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Safe storage of ammonium nitrate products

– scientific framework for government regulations

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Summary

Ammonium nitrate (AN) is a solid chemical compound of paramount significance in the field of agriculture, as a high-nitrogen fertilizer component, and in the formulation of blasting explosives having major civilian applications within mining, quarrying and infrastructure construction work. Global production of AN totals several tens of millions of tonnes per year.

AN is both a principal source of plant nutrient nitrogen and the world's main source of explosive power for heaving and shattering, making the material common in manifold parts of civil society. Although stable under normal conditions of transportation and storage, AN harbors significant energetic potential, even when uncontaminated and without sensitizing admixtures. It may decompose explosively under certain adverse conditions – fire scenarios in particular.

Historically, accidental bulk explosions of AN materials have given occasion to several of the worst industrial disasters of the last hundred years, killing thousands of people and inflicting enormous material destruction. The grave accident record related to AN has been persistent. Serious accidents with AN involved, with some of these being of truly catastrophic proportions, have hit city and port areas in the USA, China and Lebanon in the course of the last decade.

Preparation of government guidelines and regulations for AN products with regard to production, transportation and storage – as solid materials (granules, prills, etc.), as aqueous solutions or in the form of aqueous emulsions, suspensions or gels – have for many years now proven to be a regulatory challenge. AN's many uses and the sheer volume of AN production, when combined with the rather unpredictable behavior of AN materials under the influence of heat and/or shock, have made existing regulations in most parts of the world a type of needed compromise.

For all practical purposes, AN is regulated for transport and storage as an oxidizing substance, even though the compound clearly harbors fundamentally explosive properties when handled in all but pure form and in large quantities. The objective of the present report is the creation of an updated scientific framework that may be used by those whose assignment is the formulation of regulations and guidelines pertaining to storage of AN products – both solid and fluid ones.

The work herein includes the categorization of AN products covered by the Seveso-III Directive into a simplified three-tier classification system and the formulation of specific recommendations on the subject of separation distances between facilities with AN products and protected places, as well as guidelines on internal arrangements of storage facilities holding critical AN products. The concepts of detonation and blast wave dynamics have been central to all work herein.

Expectantly, this text may prove useful for those involved in handling or regulating AN products. Effective regulation of AN products must ultimately address the fundamental unpredictability of the nature of AN: it normally behaves as a conventional solid oxidizing substance, hazardous yet fairly controlled, but it can now and then suddenly take on violently explosive characteristics. Significantly, it has proven all but impossible to predict exactly under what conditions that is likely to happen. The prospect of detonation must therefore regularly be taken into account.

Sammendrag

Ammoniumnitrat (AN) er en fast kjemisk forbindelse av svært stor betydning innenfor jordbruk, som en særlig nitrogenrik gjødselkomponent, og i tilvirkningen av sprengstoff med avgjørende sivile anvendelser innen gruvedrift, dagbruddsdrift og infrastrukturarbeid. Verdensproduksjonen av AN er på flere titalls millioner tonn per år.

AN er både en primærkilde til nitrogennæring for planter og verdens hovedkilde til eksplosiv kraft for heving og knusing, noe som gjør materialet utbredt i mange deler av sivilsamfunnet. Selv om materialet er stabilt under normale transport- og lagringsforhold, har AN et betydelig energetisk potensiale, selv i ren form og uten sensiterende tilsetninger. Det kan dekomponere eksplosivt under enkelte særlig ugunstige forhold, spesielt i brannscenarioer.

Bulkeksplosjoner av AN-materialer har historisk sett vært årsak til flere av de aller verste industrikatastrofer de siste hundre årene, med tusener av dødsfall og voldsomme materielle ødeleggelser som resultat. Den alvorlige ulykkeshistorikken tilknyttet AN har vært vedvarende. Alvorlige ulykker med AN involvert har rammet by- og havneområder i USA, Kina og Libanon bare i løpet av det siste tiåret. Enkelte av uhellene har vært av katastrofale proporsjoner.

Utforming av myndighetsbestemmelser og retningslinjer for håndtering av AN-produkter med hensyn på produksjon, transport og lagring – enten som faste materialer (granuler, priller, etc.), som vandige oppløsninger eller i form av vandige emulsjoner, suspensjoner eller geler – har vært utfordrende over lang tid. ANs mange bruksområder og stoffets store produksjonsvolum, kombinert med AN-stoffers uforutsigbare oppførsel under påvirkning av varme og/eller sjokk, har gjort eksisterende reguleringer i de fleste deler av verden til et nødvendig kompromiss.

For alle praktiske formål reguleres AN for transport og lagring som et oksiderende materiale, selv om stoffet besitter grunnleggende eksplosive egenskaper når det håndteres i tilnærmet ren form og i større mengder. Denne rapporten har til hensikt å skissere et oppdatert vitenskapelig rammeverk som kan brukes av de organer som utarbeider reguleringer og retningslinjer for lagring av AN-produkter – både faste og flytende.

Arbeidet i denne rapporten inkluderer kategorisering av alle AN-produkter i Seveso III-direktivet ved bruk av et enkelt tretrinns klassifiseringssystem, formulering av konkrete anbefalinger hva angår sikkerhetsavstander mellom lagre for AN-produkter og den omkringliggende bebyggelse, i tillegg til retningslinjer vedrørende intern ordning av lagerbygninger med kritiske AN-produkter. Detonasjon og sjokkbølgedynamikk har vært sentrale konsepter for alt arbeid involvert.

Forhåpentligvis vil denne rapporten være et nyttig verktøy for de som er involvert i håndtering eller regulering av AN-produkter. Regulering av AN-produkter må ta hensyn til disse stoffenes uforutsigbare egenskaper. AN oppfører seg typisk som et oksiderende faststoff, det vil si farlig men relativt forutsigbart. Av og til kan det imidlertid oppføre seg eksplosivt. Siden det har vist seg vanskelig å forutsi når dette kan inntreffe, må muligheten for hendelser som involverer eksplosiv omsetning av stoffet (detonasjon) derfor regelmessig tas i betraktning.

Contents

Preface

The present text was prepared at the request of the Norwegian Directorate for Civil Protection (DSB, Direktoratet for samfunnssikkerhet og beredskap), a Norwegian government agency tasked with maintaining an all-inclusive overview of various risks and vulnerabilities to the Norwegian society and population in general – at the local, regional and national levels.

DSB regulates the handling, transport and storage of many hazardous substances in Norway, including ammonium nitrate (AN) products. In order for the agency to formulate an updated set of regulations applying to the entire range of AN products covered by the Seveso-III Directive in a comprehensive manner, the Norwegian Defence Research Establishment (FFI) was asked to prepare an updated scientific framework that could be applied as a foundation for such work.

The aim of the work presented herein has been three-fold: 1) classification of all AN products covered by the Seveso-III Directive according to thermal decomposition hazards; 2) formulation of specific recommendations on the subject of separation distances between storage facilities holding AN products and protected places; 3) creation of guidelines pertaining to particular aspects of the internal arrangement of storage facilities holding critical AN products.

The work herein has been limited to those aspects of AN storage that depend fundamentally on the concepts of explosivity, detonation and blast wave dynamics. For instance, it does not cover issues such as construction materials for AN stores, this having been well established by others. Release of toxic gaseous species from decomposing AN, and likely implications, is not covered. Although scientific aspects presented herein, as well as many of the recommendations, should probably be applicable to countries across much of the world, the key context is of course European conditions – and then Norwegian conditions in particular.

A few comments on orthography and similar are in order. With respect to spelling, it should be pointed out that this text incorporates sizable text extracts from official directives and the like, and these extracts may not use the same standards of spelling as the main text. Therefore, textual deviations with regard to, for instance, American and British English may occur periodically, as in fertilizer versus fertiliser, oxidizer versus oxidiser, and so forth.

A fundamental term herein, ammonium nitrate, will be spelled out fully in headings and some table captions, but the abbreviation AN will be applied almost exclusively within the main text. All percentages reported herein are weight percentages, unless otherwise indicated.

The authors thank officials of the DSB for discussions of chapter drafts, as well as information, suggestions and crucial advice on the many complicated facets of government regulatory work. Input on the numerous nuances becoming relevant when formulating such legal foundations has proven decisive for this report. However, all opinions and recommendations forwarded herein are our own – the viewpoint of scientists trying to apprehend how to regulate AN.

Kjeller, 27 October 2022 Tor Erik Kristensen, Andreas Nygård Osnes

1 Introduction

Ammonium nitrate (AN) – NH_4NO_3 – is a colorless, crystalline and hygroscopic nitrate salt. Having a long history, stretching as far back as to the mid-1600s, the chemical compound is at present one of the most important nitrogen fertilizer materials for agriculture. It is also the major constituent of most commercial explosives for mining, quarrying and civil construction work.

A thorough review of the basic physical and chemical characteristics of AN, including thermal decomposition of both pure and contaminated material, can be found in an open FFI report [1]. Accordingly, the work herein will not expound further on such fundamental properties of AN. Chemical incompatibilities of AN with foreign materials have also been well established [1].

Hazards associated with AN production, transport, storage and use have been acknowledged for more than a century. While a perfectly stable substance at normal conditions, AN may pose an explosion hazard under fire conditions, depending on material traits such as chemical purity, crystal morphology, bulk density, etc. Several of history's absolute worst industrial disasters have been occasioned by the unanticipated, explosive decomposition of AN materials [2].

As AN forms the basis of such a large number of high-tonnage industrial products, with diverse agricultural and technical applications, regulations pertaining to handling, transport and storage of AN products have always had to compromise in balancing considerations of convenience and strictness. Therefore, in order to accommodate AN within key regulatory frameworks relating to hazardous materials, the compound has been classified as an oxidizing substance, in spite of its latent explosive properties having been well established already for a long period of time.

In order to prepare functional government regulations covering the entire range of AN products, the regulating authority needs to recognize nuances relevant for this class of chemical products. While (nearly) pure AN harbors certain explosive potential, other AN products clearly do not present any such hazard. Many solid AN compound fertilizers,[*] for instance, do not have the requisite potential for detonation, although they may undergo self-sustaining decomposition.

The scientific framework reported here aims to dissect the many AN products available into a small number of hazard classes and then formulate a set of science-based guidelines for each category. The report is structured as follows: Classification of all AN products covered by the Seveso-III Directive, according to thermal decomposition hazards, is completed in Chapter 2. Guidelines for the three resultant categories of AN products, concerning separation distances to protected places and internal arrangements of AN product stores, follow in Chapter 3 and 4.

Importantly, all work presented here on separation distances for AN products to protected places assumes completely flat and unobstructed terrain. In concrete locations of AN products storage, this may of course be an issue that will then have to be addressed on a case-by-case basis.

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[*] A solid AN compound fertilizer is a uniform mixture that contains at least two of the three primary plant nutrients nitrogen (N), phosphorus (P) and potassium (K).

A primary purpose of the present work is the realignment of government regulations applying to AN, from a risk-based framework, which contain probabilities that may be difficult to assess, into a less ambiguous hazard-based framework, more similar to those applied for explosives.

The explosion hazards of AN, a crystalline solid with oxygen surplus, can be assessed with a reasonable degree of accuracy, with these hazards being definite also when applied across an extensive range of particular circumstances – here referring to specifics such as container type, storage building construction, climatic conditions and topography of surrounding terrain.

Some dangerous materials, and flammable gases and liquids in particular,[*] represent explosion hazards that are more difficult to quantify because these substances have to be dispersed in air in order to attain any explosive qualities. Hence, they present a sort of continuous scale of hazards that depend on numerous factors (climatic conditions, terrain, etc.), with this making them less appropriate for a more determinate hazard-based framework and more suitable for risk-based frameworks that can incorporate the many potentialities involved in such situations.[†]

Throughout this report, the concepts of on-site and off-site structures will be used recurrently. As used in this text, the term on-site structures mean buildings and installations that belong to a single operating entity, as well as functioning at a specific location under the supervision of a well-defined management. Persons present at the site are those operating the site (first persons) and those that may happen to visit the site in order to undertake specific tasks (second persons).

Buildings or other installations outside the site premises are to be regarded as off-site structures. Here, persons entirely unrelated to the operation of the site area (third persons) may be present. Use of the terms on-site/off-site structures is convenient and has relevance for the separation distances to protected places discussed in Chapter 3. Structures defined as on-site can generally be evacuated more efficiently and more quickly than off-site structures.

Finally, one cautionary remark concerning all work on guidelines for handling and storage of AN products, believed to be particularly relevant for porous prilled AN and other low-density products having a high percentage of AN. Certain commercial products may contain substantial quantities of AN fines, AN dust or similar. This may bestow on the AN product an unusually high degree of shock sensitivity, making it overly susceptible toward detonative impulses.

Therefore, a high level of quality control needs to be exercised for commercial AN products. One should also take into consideration that AN products are materials that may unintentionally become sensitized while stored (prills in particular), for instance by temperature fluctuations, atmospheric humidity or aging processes – either locally or in bulk.

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[*] Hydrogen, liquefied natural gas (LNG), propane, butane, gasoline, etc. Flammable dusts can behave similarly.

[†] In spite of our aims, the mostly hazard-based framework developed for AN products herein will bear the hallmark of risk-based frameworks at some points. This particularly applies to the framework developed for AN fluid products, whose theoretical explosive performance is greater than for pure AN but who are deemed less likely to be involved in detonative events. In that case, the low likelihood of detonation is the rationale for lowering separation distances.

2 Classification of ammonium nitrate products according to thermal decomposition hazards

The aim of the present chapter is the classification of AN products according to thermal decompositions hazards, including deflagration and detonation, by harmonization of how the materials are categorized according to the Seveso-III Directive and the ADR transport treaty. The coordination of the two listings will allow for the division of all AN products into a simple three-tier classification system (red, orange, yellow). This classification system will be used throughout later chapters for preparation of guidelines for regulatory frameworks.

2.1 The Seveso Directive and ammonium nitrate products

Directive 2012/18/EU, commonly referred to as the Seveso-III Directive,[*] is a European Union (EU) directive aimed at control of major-accident hazards involving dangerous substances [3]. The directive is implemented in national legislations throughout the European Economic Area (EEA). It establishes minimum quantity thresholds – for reporting/safety permits – of certain dangerous chemical substances. AN products are among those included in the directive [3].

There are two lists in the directive. One list contains hazard categories of dangerous substances, where specific substances are not named individually [3]. Another list contains named particular substances [3]. Threshold quantities in the two lists are split into two categories. The lower-tier category specifies quantities for reporting, and the upper-tier category specify higher quantities that are subject to both reporting and a more stringent set of control measures [3].

Among the named dangerous substances listed in Part 2 of Annex I of the Seveso-III Directive, four classes of "Ammonium nitrate" are included, using four descriptive notes (no. 13–16) [3]. These AN products, including the descriptive notes specifying them, as well as their applicable lower- and upper-tier threshold quantities, are listed in Table 2.1.

In addition to the above, in Part 1 of Annex I, oxidizing liquids and solids (Category 1, 2 and 3) are among the hazard categories listed [3]. These categories are included at the end of Table 2.1. Certain AN products, like AN emulsions/suspensions/gels, are covered by this category.

