Comparison of Quantity-Distance Standards for Earth-Covered Magazines in Various National/International Manuals

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ABSTRACT

National and multi-national agencies tasked with regulation of explosives storage have produced a number of different manuals governing the maximum amounts of HD 1.1 material that can be stored in an earth-covered magazine (ECM). These quantity-distance (Q-D) requirements are set forth in prescriptive language in manuals published for use by the engineering and planning community.

A recent comprehensive review of five such manual sources resulted in a compilation of a set of comparative tables in which the requirements for minimum separation distance, as well as for blast loading on various elements of the ECM, were outlined side by side. The five manuals represent requirements for the United Kingdom, Canada, and U.S.A., as well as multi-national entities such as NATO and the United Nations. All manuals use the same designations for categories of ECMs (namely, 7-bar, 3-bar, or undefined). But the actual requirements, both in terms of scaled distances and the applied loading (pressure and impulse), are not entirely consistent across the various requirements. This paper identifies some of those inconsistencies, as well as potential inconsistencies in the correlation between separation distance and its corresponding pressure and impulse.

BACKGROUND

In early 2017, BakerRisk was engaged by the Department of National Defence, Canada, to evaluate their long-span earth covered magazine (ECM) design for blast loads from an accidental detonation in an adjacent magazine. The study was a comprehensive one involving high-fidelity finite element models of structural response as well as the latest analytical estimates of blast loads from ECMs. That study is documented in a separate paper [1], as well as a fully detailed technical report [2].

In the course of that study, the authors were tasked to review a broad range of national and international safety standards for storage of ammunition, particularly as they related to design requirements for siting of ECMs. Five such standards were identified representing the US, UK, UN, NATO, and Canadian requirements. All are formulated in terms of quantity-distance (Q-D), and so they all provide minimum separation distances; in addition, most provide at least some design loads (pressure and impulse) that ECMs must satisfy in order to qualify for one of three different standard ratings, depending on the load that the headwall of the ECM is designed to resist:

- 7-bar
- 3-bar
- Undefined

It may come as no surprise that, when aligned against one another, the five references do not align perfectly, and in fact present certain glaring points of dissimilarity. This paper attempts to compare those standards and highlight their areas of agreement as well as disagreement. We are not so bold as to offer a suggested path towards harmonization of the standards, but it is our hope that this paper may stimulate discussions among the various parties involved that may, one day, result in such a harmonization.

DEFINITIONS

For clarity, the assumed configuration of ECMs in a constructed array is shown in Figure 1. The requirements for separation distance from the donor (or potential explosion site, PES) to the acceptor (or exposed site, ES) are prescribed in terms of clear distances from the nearest surfaces of each ECM. These are termed the inter-magazine distance, or IMD. Note that these would *not* be the same distances one might use to calculate blast load as a function of charge weight and distance. In the latter case, an alternate set of dimensions would be used from the centroid of the explosive mass (generally the centroid of the magazine, unless one knows that the storage arrangement would be deliberately skewed or off-center) to the center of the structural component being evaluated. This is illustrated in Figure 2. For example, the side-to-side load on the roof of an acceptor would be calculated from the centroid of the donor to the centroid of the acceptor, and could be a significantly larger distance than that used for the side-to-side separation distance, depending on the plan dimensions of the magazine.

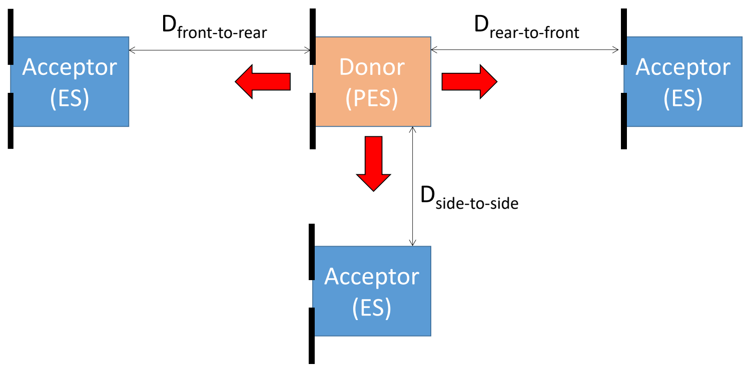

Figure 1: Definition of separation distances between ECMs.

