following terms (later referred to N_{ij}):

1) N_{te} (for tension/extension);
2) N_{tf} (for tension/flexion);
3) N_{ce} (for compression/extension); and
4) N_{cf} (for compression/flexion).

The N_{ij} is calculated as follows:

$$N_{ij} = \frac{Fz}{Fz_c} + \frac{My}{My_c}$$

where:

Fz is the tension or compression force;

Fz_c is the critical value for tension or compression;

My is the extension or flexion bending moment; and

My_c is the critical value for extension or flexion.

The N_{ij} calculation then consists in four calculations for the different loading modes (N_{te}, N_{tf}, N_{ce} and N_{cf}) and the maximum of these values gives the N_{ij} response. Eppinger et al., 2000 proposed N_{ij} injury risk equations illustrated in Figure G.3.

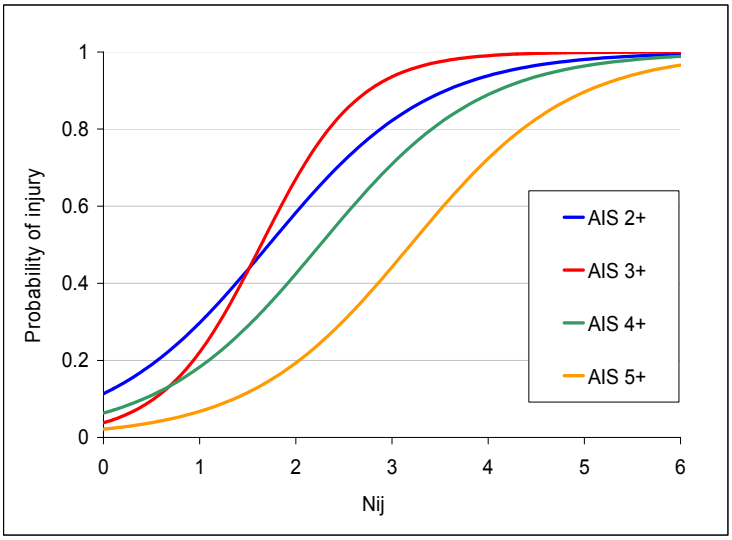

Figure G.3: N_{ij} Risk Curves (Proposed by [Eppinger et al., 2000]).

These curves are applicable to various dummy sizes to which different critical values are associated. The following critical values are used for the 50th percentile male Hybrid III [CFR 49, 2003]:

Fz_c (for tension) = 6860 N

Fz_c (for compression) = -6160 N

My_c (for extension) = -310 N.m

My_c (for flexion) = 135 N.m

The AIS 2+ risk curve presented in Figure G.3 indicates a risk of 11.4% when the N_{ij} is zero, which is physically not possible. All other curves also suggest a risk greater than zero when the N_{ij} is zero, giving a low confidence in the validity of the curves for low risk value. The Nij was primarily based on the results of paired swine and 3-years-old dummy tests, in which they were mainly subjected to tension-extension loadings [Shewchenko, 2001]. The type of loading for which the N_{ij} was developed (tension) was not representative of those seen in AV mine situations, where the neck is mainly loaded by axial compression. Also, the N_{ij} was first developed for the child dummy and then extrapolated for adult dummies, which introduced other uncertainties in the model. Given the different uncertainties about the N_{ij} mentioned above, the HFM-090/TG-25 decided not to use this model and considered each of the loading mechanisms (compression, flexion, extension) separately.

G.6 OTHER NECK INJURY CRITERIA

[Mertz, 1984] proposed injury tolerance curves, similar to the ones for compression, for neck tension and shear loads and are presented in Figures G.4 and G.5. For shear force, the coordinates of the curve are 0 ms and 3100 N, 25 to 35 ms and 1500 N, and greater than 35 ms, 1110 N. For tension, the coordinates of the curve are 0 ms and 3300 N, 35 ms and 2900 N, and greater than 45 ms, 1110 N. Following the same approach given in Section G.3, if any of the line segments lie above the curve, the neck shear/tension force is considered to have the potential to produce **serious neck injury**. If no line segment lies above the curve, then neck injury caused by shear/tension is considered unlikely.