We see from Table 2.1 that the AN products covered by the Seveso-III Directive belong to one of five classes: 1) AN compound fertilizers with up to 70% AN and capable of self-sustaining decomposition, but resistant to detonation; 2) AN fertilizers containing higher percentages of AN that are still resistant to detonation; 3) AN technical grades (including some AN solutions), containing over 70% AN and small amounts (not more than 0.2/0.4%) of combustibles, which need not be resistant to detonation; 4) AN 'off-specs'; 5) AN emulsions/suspensions/gels.

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[*] The directive is named after the 1976 Seveso disaster in the Lombardy region of Italy, where a thermal run-away in the production of 2,4,5-trichlorophenol (an intermediate for hexachlorophene) from 1,2,4,5-tetrachlorobenzene and sodium hydroxide led to the uncontrolled release of highly toxic 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD).

Table 2.1 Ammonium nitrate (AN) products covered by the Seveso-III Directive.

Dangerous substances	**Notes to Annex I**	**Lower-tier requirements [tonnes]**	**Upper-tier requirements [tonnes]**
Point 1 (Annex I, Part 2) Ammonium nitrate fertilisers capable of self-sustaining decomposition	Note 13: This applies to ammonium nitrate-based compound/composite fertilisers (compound/composite fertilisers contain ammonium nitrate with phosphate and/or potash) which are capable of self-sustaining decomposition according to the UN Trough Test (see UN *Manual of Tests and Criteria*, Part III, subsection 38.2), and in which the nitrogen content[*] as a result of ammonium nitrate is — between 15,75 % and 24,5 % by weight, and either with not more than 0,4 % total combustible/organic materials or which fulfil the requirements of Annex III-2 to Regulation (EC) No 2003/2003 of the European Parliament and of the Council of 13 October 2003 relating to fertilisers,[†] — 15,75 % by weight or less and unrestricted combustible materials.	5000	10 000
Point 2 (Annex I, Part 2) Ammonium nitrate fertiliser grade	Note 14: This applies to straight ammonium nitrate-based fertilisers and to ammonium nitrate-based compound/composite fertilisers which fulfil the requirements of Annex III-2 to Regulation (EC) No 2003/2003 and in which the nitrogen content as a result of ammonium nitrate is	1250	5000

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[*] Chemically pure AN contains close to 35% nitrogen (by weight). Therefore, 15.75% nitrogen as a result of AN corresponds to 45% AN, 24.5% nitrogen as a result of AN corresponds to 70% AN and 28% nitrogen as a result of AN corresponds to 80% AN.

[†] Annex III-2 of Regulation (EC) No 2003/2003 is a description of the test of resistance to detonation concerning ammonium nitrate fertilisers of high nitrogen content (in seamless steel tube with at least 5 mm wall thickness).

	— more than 24,5 % by weight, except for mixtures of straight ammonium nitrate-based fertilisers with dolomite, limestone and/or calcium carbonate with a purity of at least 90 %, — more than 15,75 % by weight for mixtures of ammonium nitrate and ammonium sulphate, — more than 28 % by weight for mixtures of straight ammonium nitrate-based fertilisers with dolomite, limestone and/or calcium carbonate with a purity of at least 90 %.		
Point 3 (Annex I, Part 2) Ammonium nitrate technical grade	Note 15: This applies to ammonium nitrate and mixtures of ammonium nitrate in which the nitrogen content as a result of the ammonium nitrate is — between 24,5 % and 28 % by weight, and which contain not more than 0,4 % combustible substances, — more than 28 % by weight, and which contain not more than 0,2 % combustible substances. It also applies to aqueous ammonium nitrate solutions in which the concentration of ammonium nitrate is more than 80 % by weight.	350	2500
Point 4 (Annex I, Part 2) Ammonium nitrate 'off-specs' material and fertilisers not fulfilling the detonation test [This class was created as a result of	Note 16: This applies to — material rejected during the manufacturing process and to ammonium nitrate and mixtures of ammonium nitrate, straight ammonium nitrate-based fertilisers and ammonium nitrate-based compound/composite fertilisers referred to in Notes 14 and 15, that are being or have been returned from the final user to a	10	50

the accident on 21 September 2001 in Toulouse, France. This explosion accident involved ‘off-specs’ AN.]	manufacturer, temporary storage or reprocessing plant for reworking, recycling or treatment for safe use, because they no longer comply with the specifications of Notes 14 and 15, — fertilisers referred to in first indent of Note 13, and Note 14 to this Annex which do not fulfil the requirements of Annex III-2 to Regulation (EC) No 2003/2003.		
P8 Oxidising Liquids and Solids (Annex I, Part 1) Oxidising Liquids, Category 1, 2 or 3, or Oxidising Solids, Category 1, 2 or 3	Criteria for categories of oxidizing liquids and solids [4]: Category 1: Any substance or mixture which, in the 1:1 mixture, by mass, of substance (or mixture) and cellulose tested, spontaneously ignites; or the mean pressure rise time of a 1:1 mixture, by mass, of substance and cellulose is less than that of a 1:1 mixture, by mass, of 50% perchloric acid and cellulose. Category 2: Any substance or mixture which, in the 1:1 mixture, by mass, of substance (or mixture) and cellulose tested, exhibits a mean pressure rise time less than or equal to the mean pressure rise time of a 1:1 mixture, by mass, of 40% aqueous sodium chlorate solution and cellulose; and the criteria for Category 1 are not met. Category 3: Any substance or mixture which, in the 1:1 mixture, by mass, of substance (or mixture) and cellulose tested, exhibits a mean pressure rise time less than or equal to the mean pressure rise time of a 1:1 mixture, by mass, of 65% aqueous nitric acid and cellulose; and the criteria for Categories 1 and 2 are not met.	50	200

2.2 The ADR treaty and ammonium nitrate products

The Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR)* is a United Nations (UN) treaty governing transnational transport of hazardous materials [5]. The origin of the treaty stems from an agreement concluded in Geneva in 1957 [5].

According to the ADR treaty, hazardous materials transported by road are categorized using hazard classes. Each entry into one of these classes has been assigned a 4-digit UN number [5]. For AN products, the two hazard classes of relevance are “Class 5.1 Oxidizing Substances” and “Class 9 Miscellaneous dangerous substances and articles” [5].

AN products covered by the ADR treaty and categorized under either Class 5.1 or Class 9 are listed in Table 2.2. In order for an AN product to be included under one of these hazard classes, it must be found too insensitive for acceptance into “Class 1 Explosive substances and articles”, as evaluated by Test Series 2 in the *Manual of Tests and Criteria* [6].†

For the AN products listed in Table 2.2, so-called special provisions, applicable to certain articles or substances in the ADR treaty, are used to define and delimit the physicochemical characteristics of the AN product listed under a specific UN number. The special provisions relevant here are included in full under each AN entry covered by Table 2.2.

One can comprehend from Table 2.2 that the AN products covered by the ADR transport treaty (Class 1 materials being exempted) belong to one of five classes: 1) UN 1942: AN with less than 0.2% combustible substances and too insensitive for acceptance into Class 1; 2) UN 2067: AN based fertilizers too insensitive for acceptance into Class 1 and classified according to specific procedures and criteria listed in Part III, Section 39 of the *Manual of Tests and Criteria*; 3) UN 2071: AN based compound fertilizers classified according to specific procedures and criteria listed in Section 39 of the *Manual of Tests and Criteria* and thereby not subject to the requirements of ADR (but still classified as hazardous materials and assigned a UN number); 4) UN 2426: Hot AN solutions with 80–93% AN and not more than 0.2% combustibles or 0.02% chlorine compound level; 5) UN 3375: AN emulsion/suspension/gel classified according to specific procedures and criteria listed in Section 18 of the *Manual of Tests and Criteria*.

By comparing the AN product classes listed in Table 2.1 (Seveso-III Directive) and Table 2.2 (ADR treaty), many analogies are apparent. Furthermore, as the AN products listed in Table 2.1, when transported, are by necessity linked to one of the AN product entries given in Table 2.2, the listings of the two tables can be coordinated. This coordination can be used as the basis for a simple system for classification of AN products according to thermal decomposition hazards.

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* The word European was removed from the title on 31.12.2020. The abbreviation ADR was originally derived from the French name for the treaty (Accord relatif au transport international des marchandises Dangereuses par Route).

† Test Series 2 therein comprises three types of test: 1) Sensitivity to shock (UN gap test), 2) effect of heating under confinement (Koenen test) and 3) effect of ignition under confinement (time/pressure test) [6]. AN that contains more than 0.2% combustible substances, or that contains not more than 0.2% combustible substances but gives a positive result when tested in accordance with Test Series 2 (see special provision 370), is classified under UN No. 0222 [5].

Table 2.2 Ammonium nitrate (AN) products covered by the ADR treaty.

UN No.	Class	Name and description	Special provisions
1942	5.1	AMMONIUM NITRATE with not more than 0.2 % combustible substances, including any organic substance calculated as carbon, to the exclusion of any other added substance	306: This entry may only be used for substances that are too insensitive for acceptance into Class 1 when tested in accordance with Test Series 2 (see *Manual of Tests and Criteria*, Part I). 611: Ammonium nitrate containing more than 0.2 % combustible substances (including any organic substance calculated as carbon) is not to be accepted for carriage unless it is a constituent of a substance or article of Class 1.
2067	5.1	AMMONIUM NITRATE BASED FERTILIZER	306: This entry may only be used for substances that are too insensitive for acceptance into Class 1 when tested in accordance with Test Series 2 (see *Manual of Tests and Criteria*, Part I). 307: This entry may only be used for ammonium nitrate based fertilizers. They shall be classified in accordance with the procedure as set out in the *Manual of Tests and Criteria*, Part III, Section 39 subject to the restrictions of 2.2.51.2.2, thirteenth and fourteenth indents. When used in the said Section 39, the term "competent authority" means the competent authority of the country of origin. If the country of origin is not a Contracting Party to ADR, the classification and conditions of carriage shall be recognized by the competent authority of the first country Contracting Party to ADR reached by the consignment.
2071	9	AMMONIUM NITRATE BASED FERTILIZER	193: This entry may only be used for ammonium nitrate based compound fertilizers. They shall be classified in accordance with the procedure as set out in the *Manual of Tests and Criteria*, Part III, Section 39. Fertilizers meeting the criteria

			for this UN number are not subject to the requirements of ADR.
2426	5.1	AMMONIUM NITRATE, LIQUID, hot concentrated solution, in a concentration of more than 80 % but not more than 93 %	252: Provided the ammonium nitrate remains in solution under all conditions of carriage, aqueous solutions of ammonium nitrate, with not more than 0.2 % combustible material, in a concentration not exceeding 80 %, are not subject to the requirements of ADR. 644: This substance is admitted for carriage provided that: - The pH is between 5 and 7 measured in an aqueous solution of 10 % of the substance carried; - The solution does not contain more than 0.2 % combustible material or chlorine compounds in quantities such that the chlorine level exceeds 0.02 %.
3375	5.1	AMMONIUM NITRATE EMULSION or SUSPENSION or GEL, intermediate for blasting explosives, liquid AMMONIUM NITRATE EMULSION or SUSPENSION or GEL, intermediate for blasting explosives, solid	309: This entry applies to non sensitized emulsions, suspensions and gels consisting primarily of a mixture of ammonium nitrate and fuel, intended to produce a Type E blasting explosive only after further processing prior to use. The mixture for emulsions typically has the following composition: 60-85 % ammonium nitrate, 5-30 % water, 2-8 % fuel, 0.5-4 % emulsifier agent, 0-10 % soluble flame suppressants, and trace additives. Other inorganic nitrate salts may replace part of the ammonium nitrate. The mixture for suspensions and gels typically has the following composition: 60-85 % ammonium nitrate, 0-5 % sodium or potassium perchlorate, 0-17 % hexamine nitrate or monomethylamine nitrate, 5-30 % water, 2-15 % fuel, 0.5-4 % thickening agent, 0-10 % soluble flame suppressants,

			and trace additives. Other inorganic nitrate salts may replace part of the ammonium nitrate. Substances shall satisfy the criteria for classification as an ammonium nitrate emulsion, suspension or gel, intermediate for blasting explosives (ANE) of Test Series 8 of the *Manual of Tests and Criteria*, Part I, Section 18 and be approved by the competent authority.

2.3 Classification of ammonium nitrate products using a three-tier classification system according to thermal decompositions hazards

The storage of dangerous goods and the transport of dangerous goods are of course interrelated. As such, by listing the various categories of AN products in the Seveso-III Directive (Table 2.1) together with the UN No. used for their transportation, according to the ADR treaty (Table 2.2), we for all intents and purposes obtain six main classes of AN products:

1. **UN 1942 products**: AN technical grades (Point 3) of the Seveso-III Directive, as well as the directive's AN fertilizer grades (Point 2) transported under this UN number.

2. **UN 2067 products**: AN fertilizer grades (Point 2) of the Seveso-III Directive.

3. **UN 2071 products**: AN fertilisers capable of self-sustaining decomposition (Point 1) of the Seveso-III Directive.

4. **UN 2426 products**: These cover the AN liquid solutions that form part of the wider class of AN technical grades (Point 3) of the Seveso-III Directive.

5. **UN 3375 products**: These cover the AN emulsions/suspensions/gels that form part of the wider class of oxidizing liquids/solids of the Seveso-III Directive.

6. Materials belonging to the AN 'off-specs' material and fertilisers not fulfilling the detonation test (Point 4) of the Seveso-III Directive. These that are unfit for transport according to ADR Class 5.1 or Class 9.

In Table 2.3, the AN product classes above have been arranged using a three-tier classification system according to thermal decomposition hazards – the term here includes both non-explosive thermal decomposition and/or explosive thermal decomposition (deflagration and detonation). The system is color-coded: red, orange and yellow according to decreasing hazards.

Table 2.3 Classification of ammonium nitrate (AN) products using a three-tier classification system according to thermal decomposition hazards.[*]

Seveso-III Directive AN products	**ADR treaty UN No.**	**Seveso-III Directive Lower-tier requirements**	**Seveso-III Directive Upper-tier requirements**
Ammonium nitrate technical grade	1942	350 tonnes	2500 tonnes
Ammonium nitrate fertiliser grade	1942	1250 tonnes	5000 tonnes
Ammonium nitrate fertiliser grade containing more than 80% AN	2067	1250 tonnes	5000 tonnes
Ammonium nitrate 'off-specs' material and fertilisers not fulfilling the detonation test	Not applicable	10 tonnes	50 tonnes
Ammonium nitrate technical grade AN liquid solutions	2426	350 tonnes	2500 tonnes
Oxidizing liquids AN emulsions, suspensions and gels	3375	50 tonnes	200 tonnes
Ammonium nitrate fertiliser grade containing less than 80% AN	2067	1250 tonnes	5000 tonnes
Ammonium nitrate fertilisers capable of self-sustaining decomposition	2071	5000 tonnes	10 000 tonnes

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[*] The term includes both non-explosive decomposition and/or explosive decomposition (deflagration and detonation).

The classifications of Table 2.3, including the AN products that are exempted from the system, can be at least partly justified by applying the following guiding principles:

- AN products exempted from all requirements of ADR, including them not being assigned any UN number, are not to be covered by the three-tier classification system of Table 2.3. One important class of such AN products is the mixtures of AN with calcium carbonate (limestone) or calcium magnesium carbonate (dolomite), physical fertilizer blends typically referred to in the trade as calcium ammonium nitrate (CAN).[*] The CAN fertilizer materials normally contain 27% nitrogen, corresponding to about 77% AN. These fertilizers have intentionally been relieved from the requirements of ADR and the Seveso-III Directive.