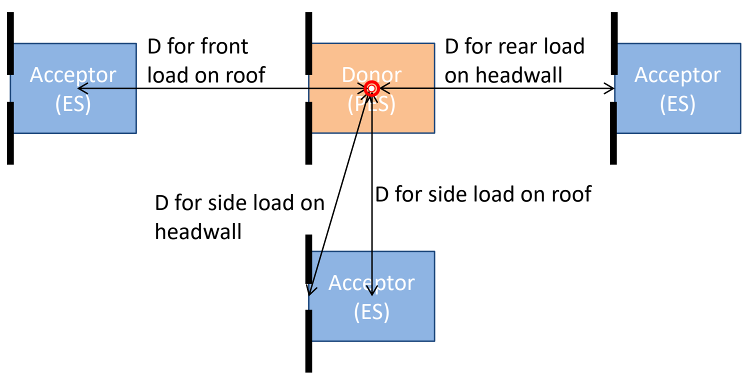

Figure 2: Examples of definition of distances for blast load computations.

We mention this here because this too is a potential source of confusion for novice users of the published standards, and to our knowledge, none of the standards go to any length in clarifying this distinction. Use of similar verbal terms (side-to-side distance, for example) referring to two different quantities carries the potential for misunderstanding and misapplication, and may be avoided with the use of clarifying graphics such as those above.

SOURCES

The five jurisdictions consulted were the United States, United Kingdom, United Nations, North Atlantic Treaty Organization, and Canada. Each publishes a voluminous body of technical literature, from which the relevant documents were identified. The specific documents and the sources for the data to be presented in the tables in the remainder of this paper are cited below.

- United States: DoD 6055.09-M [3] establishes safe stand-off distances between various PESs and ESs. For IMD, the pertinent tables are Table V3.E3.T6 (HD 1.1 IMD Hazard Factors) and Tables V3.E3.T7 (QD for HD 1.1 AE for K = 1.1, 1.25, 2, 2.75, 4.5 and 5) and V3.E3.T8 (QD for HD 1.1 AE for K = 6, 8, 9, 11, 18 and 40). ECM component design blast loads are defined in Vol. 2, Para. V2.E5.5.2.4.
- United Kingdom: JSP 482 [4] establishes safe stand-off distances between various PESs and ESs. For IMD, the pertinent tables used are in Chapter 10, Section 2, Annex A, Table 1A (HD 1.1 QD Matrix for Earth Covered Storage). ECM component design blast loads are defined in Chapter 6, Annex A, Para. 1.2 (Design Loads for Igloos as Exposed Site).
- United Nations: IATG 02.20 [5] establishes safe stand-off distances between various PESs and ESs. For IMD, the pertinent tables used are in Annex A, Table D.2 (Hazard Division 1.1 QD Matrix (above ground storage, NEQ > 50 kg). ECM component design blast loads are defined in a separate document, IATG 05.20 [6], Annex C, Para. C.1.1 (Design Loads for Igloos as Exposed Site).
- NATO: AASTP-1 [7] provides IMDs for ECMs in Section II, Table 1A (HD 1.1 QD Matrix for Earth Covered Storage). ECM component design blast loads are defined in Section II, Para. 2.3.2.2-2 (Design Load for Head-Walls and Doors).
- Canada: DND Canada has issued C-09-005-0021 [8] as that country's explosive safety standard. QD tables are provided in Appendix A, Section II, Table A-2 starting on p. A-13. These are identical in form and content to those in the NATO standard AASTP-1 (at least with regard to the ECM PES and ES combinations). However, to the best of our ability to determine, tables or paragraphs providing design loads for ECMs are not provided.