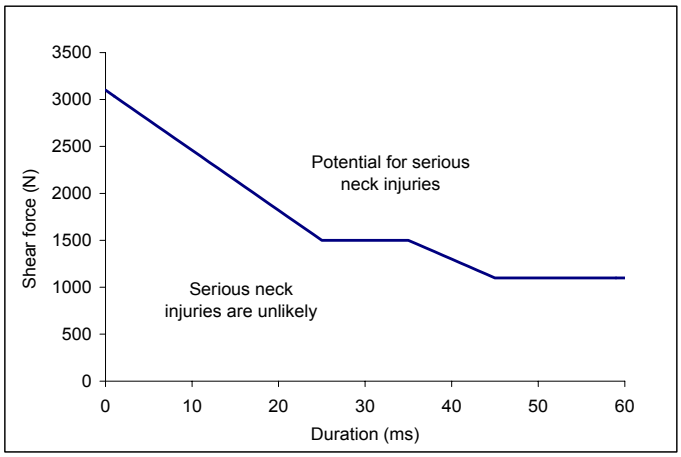

Figure G.4: Neck Shear Injury Tolerance Curve for the 50th Percentile Male Hybrid III (Proposed by [Mertz, 1984]).

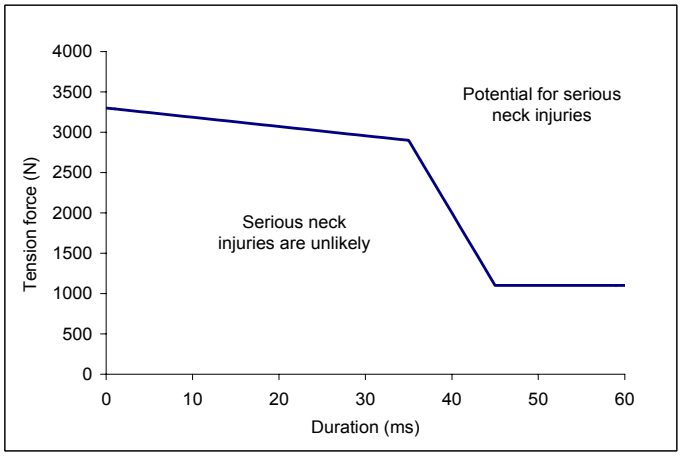

Figure G.5: Neck Tension Injury Tolerance Curve for the 50th Percentile Male Hybrid III (Proposed by [Mertz, 1984]).

Lateral bending injury tolerance levels were studied in automotive [Patrick and Chou, 1976; Koshiro et al., 2005] and aviation [Soltis et al., 2003] fields with PMHS and human volunteer, as well as with numerical human models. However, no appropriate injury assessment method for AV mine was found for this specific loading regime at this point.

G.7 SUMMARY

The neck injury assessment method proposed in this report includes tolerance levels developed by Mertz and Patrick [Mertz, 1971], Patrick and Chou [Patrick, 1976] and Mertz [Mertz, 1971] for axial compression, flexion and extension. Each of the injury mechanisms is evaluated separately as opposed to what suggests the well known Nij model [Eppinger et al., 2000], which considers combined loading modes on the neck. After evaluation of the Nij model, it appeared that it was not suitable for the current application, in which axial compression is the major loading mode. Since neck injuries may be very severe and life-threatening, it is recommended to extend assessment if appropriate methods exist. Tolerance curves for shear and tension are available [Mertz, 1984] and lateral bending injury assessment is currently being studied for aviation applications [Soltis, 2003].

Although the Hybrid III neck is the most widely used and accepted dummy neck, it possesses major limitations in terms of biofidelity and anthropometry [Shewchenko, 2001]. Some concerns were expressed by the automotive industry regarding the assessment of flexion/extension injuries [Shewchenko, 2001]. As opposed to the axial compression tolerance level, flexion/extension tolerance levels are based on human cadavers and/or volunteers responses, and not the Hybrid III neck response. Since the direct correlation between human and Hybrid III neck response is actually unknown, the accuracy of flexion/extension responses may be questionable. Automotive industry has addressed neck biofidelity improvements with the development of the THOR, however the Hybrid III dummy still remain the standard for car crash testing.

G.8 REFERENCES

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