- AN products not subject to the requirements of ADR, yet classified as hazardous materials and assigned a UN number, are covered by the three-tier classification system of Table 2.3, as the Seveso-III Directive still applies to them (important for the UN 2071 products).

- AN fertilizers capable of self-sustaining decomposition, but incapable of explosive-type decomposition (UN 2071 products and UN 2067 products containing less than 80% AN) should be considered primarily a fire hazard and can be included in the mildest (yellow) category – but only when uncontaminated. Regulations pertaining to this class need to take into account proper fire prevention/control measures, but they need not encompass separation distances of the type relevant for materials with explosive potential.

- Essentially pure AN for either technical or agricultural applications (UN 1942 products) should certainly be included in the most stringent (red) category of Table 2.3, as based on the best available information and records of past accidents. AN products of this class are suitable for a regulatory framework bearing resemblance to those applicable to explosives. While the potential for explosion accidents is closely coupled to the porosity/density of the particular AN material to be evaluated, these characteristics are probably not sufficient to exempt any such AN material from the most stringent category altogether. As an alternative, certain UN 1942 products of high density, such as AN crystalline grades, may be diverted to another category. However, taking the accident history of the last decade into consideration, with prilled AN materials of high density giving disastrous outcomes under fire conditions,[†] all UN 1942 products should most properly be included in the most stringent category.

- AN products belonging to the category of "Ammonium nitrate 'off-specs' material and fertilisers not fulfilling the detonation test" of the Seveso-III Directive are included in the most stringent (red) category, as these products (can) have indeterminate composition.

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[*] Not to be confused with the double salt $5Ca(NO_3)_2 \cdot NH_4NO_3 \cdot 10H_2O$ of the same name (also used in fertilizers). Ideally, the name calcium ammonium nitrate should have been reserved for this double salt to avoid any confusion.

[†] This is a reference to the West Fertilizer Company explosion on 17 April 2013, involving 40–60 tons fertilizer grade AN (of which about 30 tons detonated), and the even more terrible Beirut explosion disaster on 4 August 2020, where 2750 tons of deteriorated high-density AN prills was involved (where 50% or more may have detonated) [7-9]. These two events, spanning nearly two orders of magnitude in size, gave high explosive yields in spite of AN materials with high density. The material involved in Beirut is often incorrectly described as low-density, porous AN. News reports strongly indicate that the AN was high-density prills of the type used for preparation of emulsion explosives.

- AN fertilizers of high AN percentage (UN 2067 products) cover materials spanning a wide range of hazard levels. Some have here been categorized in the mildest (yellow) category, being incapable of explosive-type decomposition, while others have been categorized in the most stringent (red) category. As such, these AN products are difficult to delimit within the simple three-tier framework of Table 2.3. UN 2067 products cover high-AN fertilizers with more than 90% AN, subject to the restrictions of not containing incompatible materials and less than either 0.2% combustibles or 5% ammonium sulfate, but they also cover fertilizers with somewhat less AN [6]. Incorporating all nuances, set out in Part III, Section 39 of the *Manual of Tests and Criteria*, within a simplified three-tier system, is certainly demanding. With this in mind, a convenient limiting criterion, splitting the UN 2067 products into two classes, is possible by applying Regulation (EC) No 2003/2003 [10]. In Chapter IV of this EU regulation relating to fertilizers, "Ammonium nitrate fertilisers of high nitrogen content" are defined as "ammonium nitrate based products manufactured for use as fertilisers and containing more than 28 % by mass of nitrogen in relation to ammonium nitrate" [10]. These products must undergo a test of resistance to detonation. The UN 2067 product class may thus be split into two, with the percentage of 80% AN, corresponding to 28% by mass of nitrogen in relation to AN, as the limiting criterion. AN products containing more than 80% AN properly belong to the most stringent category, while AN products with less than 80% AN can be assigned to the mildest category.[*]

- AN fluid products, including AN liquid solutions (UN 2426 products) and AN emulsions or suspensions or gels (UN 3375 products) have been categorized in the intermediate (orange) category of Table 2.3. The hazards of AN products typically diminish with water content, generally making the hazard evaluations of these more specialized AN products come out more favorably than those for the AN products belonging to the most stringent category. Waterless AN products generally need to be regulated more strictly than aqueous products, everything else kept equal or similar. This topic will be treated in detail in Section 3.8.

The justifications above are based on scientific principles and records of past AN accidents. They are necessarily still subject to discussion. AN products can be moved between categories if new information is uncovered, indicating a different hazard profile from the one herein. The categorization of Table 2.3 is a baseline classification based on the best available information. The fundamental principle applying for hazard evaluation of all AN products should be the now well-confirmed empirical fact that all materials of high AN content may show unpredictable – possibly explosive – behavior when exposed to fire conditions or other adverse event types (heating under confinement, chemical contamination, projectile impact, etc.).

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[*] It is important to point out that a test of resistance to detonation does not exempt the AN product to be evaluated from all hazards coupled to explosive decomposition, as AN materials are severely affected by heat maltreatments, such as those encountered during fire conditions or as a result of inadequate storage over time. As a crucial factor, AN easily melts when heated (m.p. 170 °C), and molten AN is considerably more sensitive than solid AN [1].

3 Separation distances between facilities holding ammonium nitrate products and protected places

Certain AN products should most definitely be treated as potentially high-explosive materials and not merely as oxidizing substances. They should therefore be subject to regulations treating the materials properly as such. Many AN products, on the other hand, pose a fire hazard but no probable explosion hazard. The subject of the present chapter is the development of a type of scientific framework suitable for evaluation of separation distances between facilities holding AN products and protected places – technical groundwork for government regulations.

3.1 How are the explosion hazards of ammonium nitrate to be assessed?

Both the fertilizer industry and the civil explosives industry are global in reach. Together they produce millions of tonnes of AN products each year. Companies making up these industries are mostly private entities operated under competitive market conditions, and these must assess the explosion hazards associated with AN. What type of assessments undergird their guidelines? Industry guidelines can be complementary to regulations imposed by government agencies.

Perhaps the most widely recognized guidelines in the AN industry is the information brochure "Good Practice Guide: Storage of Solid Technical Grade Ammonium Nitrate", prepared by the International Industry Working Group on Ammonium Nitrate, an entity organized under the umbrella of the Swiss-based learning organization SAFEX International [11].

The SAFEX guide for technical grade AN was "developed by the global manufacturers of ammonium nitrate to provide guidelines for the storage of Technical Grade Ammonium Nitrate (TGAN) at manufacturing, distributors' and end-user sites" [11].[*] In it, separation distances for AN storage sites are evaluated by determining a net explosives quantity (NEQ) of the TGAN mass under consideration, using the concept of TNT equivalency (treated in Section 3.2) [11].

The NEQ is calculated by multiplying the total mass of TGAN under consideration with an "overall TNT equivalence", a factor that is made by combining a "chemical TNT equivalence" with an "explosive yield" [11]. The chemical TNT equivalence is a ratio based on the relative heat of combustion of TGAN compared to TNT, and it is estimated at 32% [11]. The explosive yield (or efficiency) is an estimate of the TGAN mass that is consumed in the detonation event, or the proportion of the TGAN mass that directly contributes to the explosion or blast effect.

While the chemical TNT equivalence is a factor of certain concreteness, the explosive yield is, by necessity, a rather indefinite element, affected by the physical characteristics of the TGAN, the degree of confinement of the material and the mode of initiation. The latter is defined by event types – chemical contamination, fire or high velocity projectiles [11].

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[*] The SAFEX guidelines do not cover fertilizer grade AN (UN 2067), AN grades that fall under UN 1942 and with a density greater than 0.90 g/cc, AN belonging to Class 1 materials or AN solutions/emulsions/suspensions/gels [11].

When evaluated by event type, the explosive yield by detonation from chemical contamination is estimated to 10–50%. The yield from detonation by fire is estimated to “Low – around 10%”, and that from detonation by high velocity projectiles is rated as “High – close to 100%” [11].[*] The explosive yields are to be multiplied with the chemical TNT equivalence (32%) to give the overall TNT equivalencies. The recommended values for such overall TNT equivalencies are 16% (chemical contamination), 5% (fire) and 32% (high velocity projectiles) [11].

From a scientific point of view, the framework provided by the SAFEX guidelines for TGAN storage has some obvious shortcomings. To begin with, using the ratio of heat of combustions, here for TGAN and TNT respectively, for approximation of the chemical TNT equivalence is problematic, because this value is not directly linked to the ratio of the blast overpressures produced by the two compounds. Secondly, the vague concept of explosive yield raises a number of difficulties. The explosive yield under fire conditions also seems rather low.

The location and layout of AN storage facilities are usually approached by using risk-based assessments. While a hazard is a possible cause of harm, a risk is the likelihood that a hazard will cause harm. In the context of AN storage, a Quantitative Risk Assessment (QRA) is used to quantify the likelihood and related possible consequences of an incident associated with the AN, as typically mandated by the relevant regulatory authority of each country.

In light of the AN explosion disasters of the last decade, there is definitely a need for improved scientific frameworks for evaluation of the explosion hazards of AN. The requirement is much strengthened by taking into account that several of the recent explosion accidents have involved AN grades of high density, as mentioned previously in this report. Due to the huge quantities of AN being kept at many AN storage sites and the dreadful consequences of AN bulk explosions, when combined with the rather inexact and ambiguous nature of the calculation of probabilities, an improved hazard-based framework applicable to AN products should be developed.[†]

In the immediately succeeding sections, a scientific framework useful for the hazard assessment of detonating AN will be presented. Combination of thermochemical calculations and advanced gas dynamic simulations will allow for extraction of the detonative properties of AN directly, bypassing the need for estimation of any TNT equivalencies and NEQ values coupled to TNT. Importantly, this will be done in the context of the actual blast effect most relevant for regulations of this type, namely the blast overpressures generated by a detonative event.

The procedure outlined above removes virtually all ambiguity associated with the calculation of a chemical TNT equivalence of the type used in the SAFEX guidelines. The explosive yield or efficiency, an estimate of the proportion of the AN mass consumed in the detonation, can be maintained in order to attenuate the tabulated distances for blast overpressure thresholds. It will be argued that any such attenuation should be based firmly on empirical data.

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[*] For porous TGAN of high density, the maximum explosive yield is estimated to 30% [11].

[†] Storage of AN is associated with hazards other than deflagration/detonation, and among these, the most important one is perhaps the release of toxic gases upon heating, such as nitric acid fumes, ammonia and nitrogen oxides (NO_X). This hazard is usually considered less consequential than the explosion hazard and will not be treated herein.

3.2 Modeling of ammonium nitrate detonative output through combination of thermochemical calculations and gas dynamic simulations

TNT has for long been the baseline material of choice for comparison of explosive materials. Extensive records of TNT blast effects have been compiled over the years, the result of decades worth of experimental testing on the scales from grams and kilograms to hundreds of tonnes.

Particularly influential have been the Kingery-Bulmash data, a set of air blast data from four TNT surface burst tests – conducted as part of the The Technical Cooperation Program (TTCP) between Canada, the United Kingdom and the USA – that were carried out during 1959–1964. These four multi-ton tests comprised 5, 20, 100 and 500 short ton TNT, respectively [12].*

Researchers from Canada, the United Kingdom and the USA recorded air blast parameters (peak overpressure, arrival time, positive duration and impulse) during the four explosion tests. Data was compiled in a 1966 report by Kingery [12]. These data were later extended in a 1984 report by Kingery and Bulmash [13]. Much TNT data has also been compiled by others.

In spite of all the comprehensive air blast data compiled for TNT, its usefulness for evaluation of AN air blast parameters is limited due to the dissimilar chemical properties of TNT and AN. While TNT is a clearly oxygen-deficient explosive, giving rise to considerable post-detonation combustion in free air, AN is an explosive material containing a substantial surplus of oxygen.

Air blast parameters resulting from the detonation of explosive materials other than TNT are habitually derived by applying the concept of TNT equivalency. However, TNT equivalency is a thorny notion because, in its broadest outlines, it encompasses three quite different aspects: 1) a convention for expressing energy (defined by convention to 4.184 GJ per metric ton TNT); 2) a relative measure for air blast phenomena; 3) a relative effectiveness factor for explosives.

The only aspect of TNT equivalency relevant for the work herein is the second aspect above. However, a number of problems arise because it is regularly confounded with the third aspect. Regarding that third aspect, it is often a rather ambiguous notion that typically designates the amount of pure TNT that somehow has the same “demolition power” as the mass unit of the considered explosive, a sort of equivalent weight factor. The concept is relatively imprecise. Various kinds of relative effectiveness factors are used as a sort of conversion factor between TNT and other explosive materials – under a range of dissimilar circumstances.

Unlike the third aspect just discussed, the second aspect of TNT equivalency can be precisely delineated. It is the amount of TNT – in pure form and shaped as a hemisphere – that during detonation, on the ground level and at a precise distance, yields the same blast overpressure or blast impulse as the mass unit of the considered explosive. It encompasses air blast parameters appropriate for the evaluation of separation distances for storage of explosive materials.

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[*] The fourth and final test, known as Operation Snowball, involved 500 short ton TNT, in the form of thousands of TNT blocks stacked into the shape of a hemisphere. The charge was detonated at the Suffield Experimental Station in Alberta, Canada, on 17 July 1964.

To avoid the uncertainties associated with the concept of TNT equivalency and determine the detonative output of AN with the greatest accuracy possible, the derivation of AN air blast overpressures reported herein has been founded on a purely theoretical model based on the combination of thermochemical calculations and gas dynamic simulations. A summary of the theoretical groundwork is provided below. Concrete results will follow in the next sections.

In a detonation, a detonation wave (shock wave) propagates through the explosive material, converting it to (mostly) gaseous reaction species and releasing the material's chemical energy. The combustion gases left behind by the detonation wave are at much higher pressures than the surrounding air. As these expand, a blast wave is driven through the air. Personal injuries and/or material damages may result from the overpressures or impulses generated by this blast wave.

Direct estimates of blast overpressures at different (scaled) distances can be obtained with the aid of computational fluid dynamics (CFD) software. These computer programs are capable of simulating how the high-pressure gases, following a detonation, expand into the surrounding air, making parameters such as gas pressures, densities, velocities and temperatures available – for any location that may be needed, and at any given point in time (as limited by the simulation). These are derived by solving the compressible Navier-Stokes partial differential equations, equations that describe the movement of mass, momentum and energy in a fluid (gas/liquid).

Gas dynamic simulations of detonation processes necessitate proper treatment of the physical characteristics of all gases involved, including detonation gases at exceptionally high pressures. Important gas state variables – pressure, density and temperature – are interrelated through the so-called equation of state (EOS). While surrounding ambient air can be modelled simply as an ideal gas (a gas with no attractive interactions between the gas molecules), the EOS for the detonation gases must be obtained with the aid of thermochemical calculations.

Thermochemical computer codes can predict detonation and combustion performances of energetic materials such as AN. Calculation of detonation parameters is based on the chemical equilibrium steady-state model of detonation [14]. By using the commercial computer code EXPLO5 (Version 6.06) [14], the EOS for AN detonation gases, as well as the conditions at the detonation wave front – at the Chapman-Jouguet (CJ) state – have been determined. The software applies a Jones-Wilkins-Lee (JWL) model for the EOS of the AN detonation gases.