SEPARATION DISTANCES

We first consider the IMD separation distances between adjacent ECMs, which once again are defined in terms of the distances shown in Figure 1. The required distances are listed in Table 1 for all three loading directions, all three PES types, and all five jurisdictions. Where divergences regarding level of protection were present in the manuals, those are noted in the footnotes. The values are provided in metric scaled distances, where the distance is normalized by the cube root of the net explosive quantity (NEQ). Cells containing values that seem at odds with the consensus are highlighted with color.

Consideration of the table indicates many areas of consistency across all five jurisdictions, as well as a number of areas of inconsistency. Roundoff aside, all five documents agree identically on all three distances for 7-bar magazines. There is near unanimity for 3-bar magazines with only two exceptions. One is the UK which allows 0.8 instead of 1.8 $m/kg^{1/3}$ separation from rear to front and is thus less conservative than the others.[1] This is doubly curious because it is the only instance of disagreement between the UK and UN/NATO/Canada. Furthermore, keeping the rear-to-front distance (which controls headwall loads) the same between 3-bar and 7-bar magazines seems inappropriate, given the very definition of the 3-bar and 7-bar values. The other exception, the absence of a side-to-side value from Canada, appears to be a formatting issue in the published version of the table, where the schematic figure and the D-value have been cut off at the top of the table (Figure 3).

[1] Note that JSP 482 provides separation distances for a receptor (ES) magazine that is "a standard UK igloo designed in accordance with Chapter 6" without distinguishing between 3-bar and 7-bar designs, both of which are covered in Chapter 6. We have interpreted this to mean that the separation distances should be applied equally for both designation. Other manuals (NATO, UN, Canada) clearly distinguish the 3-bar from the 7-bar ES in their tables.

Table 1: Minimum scaled separation distances [m/kg$^{1/3}$] for ECMs.

Receptor (PES) ECM Type	Direction	US	UK	UN	NATO	Canada
Undefined	Side-to-side	0.79[a] 0.50[b]	1.8[c] 0.8[d]	1.8[c] 0.8[d]	1.8[c] 0.8[d]	1.8[c] 0.8[d]
	Rear-to-front	2.38	2.4[e]	2.4[e]	2.4[e]	2.4[e]
	Front-to-rear	0.79	1.8[c]	1.8[c]	1.8	1.8
3-bar	Side-to-side	0.5	0.5	0.5	0.5	—
	Rear-to-front	1.79	0.8	1.8	1.8	1.8
	Front-to-rear	0.79	0.8	0.8	0.8	0.8
7-bar	Side-to-side	0.5	0.5	0.5	0.5	0.5
	Rear-to-front	0.79	0.8	0.8	0.8	0.8
	Front-to-rear	0.79	0.8	0.8	0.8	0.8

(a) for NEQ < 113,400 kg
(b) for NEQ > 113,400 kg
(c) for virtually complete protection
(d) for high degree of protection (no primary explosives, no items vulnerable to spall)
(e) assuming the ES has a headwall and hardened door; high degree of protection