The baseline used for the evaluation of AN detonation herein, via the gas dynamic simulations, has been an ideal detonation of a spherical charge of AN in air, without any kind of obstruction. In this configuration, the blast wave is allowed to expand outwards indefinitely, and calculated blast overpressures and blast impulses can be obtained at the distances required.

Blast overpressures resulting from detonation of a 1-kilogram spherical charge of AN have been computed with modified CFD software. CFD simulations necessitate the setting of appropriate initial conditions, and the simulation was started at the instant when the entire AN charge had been converted to gas. The conditions of the gas at this stage were specified by means of the calculated CJ conditions, using the method reported by Kuhl, where it is assumed that the detonation is initiated at the charge center (calculations are spherically symmetric) [15].

3.3 Fundamental table of separation distances for storage facilities holding the most hazardous ammonium nitrate products

By applying the theoretical model detailed in the previous section, combining the attributes of a thermochemical computer code with a gas dynamic simulation, we can establish the appropriate separation distances, for blast overpressure thresholds, for almost any AN product of interest.

The most important TGAN type, porous prilled AN, typically has a density of about 0.80 g/cc.* By using the EXPLO5 (Version 6.06) computer code on 100% AN of this density, employing the Exp-6 EOS, JWL coefficients were derived via the detonation products expansion isentrope, freezing the chemical equilibrium at a temperature of 1800 K (data given in Appendix A) [14].

Overpressures resulting from detonation of a 1-kg spherical charge of the AN type above were extracted from a simulation completed using a modified version of the CFD software "Charles", developed by Cascade Technologies [16]. The CFD software was modified to accommodate simulation of multicomponent gas dynamics. Separation distances were established based on the largest distance where defined overpressure thresholds were reached. These were determined for the 1-kg charge and scaled up to larger charge sizes through the scaled distance commonly used in blast characterization (see Section 3.4 for scaling of blast effects and scaled distance).

The results of the modeling detailed above will be referred to here as the fundamental table of separation distances. This key table, with distances for AN air blast overpressure thresholds, is given in Table 3.1. An attentive reader may note that these separation distances are very similar to the recommended minimum separation distances for AN stores in the "Safe storage of solid ammonium nitrate – code of practice" of the Government of Western Australia [17].

As Australia is an important market for TGAN, the similarity of the values of Table 3.1 and those of Table 4.1 of the Australian code of practice merits a few comments. In a note attached to the table with the Australian separation distances, it is specified that these were calculated via a regular TNT framework, where the "AN is taken to have a TNT equivalence of 25%" [17].

How are the values presented in Table 3.1, based on the theoretical model detailed previously, to be understood when evaluated from the perspective of a standardized TNT-type framework? Figure 3.1 shows blast overpressures versus scaled distance for AN (with density 0.80 g/cc) and for TNT. The curve for AN is based on the theoretical model above, whereas that for TNT has been prepared from the Swisdak polynomials derived from the Kingery-Bulmash data [18].

In Figure 3.2, a curve showing overpressure TNT equivalents versus scaled distance for AN has been prepared by comparing the values obtained from the theoretical model above with the Swisdak polynomials for TNT (the slight discontinuity is due to non-overlapping polynomials).

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* In addition to AN with density 0.80 g/cc, a completely analogous modeling to the one described in this section has been carried out for AN with density 0.95 g/cc (more typical for AN fertilizer grades), by applying the same settings. Distances for blast overpressure thresholds are then exceedingly similar to the ones given in Table 3.1, deviating from them with only a few percent. As such, Table 3.1 will suffice to cover all the most hazardous AN products relevant.

Table 3.1 Distances for blast overpressure thresholds by detonation of ammonium nitrate, 100% AN of density 0.80 g/cc and distances rounded to the nearest tens of meter. Note: The AN product quantities in the table below correspond to the ones in the largest product stack or pile that fulfills the requirements of inter-stack separation as established and prescribed here in Chapter 4. It is not the total quantity stored.

Quantity of AN [metric tonnes]	**Distances for AN air blast overpressure thresholds [m]**					
	2 kPa	**5 kPa**	**7 kPa**	**14 kPa**	**21 kPa**	**40 kPa**
1	290	140	110	60	50	30
2	360	180	140	80	60	40
5	490	240	180	110	80	60
10	620	300	230	140	110	70
15	710	340	260	160	120	80
20	780	380	290	180	130	90
25	840	410	310	190	140	100
30	900	430	330	200	150	100
40	990	480	370	220	170	110
50	1060	510	400	240	180	120
75	1220	590	450	270	210	140
100	1340	640	500	300	230	150
125	1440	700	540	320	250	160
150	1540	740	570	350	260	180
175	1620	780	600	360	280	180
200	1690	810	630	380	290	190
250	1820	880	680	410	310	210
300	1940	930	720	440	330	220
350	2040	980	760	460	350	230
400	2130	1020	790	480	360	240
450	2220	1060	820	500	380	250
500	2290	1100	850	520	390	260
750	2630	1260	980	590	450	300
1000	2890	1390	1080	650	490	330
1250	3110	1500	1160	700	530	360
1500	3310	1590	1230	740	570	380
2000	3640	1750	1360	820	620	420
2500	3920	1890	1460	880	670	450

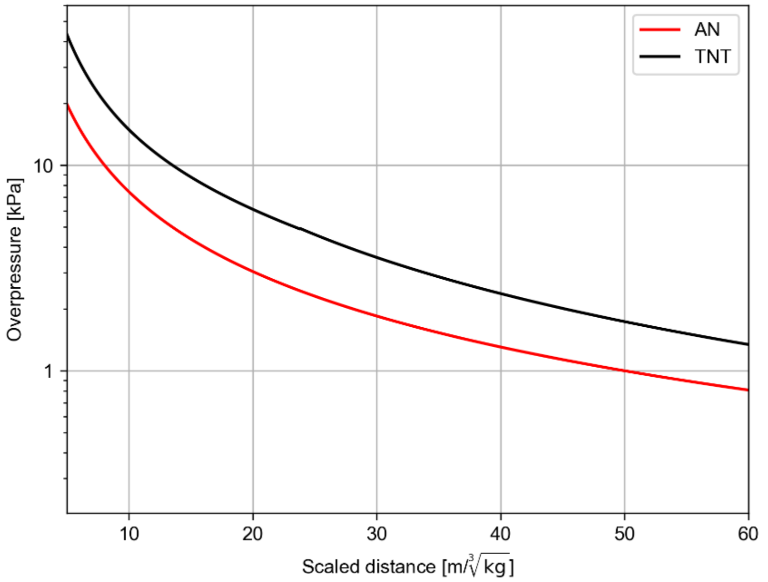

Figure 3.1 Blast overpressure versus scaled distance for AN, based on the theoretical model detailed in Section 3.2/3.3, and for TNT, based on the simplified polynomials derived by Swisdak in 1994 (from the 1984 Kingery-Bulmash data) [18]. Notice the logarithmic scale for the blast overpressure values.

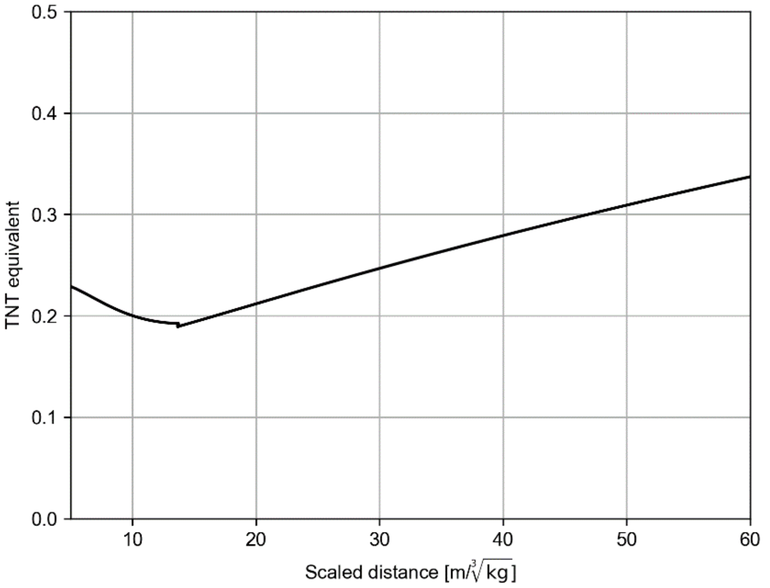

Figure 3.2 Overpressure TNT equivalent versus scaled distance for AN. The curve has been prepared by comparing values from the theoretical model herein with the Swisdak polynomials (the slight discontinuity is due to non-overlapping polynomials).

From Figure 3.2, it is apparent that the overpressure TNT equivalents for AN at different scaled distances are non-constant, and that they have a non-linear relationship. The overpressure TNT equivalents vary within the approximate range of 0.20 to 0.33 at scaled distances up to about 60. These values seem to justify the application of a simplified TNT framework for AN where the TNT equivalency is set to ca. 25%, as exemplified by the Australian code of practice [17].

A roughly linear relationship at greater scaled distances, with the overpressure TNT equivalents increasing slightly, is manifest from Figure 3.2. When comparing a theoretical model, derived from simulations, with figures obtained from experimental explosives testing, such as the Kingery-Bulmash/Swisdak data, an increasing overpressure TNT equivalent at greater scaled distances is to be expected due to various energy loss factors affecting experiments, such as wind conditions, temperature gradients, air moisture content and ground surface roughness.

3.4 The cube root scaling law for blast effects: Separation distances and their relation to explosives quantity and explosive yield

Many theoretical and experimental studies, when taken together with empirical data from an extensive record of past accidental explosions, have shown that the destructive potential of unconfined explosives follows an elementary scaling law with a reasonable degree of accuracy. A central historical figure in the field, Melvin Alonzo Cook (1911–2000), the inventor of the water-gel slurry explosives, has referred to this simple law as the “law of similitudes” [19].

The cube root scaling law for blast effects states that the range of effectiveness of any particular characteristic of an explosion will vary as the cube root or one-third power of the energy or potential of the explosive [19]. In more precise terms, a variant of the cube root scaling law states that the ratio of either the blast overpressures or the blast impulses resulting from two explosions will scale according to the cube root or one-third power of the ratio of the total explosives quantities involved in the two explosions (see Table 3.2 for detailed equation).[*]

The scaling law was discovered by the British professor Bertram Hopkinson (1874–1918) in 1915. It was independently discovered by the German physicist Carl Julius Cranz (1858–1945) in 1925. The law is therefore often referred to as the Hopkinson law or Hopkinson-Cranz law. Changes in atmospheric conditions (e.g. altitude) can be corrected through Sachs scaling law, developed in 1944 by American physicist Robert Green Sachs (1916–1999) [20].

The quantity-distance scaling law is an underpinning widely used in the recommendations of building and magazine spacings in regulations applying to storage of explosive materials. Yet, <u>the implications of the scaling law can be counterintuitive</u>. For example, if the storage limit for explosives kept in a magazine, in terms of mass, is halved, the separation distance applying to the magazine will be reduced by only 20% (as one divided by the cube root of two is ~0.80).

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[*] Certain restrictions must be taken into consideration when applying the law. The cube root scaling law should only be applied if the explosions are air blasts at the same height and in the same atmosphere. The charges must also have similar shapes and consist of the same type of explosive material.

Table 3.2 The cube root scaling law for blast effects ("law of similitudes").

<table>
<tr><td colspan="4">$$\frac{D_2}{D_1} = \frac{I_2}{I_1} = \left(\frac{Q_2}{Q_1}\right)^{1/3}$$</td></tr>
<tr><td>D_1</td><td>Distance for blast overpressure of magnitude P when explosive quantity Q_1 is detonated.</td><td>I_1</td><td>Blast impulse at distance D_1 when explosive quantity Q_1 is detonated.</td></tr>
<tr><td>D_2</td><td>Distance for blast overpressure of magnitude P when explosive quantity Q_2 is detonated.</td><td>I_2</td><td>Blast impulse at distance D_2 when explosive quantity Q_2 is detonated.</td></tr>
<tr><td colspan="4">Note: The scaling law above applies strictly to <i>comparisons of the same type of explosive</i>. Comparisons of dissimilar explosives necessitate introduction of a constant. Setting D_1 and Q_1 above to unity and introducing an explosive-specific constant, we can derive: $\boldsymbol{D = k \cdot Q^{1/3}}$
The constant k will vary according to magnitude of overpressure and type of explosive material (see footnote in Section 3.5). Such equations are well known from explosives regulations.</td></tr>
</table>

Moreover, in order for the blast overpressure/impulse at a given distance to be doubled, the amount of explosives would need to be increased eight times (as the cube root of eight is two), that is, nearly an order of magnitude. Therefore, increasing the quantity of explosive material gives, when expressed a bit casually, "less effect" than that which is perhaps grasped intuitively. Conversely, small charge sizes give "more effect" than maybe alleged instinctively.

Cast in terms of separation distances, including those that can apply to storage of AN products, the cube root scaling law implies that any attenuation in charge size, for example a reduction due to low explosive yield (the proportion of the explosive material consumed by detonation), can actually be of less consequence than suspected. In order to make comparisons independent of charge sizes (as in Figure 3.1 and 3.2), the so-called scaled distance is usually introduced, whereby the distance has been divided by the cube root of the charge size.[*]

The values presented in the fundamental table of separation distances for AN (Table 3.1), with its distances for blast overpressure thresholds, can be corrected for explosive yield/efficiency by application of the cube root scaling law of Table 3.2 above. For convenience, some possible values for such attenuation by explosive yield/efficiency (corresponding to explosive yields of 75%, 50%, 30%, 25%, 20%, 15%, 10% and 5%) are given in Table B.1 to B.8 of Appendix B.

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[*] The theoretical model in Section 3.2/3.3 is based on the perfect detonation of a 1-kg spherical charge of pure AN. With this convenient basis, the separation distances for the larger charge sizes were obtained by simple multiplication of the distances for the 1-kg charge by the cube root of the weight of the larger charges. Due to symmetry, detonation of a hemispherical charge (at center), as in large-scale testing, is equivalent to detonation of a spherical charge in air.

3.5 Blast overpressures and damage effects

Before continuing to the specific recommendations for storage facilities holding each category of AN products, it may be useful to briefly review the context of blast overpressures and the resulting damage effects to material structures, as well as the potential injuries to persons.

Table 3.3 lists some damage effects connected with specified levels of blast wave overpressure, as extracted from a standard reference work [21]. According to a damage classification listed in the same work, stemming from 1970, a damage level category of "total destruction" is specified at a peak side-on overpressure of >83 kPa. According to that scheme, a damage level category of "severe damage" is coupled to >35 kPa, "moderate damage" to >17 kPa and "light damage" to <3.5 kPa [21]. Other listings are available, but they will not add materially to the discussion.

Table 3.3 Some damage effects associated with specified levels of blast wave overpressure, taken from a well-regarded reference work on loss prevention [21].

Damage effect on structures	**Peak side-on overpressure [kPa]**
Typical pressure for glass failure [a)]	1.0
Limited minor structural damage	2.8
Minor damage to house structures	4.8
Partial demolition of houses (made uninhabitable)	6.9
Partial collapse of walls and roofs of houses	13.8
Lower limit of serious structural damage	15.9
50% destruction of brickwork of house	17.3
Cladding of light industrial buildings ruptured	27.6
Wooden utilities poles (telegraph, etc.) snapped	34.5
Loaded train wagons overturned	48.3
Loaded train box cars completely demolished	62.1
Probable total destruction of buildings	69.0

[a)] May vary considerably. For instance, in some guidelines 1.0 kPa specifies the minimum overpressure level for glass failure.

Some elementary "rules of thumb" can be extracted from listings such as those in Table 3.3. Approximately 1 kPa overpressure can suffice for glass breakage, and overpressure levels up to 2–3 kPa causes only light damage effects – broken windows, light cracks in walls and damage to wall panels and roofs. The level of about 15 kPa and above signifies a transition to moderate damage effects, causing partial collapse of walls and roofs of houses. Structures damaged by these overpressures may still be usable, but structural repairs are required. Overpressure levels of around 35 kPa and above indicate a gradual transition to severe damage effects with partial collapse and/or failure of structural members. At levels of 50–100 kPa blast wave overpressure, total destruction of buildings, with damage beyond economical repair, is to be expected [21].

Overpressure loads and their bearing on human injuries are complicated and beyond the scope of the present text. Extended treatments of the subject are available in reference works [21,22]. Although a detailed treatment of the topic is not mandated here, it should be noted that typical explosion injuries to persons in the open – eardrum rupture, lung hemorrhage and whole body displacement injury – normally occurs at overpressures similar to, or exceeding, those where persons indoors will be injured primarily as the result of material structural damages [21].[*]

In regulations applying to explosives, overpressure threshold levels are linked to categories of protected places. For the purpose of illustration, categories of protected places and associated threshold values applying to storage of high-explosives in Norway (NOR) are listed in Table 3.4 together with those that apply for storage of AN in Australia (AUS). Permitted thresholds limits for various kinds of buildings and infrastructure will of course vary from country to country.

Table 3.4 Categories of protected places and overpressure threshold values as they apply for storage of high-explosive materials in Norway and for AN in Australia [17,23].[†]

Category of protected places	Overpressure threshold [kPa]
NOR: Hospitals, schools, kindergartens, apartment blocks and community centers.	2
NOR: Residential buildings. AUS: Vulnerable facilities and critical infrastructure.	5
AUS: Residential buildings including hotels, motels and other accommodation places.	7
NOR: Public roads, harbor areas and railways.	9
AUS: Commercial developments including retail centers, offices and entertainment centers.	14
AUS: Industrial buildings.	21

In sections to follow, the scientific framework outlined previously in this chapter will be used, in combination with the brief summary of blast overpressures and damage effects sketched here, to provide specific recommendations for storage facilities holding critical AN products. Any effects due to release of toxic gases, from decomposing AN products, will not be included.

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[*] Injuries by fragments, burns, asphyxiation and exposure to toxic agents are also possible, but is not treated herein.

[†] Using the equation $D = k \cdot Q^{1/3}$ (see Table 3.2), the constant k for TNT will be linked to overpressures as follows: 55.5 = 1.5 kPa, 44.4 = 2 kPa, 33.3 = 3 kPa, 22.2 = 5 kPa, 17.8 = 7 kPa, 14.8 = 9 kPa, 10.4 = 14 kPa, 9.6 = 16 kPa, 8.0 = 21 kPa, 7.2 = 24 kPa, 3.6 = 70 kPa and 2.4 = 180 kPa. Minor variation in the numbers, due to rounding, may occur. The coefficients above apply when D is the separation distance in meter and Q is the explosives quantity in kilogram.

3.6 Recommendations for storage facilities holding ammonium nitrate products belonging to the most stringent (red) category

Chapter 2 of the present text was dedicated to the classification of AN products according to thermal decomposition hazards by harmonization of how these AN products are categorized according to the Seveso-III Directive and the ADR transport treaty. The end result of that chapter was a simplified three-tier (red, orange, yellow) classification system (Table 2.3).

The objective of introducing such a simplified classification system is the realignment of government regulations, pertaining to AN products, from a complicated and almost infinitely bendable risk-based system, into a more unambiguous hazard-based framework (Section 3.1). This section will address recommendations relevant for the most hazardous AN products.

For AN products belonging to the most stringent (red) category of Table 2.3, the simplest approach to a regulatory framework is the application of the separation distances of Table 3.1, for all products concerned. An alternative, allowing for some degree of attenuation by yield, is to apply one of the tables of Appendix B. Given the grueling experiences of the last decade, Table B.2 (50% explosive yield) is almost surely the least stringent one acceptable [7-9].

Should separation distances for storage facilities holding the most hazardous AN products incorporate attenuation by explosive yield? If incorporated, the guiding principle of any such lessening by explosive yield must be empirical facts gained through the hard-earned experiences of accidental AN explosions, and any attenuation should be conservative. Given that explosive yields in recent AN accidents have been estimated at up to as high as 50% and beyond [7-9], a reasonable compromise will be to apply Table B.1 (75% explosive yield).

A difficult issue concerning storage of materials with explosive potential is determination of minimum threshold quantities. As this is partly a question of compromise and reasonableness, some empiricism can be illustrative. In the Australian code of practice mentioned previously, the following is stated [17]: “Stores of AN of 10 t or less should be separated from the site boundary and on-site protected works by a minimum distance of 5 m. The separation distance should be at least 15 m for off-site protected works, and 50 m for vulnerable facilities.”

From the purely scientific point of view, it is evident from Table 3.1 that detonation of AN, also in the quantity range of 1 to 10 tonnes, will call for non-trivial separation distances if due considerations to safety is taken into account. However, given that accidental explosion of AN almost exclusively occurs as the result of fire conditions, a scenario that usually unfolds over a certain period of time, possibly consuming a considerable amount of the AN material involved, lowered separation distances may be allowable for smaller quantities.

An important factor when discussing detonation of AN materials is the notion of what is called critical diameter, that is, the smallest cross-sectional area of explosive material that can sustain a steady detonation process. For pure AN, the critical diameter can actually be on the scale of tens of centimeters and upward, depending on material characteristics such as porosity, density, etc.

Yet, explosive events that involve AN products typically comprise some type of fire scenario, and detonation can here be the end result of an escalating decomposition process that may also involve violent deflagration, a potentially explosive event that by itself can lead to significant material destruction and human injuries. Moreover, molten AN has entirely different explosive characteristics and sensitivity than solid AN [1]. In summary, it is actually very difficult to use critical diameter as a qualifying criterion in the discussion of minimum threshold quantities.[*]

We here suggest, for the most hazardous AN products, in amounts less than 10 tonnes, to use the distances in Table B.4 of Appendix B (25% explosive yield), applying to off-site structures and with numbers rounded off slightly. We find 25% yield reasonable, given a fire scenario that consumes a significant proportion of the AN material prior to any detonative event and the large critical diameter of these materials, making it difficult to set up and uphold a detonation process in small quantities. Table B.9 of Appendix B is thus our recommended overall distance table.

3.7 Recommendations for storage facilities holding ammonium nitrate products belonging to the mildest (yellow) category

AN products belonging to the mildest category is made up of AN fertilizer products containing moderating additives, providing a decisive lessening of hazard because the potential for violent deflagration or detonation is all but removed, both when uncorrupted and when contaminated. As such, they pose no probable explosion hazard. Chemical contamination of these materials may indeed intensify progression of any thermal decomposition, but examples of development into any truly explosive- or detonative-type events are not known by the authors.

However, these products do have the potential for self-sustaining, exothermic decomposition under some storage conditions – depending on mass, packaging, etc. They therefore present a potential fire hazard that need to be taken into consideration. Storage facilities holding these types of products should have a fire-break distance of at least 10 meter to any nearby buildings, thereby preventing any thermal decomposition of these AN materials from spreading further.[†]

AN products covered by the Seveso-III Directive necessitate safeguarding of the surroundings, and coming in addition to the fire-break distance is supplementary separation distance required due to any likely release of toxic chemical species, ensuing from thermal decomposition of AN. Also the AN products belonging to this category can and will release toxic gases upon heating, with this including nitrogen oxides (NO_x). However, hazard assessments of such gaseous releases will not be incorporated into the scientific framework outlined in this report.

Since the AN products of this category are to be considered primarily a fire hazard, and not an explosion hazard, no tables of separation distances are provided. However, like all AN products, also these AN products should be protected from chemical contaminations.

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[*] Projection hazards, due to fragments thrown out by deflagrating/detonating AN, are yet another decisive factor that complicates any hazard evaluation of AN products. However, it is a factor that is notoriously difficult to quantify.

[†] Fire-break distances in almost all regulations and practice codes seem to be either 5 or 10 meter.

3.8 Recommendations for storage facilities holding ammonium nitrate products belonging to the intermediate (orange) category

Of all the AN products dealt with in Chapter 2, those belonging to the intermediate (orange) category almost certainly present the most difficult ones with respect to separation distances, both from the scientific and regulatory points of view. As set out previously in Table 2.3, the intermediate category of AN products is made up of AN fluid products, a term here denoting (aqueous) AN liquid solutions (ANSOLs), AN emulsions (ANEs) and AN suspensions/gels.[*]

Common to all AN fluid products is the extreme difficulty of propagating any detonation event in them when non-sensitized. They present little or no explosion hazard in unaffected condition. Yet, heat maltreatments, as encountered in fire scenarios, can induce reactions and evaporate water, possibly forming sensitized compositions with capability for explosive decomposition. Conversely, these AN fluid products are customarily kept in storage tanks (commonly metal), and are therefore more protected in case of fire events than most bagged AN products.

An additional element complicating the hazard evaluation of two types of AN fluid products, comprising the AN emulsions and AN suspensions/gels, is their content of fuel components, improving the oxygen balance of these compositions relative to pure AN or to AN solutions, possibly also heightening their chemical reactivity and lowering decomposition temperatures.

There are essentially two approaches to hazard evaluation of the AN fluid products mentioned. The first one consists in treating these compositions as fundamentally non-explosive, imposing only a fire-break separation distance for their storage (some 5–10 meter). The second approach is to treat them essentially as regular explosive materials, imposing separation distances that reflect their full (that is, theoretic) explosive potential. Both of these approaches, representing the ends of a spectrum of explosibility, can form entry points to a regulatory framework.

The Health and Safety Executive (HSE), a government agency of the United Kingdom (UK), has issued guidance for manufacture and storage of ammonium nitrate blasting intermediate (ANBI) [24]. The guidelines in that publication treat ANBIs as if they were regular explosives, and the separation distances to protected places for ANBI given Table 1 in Appendix 2 therein, exemplified here for those belonging to Category 3 of protected place (vulnerable population), are quite similar to those in the 7 kPa threshold range for 100% AN in Table 3.1 above [24].[†]

In the HSE guidelines, ANBIs are mostly, but not consistently, treated as regular explosives. The separation distance applying to Category 1 of protected place, used for industrial units and certain other places that can be evacuated within 45 minutes of a fire starting on an ANBI site, is actually zero meter for ANBI quantities up to 100 tonnes (a sizable quantity) [24].

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[*] As set out in more detail in Table 2.2, ANSOLs contain only AN and water, while ANEs and AN suspensions/gels, being intermediates for blasting explosives, also contain fuel components in addition to water. While ANEs contain mainly paraffinic-type fuels, AN suspensions/gels may contain other types of fuel components.

[†] It is important to note that ANBI and AN cannot be directly compared. According to the theoretical model presented in Section 3.2/3.3, typical AN emulsions have higher (theoretic) overpressure TNT equivalents (approximately 0.80).

The HSE guidance acknowledges that "Historical information identifies that the likelihood of a catastrophic event involving ANBI is very low when compared to the potential of conventional explosives" [24], and that the same type of information has identified that one of the principal explosion hazards associated with ANBI occur because of "the prolonged engulfment by fire of ANBI in storage tanks" [24]. This will be a central point in the discussion to follow.

UK regulations on ANBI by HSE represent a sort of stepwise approach where most categories of protected places will lead to separation distances for ANBI similar to regular explosives, but where a certain category of such places (Category 1) exempts storage of up to 100 tonnes of ANBI material from such restrictions (with regard to separation distances) [24].

In Sweden, the regulatory authority has recently issued regulations applying to the handling of AN emulsions/suspensions/gels (containing at least 60% AN and more than 1% combustibles), including UN 3375 products [25]. In these regulations, stores holding such AN products must be separated from combustible buildings by at least 10 meter. They must also be separated from residential buildings, offices and external settlements by at least 25 meter [25].[*]

Swedish regulations therefore impose only a fire-break distance of 10 meter to buildings inside the storage site premises, as well as a flat separation distance of 25 meter to buildings outside the site premises, for the AN fluid products concerned, while UK guidelines for most categories of protected places impose separation distances similar to regular explosives. Such differences are illustrative of the difficulties associated with the making of appropriate regulations.

In order for the AN fluid products belonging to the class of AN emulsions/suspensions/gels to be insensitive enough for inclusion in Division 5.1 in the ADR transport treaty, they must pass a series of tests, including gap testing[†] for the determination of shock sensitivity and Koenen test to ascertain the effect of intense heating under strong confinement [6]. Suitability of the product for containment in portable tanks as an oxidizing substance by a vented pipe test is included [6]. As such, these AN fluid products have undergone a level of quality control relevant for storage.

The accident record of ANEs, the most prominent type of AN fluid product, is very limited. Only a few mishaps have been reported, and in all of these incidents (related to transportation), it is in fact unclear if the substance involved was actually ANE. Among the episodes reported, two of them includes both ANE and AN prills, making the exact role of ANE unclear. Only an accident in 2004 in Russia seems to have led to an explosion and to have involved only ANE.[‡]

Given the very sparse accident record and lack of regulatory precedent, it is challenging to come to grips with how to formulate a scientific framework useable for regulating AN fluid products. The problem will here be approached by first formulating some overall guiding principles and assessing an absolute worst-case scenario. We will then try to reach a reasonable compromise.

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[*] The presence of physical barriers can reduce these distances.

[†] Please see Section 4.1 in the next chapter for details on gap testing.

[‡] This information has been extracted from a presentation on the theme by a major explosives manufacturer.

Some guiding principles for regulation of AN fluid products belonging to the intermediate (orange) category can be formulated on the basis of scientific principles and empirical facts:

- Records of past explosion accidents have shown quite conclusively that AN fluid products (solutions, emulsions and suspensions/gels) are less prone to accidental explosions when exposed to fire conditions than waterless AN products, such as AN prills (here meant to cover both technical and fertilizer grades) or AN fuel oil (ANFO) explosives [2].

- AN fluid products pose little or no detonation risk when unaffected by heat maltreatment (e.g. fire) because of their poor ability, or outright inability, to propagate detonation.

- Due to their content of water, AN fluid products must be considered inherently more fire resistant than waterless AN products because the vaporization of water consumes heat.

- Among the AN fluid products, AN solutions are less critical than the AN emulsions or the AN suspensions/gels, because the latter two types of AN products contain fuel components. Overpressure TNT equivalencies of AN emulsions lie in the approximate range of 0.7–0.8, while that for pure AN is 0.2–0.3 (see Figure 3.2 for pure AN).

- Storage tanks for AN fluid products must be equipped with suitable pressure-relief devices in order for them to resist fire conditions without undue build-up of internal tank pressure.