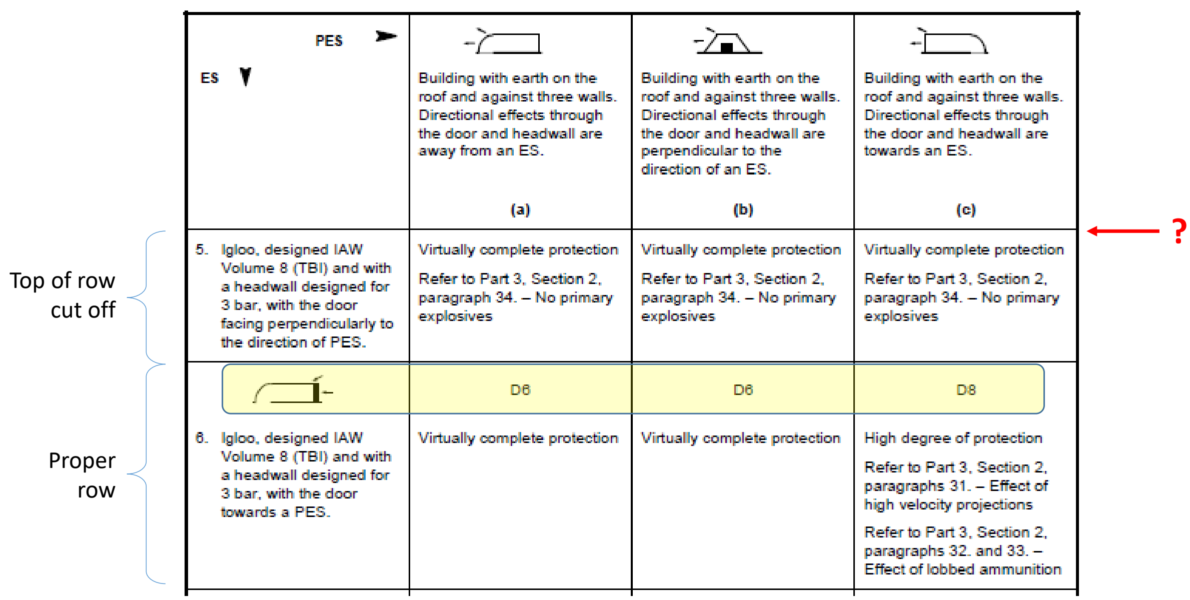

Figure 3: Missing information for 3-bar magazine, side-to-side loading (extract from [8]).

For the Undefined magazine, there are two values that stand in contrast with the majority consensus, and both belong to the US. For both side-to-side as well as front-to-rear loads, the US allows significantly smaller separation distances. The comparison is less clear because of the ambiguities in application (US distinguishes large from small NEQs, while the others distinguish between varying levels of protection). Nevertheless, the US is significantly less conservative than the other jurisdictions in the side-to-side and front-to-rear spacing, but it is quite consistent in the rear-to-front spacing.

DESIGN LOADING

We turn next to the loads for which an ECM is to be designed (Table 2), and here the situation grows more complex. First, there are two load values to consider, pressure *and* impulse. Second, the standards are far less thorough in prescribing loads than they were in prescribing IMDs; in this case, much of the table is blank. Third, since there are fewer "votes," it is harder to determine a consensus opinion and identify outliers.

Table 2: Prescribed design pressures and scaled impulses for ECMs.

Metric	Donor (PES) ECM Type	Acceptor (ES) Component	US	UK	UN	NATO	Canada
Pressure [kPa]	Undefined	Head wall	—	—	—	—	—
		Roof	745	—	—	—	—
		Side wall	—	—	—	—	—
	3-bar	Head wall	300	300	300	—	—
		Roof	745	600	600	—	—
		Side wall	—	300	300	—	—
	7-bar	Head wall	700	700	700	700*	—
		Roof	745	600	600	—	—
		Side wall	—	300	300	—	—
Impulse [kPa-ms/kg$^{1/3}$]	Undefined	Head wall	—	—	—	—	—
		Roof	170	—	—	—	—
		Side wall	—	—	—	—	—
	3-bar	Head wall	100	100	100	—	—
		Roof	170	100	100	—	—
		Side wall	—	100	100	—	—
	7-bar	Head wall	123	200	200	200*	—
		Roof	170	100	100	—	—
		Side wall	—	100	100	—	—

(*) for NEQ ≤ 75,000 kg

Let's begin with the obvious: Canada does not prescribe any design loads at all. Coming close behind, NATO only gives head wall loads for 7-bar magazines and nothing else. Those loads apply for NEQ of 75,000 kg or less; for larger NEQs, designers are advised to consider using higher values (but no actual value is prescribed).