- If storage tanks holding AN fluid products can be protected against prolonged engulfment by fire, by lack of combustible materials in their vicinity, and these tanks are sufficiently pressure-relieved and can contain the AN material throughout the period of heat exposure, there is most probably little or no chance of an explosive-type event.

- Because AN fluid products have an inherent fire resistance, albeit of unknown durability, evacuation time may be a valuable factor to take into account when formulating regulations. If short evacuation times can be realized, separation distances can be reduced.[*]

A worst-case scenario can be estimated by applying the methodology of Section 3.2/3.3 to a representative member of the class of AN fluid products. We have here chosen to use a generic ANE composition, because ANEs are the most prominent members of these AN fluid products. Combined thermochemical calculations (data in Appendix C) and gas dynamic simulations then give the distances in Table 3.5 for blast overpressure thresholds. Distances for ANE quantities up to 200 tonnes, the Seveso-III Directive upper-tier level (Table 2.3), have been included.

The density of the generic ANE used in Table 3.5 corresponds to the ANE in non-sensitized condition, as stored. In an actual fire scenario, this will obviously not parallel the density of the ANE at the point of explosion, due to decomposition of the ANE matrix when heated strongly. Nevertheless, the density of the ANE at that point is difficult to estimate, and for the purpose of modeling a hypothetic worst-case scenario, such deviations are probably of minor importance.

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[*] Some countries, including Norway, do not incorporate such evacuation times as part of the regulatory practice.

Table 3.5 Distances for blast overpressure thresholds by detonation of generic AN emulsion of composition 76.0% AN, 17.0% water, 5.6% paraffin and 1.4% polyisobutylene, with density 1.35 g/cc (all distances are rounded to the nearest tens of meter).[*]

Quantity of AN emulsion [metric tonnes]	**Distances for air blast overpressure thresholds [m]**					
	2 kPa	**5 kPa**	**7 kPa**	**14 kPa**	**21 kPa**	**40 kPa**
1	340	160	130	80	60	40
2	430	210	160	100	70	50
5	580	280	220	130	100	70
10	730	350	270	160	120	80
15	840	400	310	190	140	100
20	920	440	340	210	160	110
25	1000	480	370	220	170	110
30	1060	510	390	240	180	120
40	1160	560	430	260	200	130
50	1260	600	470	280	220	140
75	1440	690	540	320	250	160
100	1580	760	590	360	270	180
125	1700	820	630	380	290	200
150	1810	870	670	410	310	210
175	1910	920	710	430	330	220
200	1990	960	740	450	340	230

Distances for blast overpressure thresholds provided in Table 3.5 are to be considered only as an absolute worst-case scenario, probably unrealistically high for most real situations. Comparison to the values of Table 3.1 show that those of Table 3.5 lie somewhat above. This is due to the greater explosive power of ANEs relative to pure AN. However, the real hazard represented by AN fluid products is considered lower than that of pure AN. Other factors must come into play.

The guiding principles presented in the previous list obviously moderate the worst-case scenario represented by the distances in Table 3.5. Possibly the best course of action for all AN products belonging to the intermediate (orange) category will then be to apply Table 3.5 as a foundation, but to incorporate a substantial attenuation because detonation is thought unlikely in practice.

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[*] Product quantities in the table correspond to the ones in the largest tank that fulfills the requirements of inter-tank separation distance as established and prescribed herein in Chapter 4. It is not the total quantity of emulsion stored. Polyisobutylene is here used to model the presence of polyisobutylene succinic anhydride (PIBSA) emulsifiers.

Dissimilar to the AN products in the most stringent (red) category, hardly any empirical facts at all exist regarding the accident record of the AN products in the intermediate (orange) category. Therefore, the use of the concept of explosive yield as a factor for the attenuation of the values of overpressures in Table 3.5, which have been calculated from simulations, is problematic.

Instead, we here propose formulating separation distances based on those in Table 3.5 by going to higher overpressures. Specifically, for the AN products in the intermediate (orange) category of Table 2.3, we here suggest applying the simplified system outlined in Table 3.6 below.

Table 3.6 Suggested separation distances to protected places for AN fluid products belonging to the intermediate (orange) category of Table 2.3 (quantity in largest tank).[*]

Quantity of AN product [metric tonnes]	**Separation distances to protected places [m]**		
	Vulnerable populations [a)]	**Residential buildings** [b)]	**Industrial buildings** [c)]
1–2	150	50	25
2–10	300	100	50
10–25	450	150	75
25–50	600	200	100
50–100	750	250	125
100–200	900	300	150

[a)] Vulnerable populations here mean those restricted by a 2 kPa blast overpressure threshold, like for example hospitals, schools, kindergartens, etc. (according to Norwegian practice). [b)] Residential buildings here means housings restricted by a 5 kPa threshold (according to Norwegian practice). [c)] Industrial buildings here means buildings and infrastructure that must comply with 15–20 kPa overpressure thresholds. The categories of protected places and overpressure thresholds above will vary from country to country.

The system of Table 3.6 presents a simplified "step-approach" where three minimum separation distances are introduced for each category of protected places, increasing from 25 to 150 meter according to increasing degree of vulnerability. Each category of protected place has stepwise increments of separation distance (25, 50 and 150 meter, respectively) as determined by the amounts of AN product, as laid out in Table 3.6. The system can be adjusted if necessary.

Now, some justification of the system presented in Table 3.6 will be useful. As a starting point, we can use minimum separation distances. From Table 3.6, we see that separation distances for 1–2 tonne and 2–10 tonne amounts there lie either 50 meter or 25 meter below those in the same quantity ranges and belonging to the most stringent (red) category of AN products, depending on category of protected places (compare values in Table 3.6 with Table B.9 of Appendix B). The AN fluid products are therefore associated with less restrictive minimum distances.

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[*] In all cases, the AN fluid products listed in Table 3.6 must fulfill the requirements for tank separations in Chapter 4. They should also be stored adequately separated from other critical AN products and potentially explosive materials. Such separations will be the subject of the next chapter and will not enter the discussion at this stage.

We can now move up from the minimum quantity ranges. Firstly, for amounts above 10 tonnes, the separations distances in Table 3.6 for the residential buildings category (5 kPa) correspond roughly to those in the 21-kPa column of Table 3.5. For the category of vulnerable populations, the distances in Table 3.6 are quite close to those in the 5-kPa column of Table 3.5.

Secondly, from Section 3.5 on overpressures and damage effects, levels of 15–20 kPa would signify a transition to moderate damage effects, and a level of ~5 kPa should give only minor damage to house structures. Accordingly, even in the extremely unlikely event of an absolute worst-case scenario, the separation distances established in Table 3.6 should provide a high level of protection for vulnerable populations, and at least a decent level of protection for persons located in residential buildings at the time of accident.

Moreover, the separations distances given in Table 3.6 for the category of residential buildings in amounts over 10 tonnes are approximately half of those that were calculated for pure AN and given previously in the 5 kPa column of Table 3.1. Those for vulnerable populations lie slightly above half of those for pure AN in the 2 kPa column of Table 3.1. Hence the simplified system of Table 3.6 presents what is a reasonable compromise.* For AN products belonging to the most stringent (red) category, we earlier argued for the preferable use of Table B.9 in Appendix B.

Discussion could here be continued, but in summary, we find the system of Table 3.6, in spite of its high degree of simplicity, to be a sensible compromise at a number of levels. We should add that for (on-site) buildings inside the storage site premises itself, as opposed to the off-site buildings discussed here, a minimum fire-break distance of 10 meter to all combustible buildings should be applied in all instances, as in the Swedish regulations [25].

For AN fluid products belonging to the intermediate category in quantities beyond 200 tonnes, only the AN liquid solutions (UN 2426 products) have quantity limits for lower- and upper-tier requirements, according to the Seveso-III Directive, that lie above this amount. As these liquid solutions consist of AN without fuel components (when in a fully dehydrated state, that is), the separation distances of Table B.9 can be applied for quantities above 200 tonnes. Since aqueous AN solutions are less critical than waterless AN products, the separation distances of one of the tables of Appendix B having a higher degree of attenuation is possible, preferably Table B.2.†

The recommendations outlined here in Section 3.6 to 3.8 have been summarized in Table 3.7. The core of these recommendations is founded on Table B.9 of Appendix B and Table 3.6, except in the case of AN products belonging to the mildest (yellow) category. For this least critical category, a fire-break distance should be applied in all instances, but as discussed previously in Section 3.7, an increased separation distance may be required also for these products due to toxic chemical species released by thermal decomposition of the material.

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[*] The importance of metal fragments, thrown out by detonation of any AN fluid product kept in a metal storage tank, is hard to assess, but the separation distances in Table 3.6 should provide a significant level of protection.

[†] The UN 2426 products constitute concentrated liquid AN solutions (80–93% AN in water, see Table 2.2) that must be stored in hot condition, something that may preclude storage of very large quantities in a single tank.

Table 3.7 Summary of recommendations for separation distances to protected places for the AN products covered by the three-tier classification system of Table 2.3.[*]

Seveso-III Directive AN products	**ADR treaty UN No.**	**Summary of recommendations for separation distances to protected places**
Ammonium nitrate technical grade	1942	• Apply the separation distances given in Table B.9 of Appendix B for all products concerned. As an alternative, apply the separation distances given in Table 3.1 or Table B.2 for quantities above 10 tonnes. Explosive yields below 50% should be regarded as unrealistically low. • Apply the minimum separation distances in Table B.9 of Appendix B for 1–2 tonne and 2–10 tonne quantities. • No recommendations given for quantities below 1 tonne. • Chemical contamination must be avoided.
Ammonium nitrate fertiliser grade	1942	
Ammonium nitrate fertiliser grade containing more than 80% AN	2067	
Ammonium nitrate 'off-specs' material and fertilisers not fulfilling the detonation test	Not applicable	
Ammonium nitrate technical grade AN liquid solutions	2426	• Apply the separation distances given in Table 3.6 for all products concerned. Apply a fire-break distance of 5–10 meter to on-site buildings. No recommendations given for quantities below 1 tonne. • Apply the separation distances listed in Table B.9 of Appendix B for quantities of AN liquid solutions exceeding 200 tonnes.
Oxidizing liquids AN emulsions, suspensions and gels	3375	
Ammonium nitrate fertiliser grade containing less than 80% AN	2067	• Apply a fire-break distance of 5–10 meter to nearby buildings. Increased separation may be necessary due to release of toxic gases upon thermal decomposition of the AN materials. No recommendations given for minimum threshold quantities. • Chemical contamination must be avoided. This applies to all AN products herein.
Ammonium nitrate fertilisers capable of self-sustaining decomposition	2071	

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[*] It is important to note that the AN product quantities given in this table correspond to the ones in the largest product assemblage that fulfills the requirements of inter-stack/tank separation as defined in the next chapter.

4 Internal arrangement of storage facilities holding critical ammonium nitrate products

In order to minimize the consequences of any thermal decomposition event taking place in a storage facility holding the critical AN products discussed in previous chapters, it is important to ensure that the separation distances between the relevant AN product assemblages internal to such storage facilities – typically stacks of bagged AN products or tanks of AN fluid products – are adequate. This is particularly critical in the event of sympathetic detonation. The purpose of the present chapter is the development of a scientific framework suitable for evaluation of the internal arrangement of storage facilities holding critical AN products.

4.1 Shock sensitivity, sympathetic detonation and gap testing

The shock sensitivity of an explosive material is its sensitivity to sudden compression by shock. While this term can now and then be meant to include compression by impact from projectiles, it is used herein strictly in the sense of compression by supersonic shocks, that is, steep-fronted compression waves propagating at supersonic velocities in the medium that they traverse [26]. The shocks considered in this chapter are those that result from rapid thermal decomposition of solid or liquid explosives by a detonation process.

Shock sensitivity of explosive materials can be probed experimentally through application of a so-called gap test. In such a test, a shock generated by a confined charge of standard booster explosive (referred to as the donor) is attenuated by an inert barrier before it enters a confined charge of the test material (referred to as the acceptor) [26]. Then, by successively varying the thickness of the inert barrier (the gap) through a test series, the shock strength from the donor charge can be varied until detonation of the test material is achieved. Such transfer of detonation from one charge to another located nearby is often referred to as sympathetic detonation.

In the many possible configurations of such a gap test, both the scale of the experiment and the type of inert barrier material can be varied. In small and intermediate scale gap testing, the inert barrier material is typically made of disks of a plastic (polymer) material[*] or a column of water. The thickness of the plastic barrier, or the height of water column, required to prevent transfer of detonation from the donor to the acceptor becomes a measure of the shock sensitivity of the material under test – the thinner the gap preventing transfer, the lower the shock sensitivity.

For explosive materials having low sensitivity and large critical diameter, the size of the donor and acceptor charges in the gap test can become substantial, with each of them weighing up to as much as several metric tonnes. In such large-scale gap tests, including those relevant for the AN products considered herein, the inert barrier material may be constituted by air. This has important implications, because air is much more compressible than plastic materials or water (by several orders of magnitude). These implications will be discussed later in Section 4.3.

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[*] A standard material for such disks/cards is the acrylic plastic poly(methyl methacrylate), shortened PMMA.

4.2 The Van Dolah large-scale investigations of sympathetic detonation

Actual data on the sympathetic detonation of large AN charges are very rare. The pioneering experiments in this context were two field investigations conducted by the US Bureau of Mines[*] during 1964–1965 and supported by a number of companies in the explosives, chemical and mining industries. The field experiments were conducted at a site west of Ashland, Wisconsin, and the results were compiled in two 1966 technical reports and a 1968 publication [27-29].

The large-scale investigations of sympathetic detonation carried out by the US Bureau of Mines in the mid-1960s will be referred to in this text as the Van Dolah experiments – named after the research director of the Explosives Research Center of the bureau in Pittsburgh, Pennsylvania.

As part of the Van Dolah experiments, large-scale air-gap tests of prilled AN were carried out,[†] with the donor and acceptor charges being of the same geometry, the same dimensions and of equal weight. In the final 1965 test series, the 60- by 60-inch (152.4×152.4 cm) donor/acceptor charges each weighed approximately 5400 pounds (ca. 2450 kg). The donor charge contained ANFO (95/5) and the acceptor charge held the same weight of prilled AN. The ANFO donor and the AN acceptor were both cylindrical and contained in laminated cardboard tubes placed on wooden platforms. The experimental design of these trials is sketched in Figure 4.1 [28].

The donor charges in the Van Dolah experiments were initiated with the help of an array of RDX pellets, where each pellet was equipped with a length of detonating cord, and with all of these being of the same length. The cords were bundled together around a cast explosive primer. The initiated end of the donor and the far end of the acceptor were closed with plywood discs. The downstream end closure of the donor could either be of a “soft” type, made from thin plastic sheeting, or of a “hard” type, made from sheet steel plating (giving fragments) [28].

During testing, the distance between the donor and acceptor charges was increased or decreased until the distance threshold was reached where the probability of detonation transfer from donor to acceptor was 50%. The procedure is known as the Bruceton up-and-down method [27-29].

At FFI, the large-scale air-gap tests detailed above have been modelled with the aid of modern CFD software. Such modeling was undertaken with the intent of establishing an initiation pressure threshold that could subsequently be applied during the CFD modeling of sympathetic detonations of AN stacks. A graphic from the simulation of the largest air-gap test conducted as part of the Van Dolah experiments, showing density gradients, is provided in Figure 4.2.