The remainder of our discussion will pertain to the US, UK, and UN documents. First, for Undefined magazines, the only requirement comes from the US and applies to the roof load only. Second, for 3-bar magazines, the US requirement for the roof is higher than that of its peers: 745 instead of 600 kPa for the pressure, and 170 instead of 100 kPa-ms/kg$^{1/3}$ for the impulse. Thus, for the roof of the 3-bar, the US is more conservative than other nations, but for the head wall it is in agreement; for the side wall, it is silent. Third, looking at the 7-bar values, the UK and UN agree closely with one another, but the US is of another opinion altogether in virtually every load metric. It is more conservative for the roof load (both pressure and impulse), but on the head wall impulse it is less conservative. The US abstains on side wall loads altogether.

In the current climate of international military cooperation between these countries and/or agencies, it is often desirable to construct a magazine that satisfies all relevant jurisdictions. Table 3 presents the worst-case design loads for 3-bar and 7-bar magazines from all the standards considered (Undefined not having enough requirements to merit inclusion in the table). Were one to design to the loads in Table 3, one could confidently assert that the magazine in question satisfies all five standards. As the table indicates:

- The US is most conservative in the roof loads;
- The UK and UN are most conservative in the side wall loads;
- And with the exception of the US, all agree on the head wall loads.

Table 3: Worst-case design pressures and impulses.

Metric	Component	QD Standards for 7-bar ECM		QD Standards for 3-bar ECM	
		Value	Source	Value	Source
Pressure [kPa]	Head wall	700	US / UK / UN / NATO*	300	US / UK / UN
	Roof	745	US	745	US
	Side wall	300	UK / UN	300	UK / UN
Impulse [kPa-ms/kg$^{1/3}$]	Head wall	200	UK / UN / NATO*	100	US / UK / UN
	Roof	170	US	170	US
	Side wall	100	UK / UN	100	UK / UN

(*) Limited to NEQ ≤ 75,000 kg

SOME QUALITATIVE QUESTIONS OF CONSISTENCY

We may pause to reflect on the IMD and blast load requirements, and make some inquiries regarding their consistency. Obviously, distance should correlate to pressure and scaled impulse, and so it is appropriate to expect that if one changes, so should the others.

- Consider the design loads for the roof prescribed by the US. For all magazine types, p=745 kPa and i=170 kPa-ms/kg$^{1/3}$. And yet the prescribed side-to-side distance (which presumably controls the roof) varies from 0.79 to 0.50 m/kg$^{1/3}$. Might we not expect the roof load to increase when the scaled distance is reduced?
- The rear-to-front standoff for 3-bar magazines, as prescribed by the UK, seems erroneous as discussed previously. If head wall loads are reduced from 7 bar to 3 bar for the two different categories, how can the rear-to-front separation distance remain constant at 0.8 m/kg$^{1/3}$ between those categories?

Speaking more generally, one may wonder at the necessity of prescribing both a separation distance (in scaled terms) as well as a design load. Would not one or the other suffice? Given a scaled distance and a loading model (such as the Kingery-Bulmash model for TNT), distance directly correlates to pressure and scaled impulse. Clearly that would not account for some of the complexities of interaction between the detonation and the donor magazine structure, or the impact of debris on the acceptor magazine, but if the designer was given a separation distance and a loading model, the loads could be calculated directly without having to be specified separately. Specifying both distance and loading seems like a duplication and leads to ambiguity. Is it sufficient merely to satisfy the IMDs, or must the structure be designed for the specified loads even when it satisfies IMD? What if the site layout exceeds the IMD requirements (larger spacings), do the design loads remain unchanged? Surely they should be reduced in that case.

A QUANTITATIVE CHECK ON CONSISTENCY

A blast model does in fact exist that, unlike Kingery-Bulmash, is directly applicable to ECMs and can be used to calculate a distinct pressure and impulse in each of three directions from a donor ECM: front, side, and rear. This model [9] and its associated spreadsheet tool (the Blast Effects Computer, or BEC) have been sponsored by the US DDESB, but they are not (yet) approved for use in design. A closely related model was also sponsored by NATO [10];

while there is no official prohibition against its use in design, there is also no official endorsement for that purpose. Both represent curve fits to a large set of experimental data and are accepted within the community as state-of-the-art with regard to blast loads from an ECM. Both models yield results that are essentially identical from a numerical point of view, even though they are formulated quite differently in mathematical terms. The main application of this model (considering both BEC and AASTP-4 as a single model) is in risk analysis methods. However, using it as a check on design would be natural to anyone who knew of its existence.

For demonstration purposes, we have devised a "sample problem" in which a rectangular array of ECMs, each one measuring 8 × 12 meters, has been sited with the prescribed minimum scaled standoff distances for 7-bar magazines (per Table 1). Note that for the 7-bar ECM, all five manuals are in unanimous agreement on the distance requirements, which streamlines our problem. We assume each ECM will store a quantity of 27,000 kg of TNT, from which the actual distances can be easily calculated. This layout is illustrated in Figure 4.

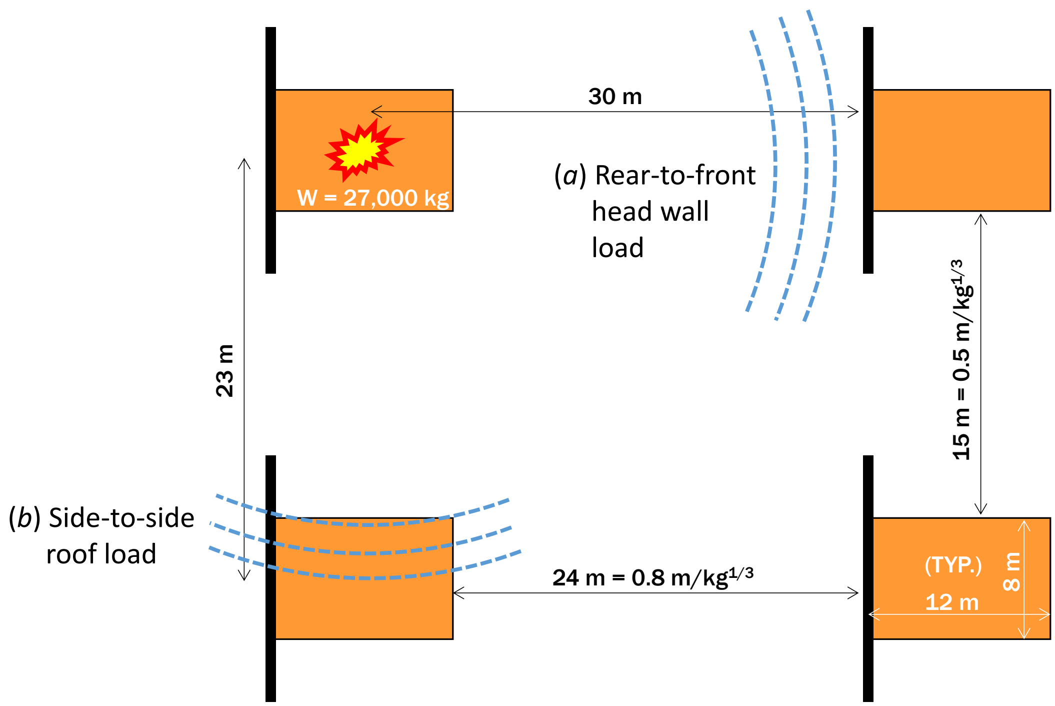

Figure 4: Dimensions and layout of ECMs for sample calculation.