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[*] This US government agency was abolished in 1996. Certain functions were transferred to other federal agencies.

[†] The bulk density of the prilled AN used in the 1964–1965 Van Dolah field experiments is apparently not provided, neither in the 1966 technical reports nor in the 1968 publication [27-29]. Detailed prill size analyses are provided in the technical reports, however, and when taken together with other technical information therein, and of other reports, the bulk density of the AN must be assumed to be close to the now standardized prilled AN with density ~0.80 g/cc. It will later be shown how the results from CFD modeling carried out at FFI on the Van Dolah experiments were supported by comparison with analogous modeling that was undertaken on another series of large-scale gap tests (where data are not in the public domain). The Van Dolah field experiments have been used in this report as the foundation for CFD results presented because data from all these trials are at present publicly available.

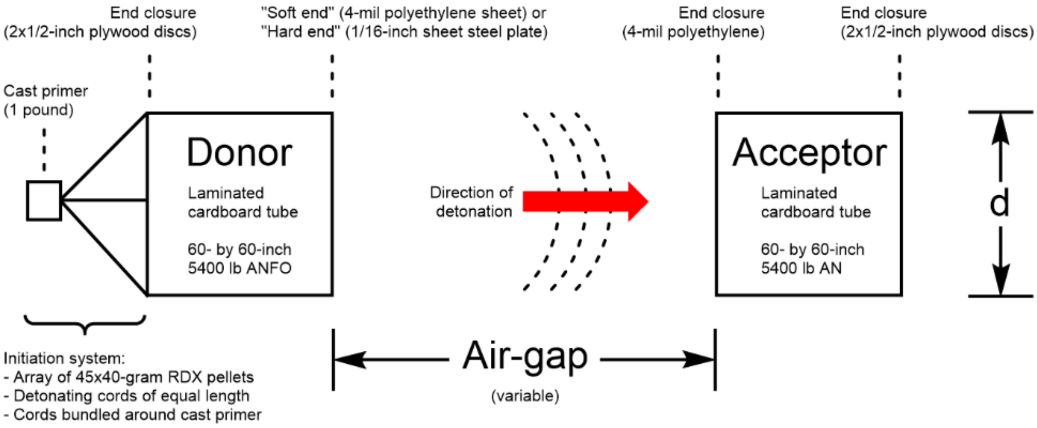

Figure 4.1 Experimental design of the final Van Dolah large-scale air-gap test of prilled AN, carried out in 1965. Both the donor charge and the acceptor charge were placed on wooden platforms (not shown). Instrumentation has not been indicated.

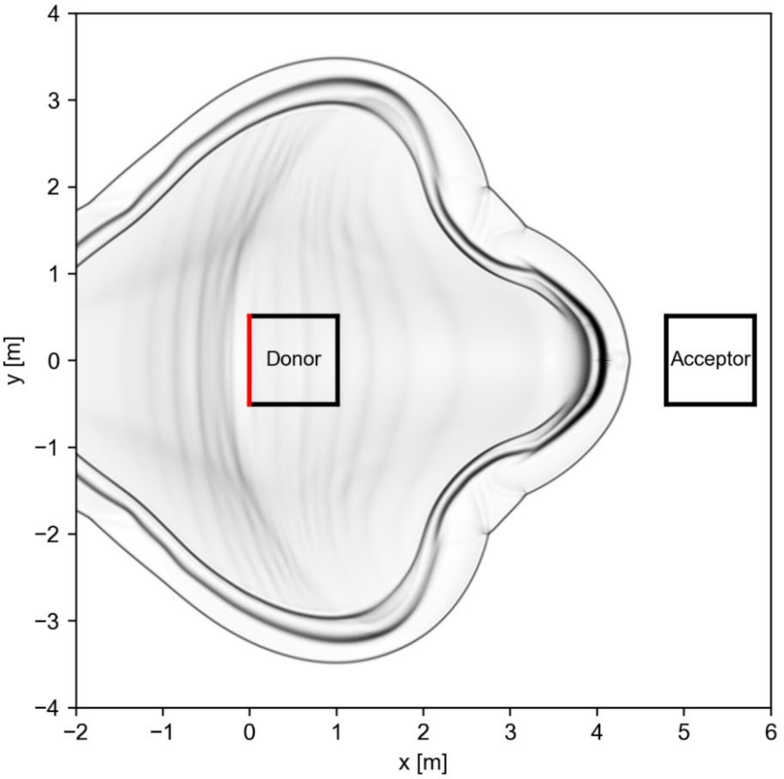

Figure 4.2 Graphic from CFD simulation at FFI of the 1965 Van Dolah large-scale air-gap test of prilled AN (showing density gradients), as viewed from directly above the test set-up. The red line indicates the initiated end of the donor. The gap shown corresponds to the one giving 50% probability of sympathetic detonation.

4.3 Shock initiation of ammonium nitrate in large-scale air-gap tests

The shock dynamics of a gap test changes according to the configuration of the experimental design and the choice of inert barrier material. In the case of air-gap tests, the shock dynamics become especially complicated due to the exceedingly compressible nature of gases and the very large differences in the material densities of solid/liquid explosive materials and air. Accordingly, the shock dynamics of air-gap tests will be briefly reviewed below.

Figure 4.3 shows pressure fields in an air-gap simulation with ANFO donor and AN acceptor. Each frame in that figure contains a bar at the bottom, indicating material boundaries, and a panel at the top specifying the pressure at each location. The sequence of time frames in the figure therefore shows pressures fields, as a function of distance, at a few fixed points in time.

In Frame 1 of Figure 4.3, a shock wave is propagating in air toward the AN acceptor, with the ANFO detonation gases trailing close behind. The shock wave compresses the air directly in front of it to a state where the pressure and velocity of the air becomes equal to that of the detonation gases trailing behind. When the shock wave then reaches the AN acceptor (Frame 2), it begins to compress it via a shock wave set up in the solid AN material. However, since the density of air is much lower than that of AN, a shock wave is also reflected back into the air. The situation at these points in time can be seen from Frame 2 and 3 of Figure 4.3.

The reflected shock wave in Frame 2 and 3 further compresses the air in front of the acceptor, and it propagates back toward the approaching detonation gases. As the reflected shock wave finally encounters the material boundary of these gases, another shock reflection process arises, as shown in Frame 4. These back-and-forth reflections continue (Frame 5 to 7) until the air has reached a state of sufficient pressure and density to halt the expanding detonation gases.

As a result of the many shock reflections described in the process above, several shock waves have been driven into the AN material of the acceptor charge, each one raising the pressure in the AN to a higher level. This rather complex dynamics lead to a pressure elevation in the AN that is significantly higher than the one that would be expected considering only an air-shock. Consequently, establishment of a critical initiation pressure threshold for AN is complex, as the shock pressure set up by the donor differs from the maximum pressure reached in the acceptor.

The Van Dolah field experiments detailed previously can be used to establish a critical initiation pressure criterion, relevant for prilled AN products, by applying appropriate CFD simulations. This criterion can then be used to determine appropriate inter-stack separation distances for the same AN products if it is combined with a CFD simulation of the relevant stack configuration.

In the next section, highly resolved CFD simulations of the largest air-gap test of the Van Dolah trial series will be used to establish a suitable critical pressure criterion. Following the definition of appropriate stack configurations for bagged AN products in a section to follow, the criterion will then be used to determine inter-stack separation distances by extracting the pressure levels for the maximal distance at which sympathetic detonation is to be expected.

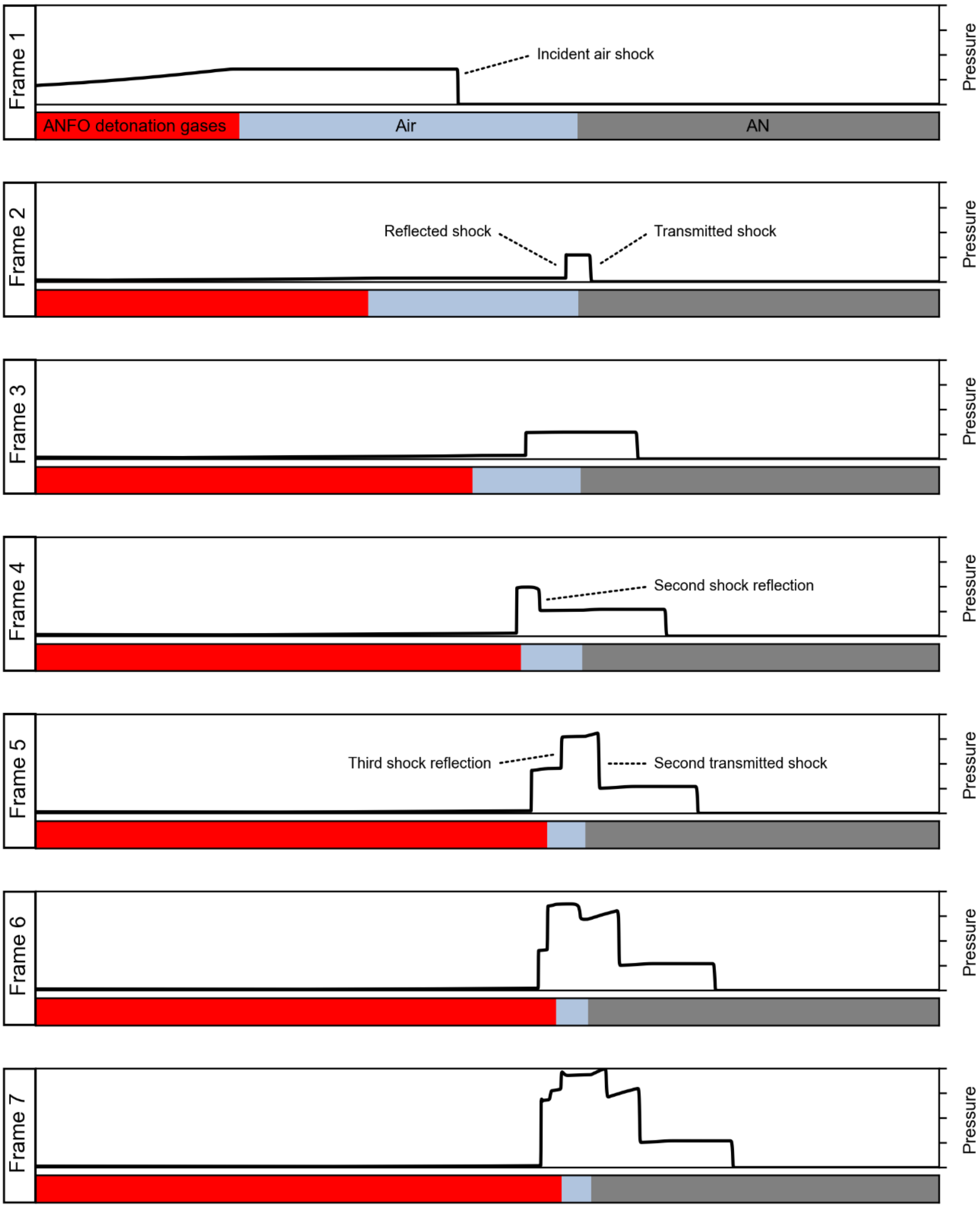

Figure 4.3 Sequential sequence of time frames showing the (one-dimensional) shock dynamics of an air-gap test. At each frame, the bar at the bottom indicates relevant material boundaries – of detonation gases, air and AN material, respectively. The panel above specifies pressures at each location. Time increases from Frame 1 to 7. Note: The pressure scale in Frame 1 is 1/10th of the scale used in other frames.

4.4 Establishment of a critical initiation pressure criterion for prilled AN

In the previous sections, the dynamics of shock-induced sympathetic detonation was discussed, together with the detailed experimental set-up of typical air-gap tests relevant for AN products. Air-gap tests, such as the Van Dolah experiments, determine distance criteria that apply only to the specific experimental set-up applied during testing, and it is difficult to use these distances directly for AN charge configurations that differ from those that were applied during the tests.

In order to overcome this difficulty, CFD simulations of the Van Dolah air-gap tests will be used to establish a critical initiation pressure criterion. This pressure criterion is a property of the AN product itself and can as such be used as a general criterion for sympathetic detonation, transferable, for instance, to simulations involving stacks of big-bags holding AN products.[*]

The simulation configuration is similar to the experimental set-up of the Van Dolah experiments (Figure 4.1). The donor and acceptor charges (of equal size), either 40×40-inch or 60×60-inch, were defined in the computer software and placed at a specified distance from each other. The donor charge was initiated from the far end, relative to the acceptor, making the resultant detonation wave propagate directly toward the acceptor charge (as in Figure 4.2).

Simulation resolution was set to 0.4 mm, ensuring a sharp resolution of the detonation wave and resulting air shock. The detonation process is simulated until the maximum pressure within the acceptor charge has been attained. This pressure is an estimate of the critical initiation pressure for sympathetic detonation of the AN material. The pressure is the consequence of a shock wave reflection process, where the pressure inside the acceptor charge is raised stepwise due to the multiple shocks that impinge on it as the hot detonation gases approach (Figure 4.3).

As mentioned in Section 4.2, the Van Dolah trials made use of the Bruceton up-and-down method, varying the donor-acceptor distance in an attempt to estimate the distance at which there is a 50% chance of sympathetic detonation. This distance is estimated by repeated trials performed at two distances defining a transition interval (delimited by go/no-go test results). Results from CFD simulations provide pressure criteria based on these two distances.

A complication arises because initiation pressure is rather sensitive toward distance variations, with small distance increments leading to relatively large differences in the pressure estimates. Furthermore, there are also discrepancies between estimated pressures for the 40×40-inch and 60×60-inch charges. For these reasons, simulations have been performed at three distances: the estimated 50% distance, the lower limit of the interval and the corresponding upper limit. Critical initiation pressures extracted from the CFD simulations are presented in Table 4.1.

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[*] Simulations will typically only have access to approximate material descriptions, and they can only be performed with somewhat limited spatial resolution. As such, the extracted critical initiation pressures will only be transferable between simulations of the same kind, and they are not necessarily fully representative of the true critical pressures. Here we are ultimately interested in determining distance thresholds applying to large assemblages of AN products, and as these configurations are of a size where numerical simulations cannot be conducted at a spatial resolution where all physical processes are well represented, it is necessary to use the approach outlined, where a critical pressure criterion is extracted from gap test simulations and applied to simulations of product assemblages.

Table 4.1 Critical initiation pressures extracted from CFD simulations of large-scale air-gap tests of prilled AN using ANFO donor (see main text for details).

Large-scale air-gap test (donor charge size) [a)]	Lower limit of interval [GPa]	Pressure at 50% estimate [GPa]	Upper limit of interval [GPa]
Van Dolah tests (40×40-inch)	1.40	1.44	1.68
Van Dolah tests (60×60-inch)	1.30	1.31	1.52
TNO-Yara tests (350 kg)	1.28	1.36	1.42
TNO-EFMA tests (700 kg)	1.40	1.49	1.58

[a)] Parameters for ANFO, used in the CFD simulations and derived from thermochemical calculations, are given in Appendix D.

In addition to the Van Dolah experiments, FFI has had access to additional large-scale air-gap test data for TGAN. This includes a gap test series conducted as part of an investigation into the storage layout of TGAN by Netherlands Organisation for Applied Scientific Research (TNO) at the request of the Norwegian fertilizer and chemical company Yara International ASA.