Let us, for demonstration purposes, calculate two loadings: (*a*) the rear-to-front loads on the headwall, and (*b*) the side-to-side loads on the roof. Both of these are illustrated in These results should be of concern to those who manage and administer these standards documents. True, BEC is not currently authorized for use in design, but any designer working in the explosives safety domain will know about it and will be curious to apply it to a problem such as this. Seeing such divergent results as those illustrated herein will surely raise eyebrows and call into question the applicability of either the loading model and the prescribed standoffs, or the prescribed loads, or both. Perhaps if BEC was consistently non-conservative relative to the standards, the situation could be explicable as a case of the standards being overly conservative, with the experienced user free to adopt methods of greater analytical fidelity. But there is no clear trend of conservatism in these results.

Table 4. For case (*a*), the actual distance from the center of the charge to the headwall component is 30 m (including half the length of the ECM), while for case (*b*) it is 23 m (including one full width of the ECM) from the center of the donor to the center of the roof of the acceptor. Using these distances and the appropriate loading model in BEC (ECM rear for (*a*) and ECM side for (*b*)), we calculate values of pressure and impulse that are listed in These results should be of concern to those who manage and administer these standards documents. True, BEC is not currently authorized for use in design, but any designer working in the explosives safety domain will know about it and will be curious to apply it to a problem such as this. Seeing such divergent results as those illustrated herein will surely raise eyebrows and call into question the applicability of either the loading model and the prescribed standoffs, or the prescribed

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Table 4. The table also lists the relevant values of the design pressure and impulse, as obtained from the respective countries' standards and as tabulated in Table 2. Clearly, there are disparities here to be reckoned with. For the headwall, BEC produces about 50% higher pressure than the standards; its impulse is either 10% high or 80% high, depending if one considers the US standard or the UK/UN/NATO. For the roof load, the situation is reversed: BEC indicates a lower pressure by 50% relative to the US and by 30% relative to UK/UN/NATO. The BEC impulse value agrees well with UK/UN/NATO, but is 30% lower compared to the US standard.

These results should be of concern to those who manage and administer these standards documents. True, BEC is not currently authorized for use in design, but any designer working in the explosives safety domain will know about it and will be curious to apply it to a problem such as this. Seeing such divergent results as those illustrated herein will surely raise eyebrows and call into question the applicability of either the loading model and the prescribed standoffs, or the prescribed loads, or both. Perhaps if BEC was consistently non-conservative relative to the standards, the situation could be explicable as a case of the standards being overly conservative, with the experienced user free to adopt methods of greater analytical fidelity. But there is no clear trend of conservatism in these results.

Table 4: Comparison of ECM design loads from BEC and standards for 7-bar sample problem.

		BEC	US	UK/UN/NATO
(*a*) Rear-to-front headwall reflected load	Pressure [kPa]	1009	700	700
	Impulse [kPa-ms/kg$^{1/3}$]	222	123	200
(*b*) Side-to-side roof incident load	Pressure [kPa]	412	745	600
	Impulse [kPa-ms/kg$^{1/3}$]	109	170	100

RECOMMENDATIONS

We make the following recommendations, which we believe to be clearly and objectively desirable:

- Correct the formatting deficiency of the Canadian C-09-005-0021, Table A-2, row 5, to show the necessary separation distances for the 3-bar side-to-side configuration (see Figure 3).
- Investigate the 0.8 value for rear-to-front separation distance in the UK's JSP 482 and, if appropriate, update to 1.8 for consistency with other standards.
- Provide simple schematic graphics in the standards, similar to Figure 1 and Figure 2, to clarify the definitions of the two different sets of distances relevant to ECM siting and design.

Beyond these, the path forward is somewhat subjective and depends on whether greater consistency is desired *within* each standard as well as *among* them. As a starting point, we do see a need for greater inter-jurisdiction coordination and collaboration on the following key questions:

- Should standards be prescribed in terms of distance, loading, or both?
- Is there a loading model that can be adopted as part of a standard? If so, can the loading prescriptions be omitted?
- Is it desirable that the separation distance standards of these (and possibly other) jurisdictions be aligned for consistency? If so, what steps can be taken to align the US with the UK/UN/NATO/Canadian values?

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