Details of the test series above are non-public and can therefore not be disclosed in this report. However, CFD simulations at FFI of these air-gap tests,[*] analogous to those carried out for the Van Dolah experiments, gave the critical initiation pressures in Table 4.1 for TNO-Yara tests.[†] Similarly, air-gap test data including TGAN, carried out by TNO in a 2005 study carried out for the European Fertilizer Manufacturers Association (EFMA), later renamed Fertilizers Europe, gave, through FFI simulation work, the values listed in Table 4.1 for TNO-EFMA tests [30].[‡]

As can be seen from the values given in Table 4.1, the critical initiation pressures obtained from CFD simulations of the various large-scale air-gap test series are comparable, although there are some non-trivial differences between estimated pressures obtained from dissimilar charge sizes.

The values from Table 4.1 cannot be used directly as a pressure criterion in the evaluation of simulations including AN stacks weighing up to hundreds of tonnes, because spatial resolution in simulations must be lowered when the amount of material involved is significantly increased. This necessitates a readjustment of the criterion as it is applied across all relevant simulations.

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[*] These tests were conducted at a military test site in Älvdalen, Sweden. They involved TGAN having densities close to 0.80 g/cc and an experimental set-up using a donor charge of ANFO (350 kg in a big-bag) and an acceptor charge of TGAN (placed in a cylindrical polymer-ceramic tube with 116 cm diameter). Unlike the Van Dolah experiments, the set-up was vertical, with the donor placed on top of a wooden platform, above the vertically placed acceptor.

[†] A complication arises in the CFD modeling of these tests. As the charge donor used, a big-bag with 350 kg ANFO, is somewhat flexible and not fully shape-fixed, the donor and acceptor charge may not be of exactly equal diameter, influencing the symmetry and packing height of explosive material contained in the donor. Small deviations in the geometry of the donor charge can affect estimated initiation pressures in the acceptor charge significantly.

[‡] In the TNO-EFMA tests, the experimental set-up was analogous to that for the TNO-Yara tests, except that the donor charge consisted of 700 kg ANFO in a big-bag (twice the size of the donor used in the TNO-Yara series).

As mentioned above, the great size of typical AN product stacks make it unfeasible to apply well-resolved CFD simulations to the problem of determining inter-stack separation distances. In this work, stack detonation simulations were conducted with a spatial resolution of 4.0 cm.

Lowered spatial resolution in the simulations is necessary because the problem of determining inter-stack separation distances is inherently three-dimensional. One might consider conducting two-dimensional simulations, as the resulting separation distances are likely to be conservative. In that case, spatial resolution can be increased, giving a sharper shock wave representation.

However, by choosing two-dimensional simulations, the stack configurations are transformed into the case of two infinitely long stacks – that is, along the omitted dimension. By so doing, initiation of detonation will occur simultaneously along the entirety of the omitted dimension. In this setting, the resulting detonation wave and air-shock will be significantly stronger than for the actual configuration. Hence, with our aim of establishing realistic separation distances, we found the application of three-dimensional simulations to be the best approach.

Lowered spatial resolution has the effect of making the detonation wave and air shock in the simulations less sharply resolved than when conducting simulations at higher spatial resolution. This will in turn limit the pressure buildup in the acceptor stack. Gap test simulations of the four test series of Table 4.1 were conducted with the same resolution used for the stack simulations. A surrogate pressure criterion of 0.8 GPa was identified. This proxy criterion was then applied to our stack simulations. It is lower than the more realistic values (~1.4 GPa) in Table 4.1.

With a critical initiation pressure criterion having now been established for the acceptor stack, inter-stack separation distances can be determined using CFD simulations of stack detonations. For each stack configuration, simulations were conducted with variable distances between the donor and acceptor stacks, and the pressure within the acceptor stack was monitored over time. If, at any time, the pressure within the acceptor stack exceeded the critical pressure criterion, the acceptor stack was assumed to detonate. Inter-stack separation distance is the smallest distance at which the pressure criterion was not exceeded at any point during simulation.

Another possible entry point to the establishment of a critical initiation pressure criterion should be addressed. Instead of attempting to model the shock reflection process treated in Section 4.3, an alternative, less complicated, approach is to use the air-shock pressure at relevant distances.[*]

An implicit assumption with this approach is that the waveform of the air-shock is the same at all distances, implying that the manner in which the pressure levels off behind the air-shock is independent of distance. This assumption is implausible for evaluation of separation distances, because the geometry of the AN product stacks, as well as the point of initiation of the stacks, can have significant influence on the waveform. Accordingly, a simple relation, coupling the air-shock pressure to the pressure buildup in the acceptor stack, may in fact not exist.

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[*] Modeled as a reflection against a resilient wall at the relevant distance. These pressures are substantially lower than the maximum pressure reached in the acceptor charge as a result of the shock reflection process treated in Section 4.3. The latter pressure is approximately four to five times higher than the air-shock pressure (~0.3 GPa versus ~1.5 GPa). As explained earlier, the shock wave reflection process compresses the acceptor charge stepwise (Figure 4.3).

Another complicating factor encountered when using air-shock pressures for establishing a critical initiation pressure criterion is the so-called triple point that occurs due to shock wave reflection from the ground. When a stack of AN products detonates, shock interactions at the ground level give rise to complicated shock dynamics. At the triple point, the reflected shock wave, the Mach stem and the air-shock all converge, hence giving a local pressure spike.

The triple point starts at ground level when shock reflection occurs, and it propagates upwards, over time, as the air-shock expands outwards. Its exact trajectory depends on charge geometry and point of initiation. For a given stack configuration, some points of initiation may lead to triple point trajectories that intersect the acceptor stack while other initiation points do not.

For this reason, the number of simulations required to accurately determine the pressure levels caused by the many possible triple point trajectories is very large. In addition, the pressure load at the point where the triple point meets the AN product stack can have a peculiar pressure-time development. It is therefore difficult to relate it to results from gap testing. Separation distances determined here will consequently not be based on such triple point pressures. However, for a given stack configuration and point of initiation, the effect of the triple point is accounted for.

Shock initiation of an explosive material, having detonative capacity, is a process necessitating a high-pressure pulse of some duration. The air-shock pressure may not be a suitable substitute for a pressure pulse such as the shock reflection process shown in Figure 4.3. In spite of this potential shortcoming, we will use the air-shock as an additional critical initiation pressure criterion in the evaluation of inter-stack separation distances, in order to add robustness.

Estimates for inter-stack separation distances using the air-shock can be used in conjunction with the results obtained from the approach based on the maximum pressure within the acceptor stack resulting from the shock reflection process as treated in Section 4.3 above. This is done by selecting separation distances that satisfy both types of critical initiation pressure criteria. Largely, the methods provide separation distances that are quite similar to each other.[*]

In spite of the number of provisions that have here been forwarded in an attempt to address the problem of determining inter-stack separation distances for AN product stacks on the basis of CFD simulations as accurately as possible, one should take into consideration that AN products are materials that may – unintentionally – have become sensitized while stored, for instance by temperature fluctuations, shifting moisture levels or aging processes, either locally or in bulk.

In the three sections to come, inter-stack separation distances for the most critical AN products will be presented, based on the critical initiation pressure criterion developed in this section. The presentation will start out with AN products having medium bulk density, followed by products having either low or high bulk density, respectively. The reader should keep in mind that in the stack simulations of sympathetic detonations, both the donor charge and the acceptor charge are made up of AN, while in the air-gap tests treated here, the donor charge is made up of ANFO.

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[*] For large stacks, use of the air-shock pressure seems to give values that are slightly less conservative, thus giving shorter separation distances. For smaller stacks, the separation distances are very comparable for the two methods.

4.5 Determination of inter-stack separation distances for the most critical ammonium nitrate products – medium bulk density (0.75–0.85 g/cc)

Because air-gap test data for AN, such as the Van Dolah experiments detailed previously above, is so much more pronounced for AN with medium density (here defined as 0.75–0.85 g/cc), it is appropriate to use these AN products as the point of departure for establishment of a framework for regulating the inter-stack separation distances of bagged AN products during storage. All of these AN products belong to the most stringent (red) category, as defined earlier in Table 2.3.

The most important type of AN product assemblage is stacks made up of big-bags containing solid AN materials (prills, granules). For AN having medium density, usually prilled materials, such a big-bag is commonly made up of a few kilograms of plastic material, often polyethylene and polypropylene (in combination), and holds either 1250 kg or 1000 kg of AN product.

For the specific purpose of CFD simulations, a generic and somewhat idealized model for such a big-bag, holding 1250 kg AN product, must first be defined. Based on numbers obtained from relevant European AN manufacturers, we have chosen to define the big-bag geometry shown in Figure 4.4 below. The filled big-bag has the shape of a cuboid with rounded corners, and this geometry was applied for all stack configurations with AN products having medium density.

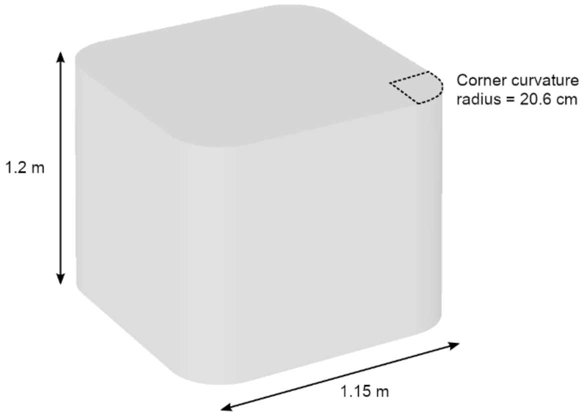

Figure 4.4 Geometry of generic big-bag holding 1250 kg AN product of bulk density 0.80 g/cc. Note: Figures of big-bags in stacks are simplified (without the corner curvature).

Based on the big-bag geometry of Figure 4.4, three types of stack configurations were defined and used for the CFD simulations, having maximally three layers of big-bags. Altogether, these three stack configuration types comprise 27 specific stacks. All of these are shown in Table 4.2 and have total weights from 1.25 tonnes (one big-bag) and up to 326.25 tonnes (261 big-bags). The upper limit was chosen based on storage practices at key European AN manufacturers.

The three stack configurations covered by Table 4.2 are all quadratic, centered and symmetric. They differ by how big-bags are stacked on top of each other – with three layers as a maximum, this being in accordance with prevalent guidelines from relevant industrial AN manufacturers:

- Configurations having no set-back at each layer.
- Configurations having ½ bag set-back at each layer.
- Configurations having 1 ½ bag set-back at each layer.

Configurations with no set-back are cuboid and have bags stacked directly on top of each other, with a vertical face to the stack. Configurations having set-back are pyramidal, profiling a stack face with a slope of at least 45º to the vertical on the relevant face (see figures in Table 4.2).[*] Arrangements with more set-back allow for more favorable (shorter) separation distances.

Using the critical initiation pressure criterion developed in Section 4.4 above, all product stacks in Table 4.2 have been modeled by CFD. In these simulations, the relevant stack configuration was allowed to detonate, with thermochemical parameters derived from AN of density 0.80 g/cc (data given in Appendix A),[†] and the distance to the adjacent stack corresponding to the critical initiation pressure criterion was extracted from the simulations (in nearest whole meter).

As mentioned in Section 4.4, these simulations could not be undertaken at the spatial resolution used for simulation of the Van Dolah experiments. The critical initiation pressure criterion had therefore to be compensated accordingly – lower resolution means the maximum pressure in the acceptor charge in the simulation will be reduced – and serve as a proxy for the critical pressure. Hence, this pressure is not to be regarded as the true (physical) critical initiation pressure.

In the estimation of critical inter-stack separation distances for stacks of bagged AN products, the points of initiation of detonation in the stacks, used in the CFD simulations, are significant. Separate CFD studies were carried out on beforehand, with the three stack configuration types being initiated at chosen points. Points believed to be the most critical ones were identified.

From the said pre-study, the most critical initiation points identified were the top corner points for stack configurations having either ½ bag or 1 ½ bag set-back – that is, the top corner of the first, the second or the third layer of big-bags. For stack configurations having no set-back, the most critical initiation point was found to be the top point (center) of the uppermost layer.

In Table 4.2, critical distance means the smallest inter-stack separation distance fulfilling the main critical initiation pressure criterion defined in Section 4.4. The recommendation refers to our best suggestions for such separation distances, with these values incorporating some degree of safety margin, as well as covering both types of pressure criteria developed in Section 4.4. As it played out, for separation distances up to or equal to five meter, one meter was added, while for separation distances above five meter, two meters were added.

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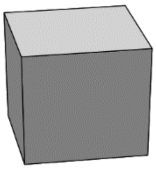
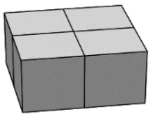
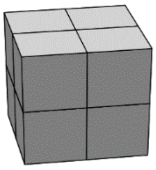
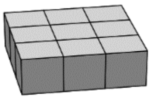
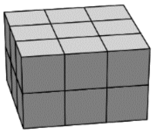
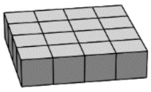
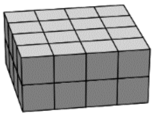
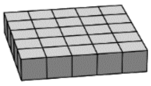
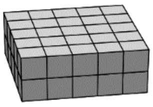
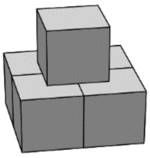
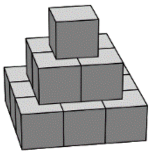
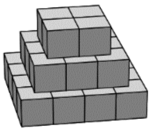
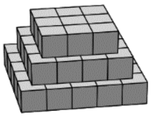
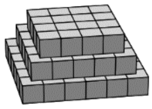
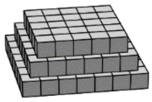
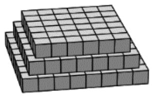
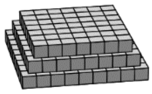
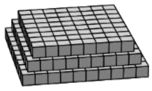
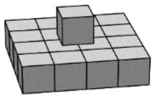
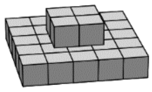
[*] Configurations having no set-back were limited to two layers in height and maximally 5×5 bags in each layer.

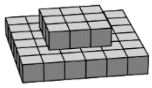
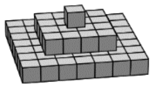
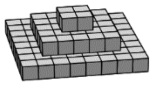
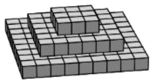
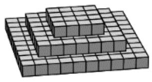
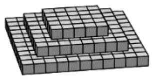
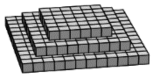
[†] All simulations are based on pure AN material and do not include any of the big-bag plastic material(s). We believe this to be of little consequence, and it would have been difficult to assess exactly how these materials contribute.

Table 4.2 Stack configurations and inter-stack separation distances for AN products with medium density (0.75–0.85 g/cc), with each big-bag holding 1250 kg AN product. Please see main text for more details on critical distance versus recommendation.

Single- or double-layered stack configurations having no set-back							
Stack no.	Figure of stack configuration	Layer 1	Layer 2	Layer 3	Total bags	Weight [tonnes]	Inter-stack separation
1		1	0	0	1	1.25	Critical distance: 1 m Recommendation: 2 m
2		2×2	0	0	4	5.0	Critical distance: 1 m Recommendation: 2 m
3		2×2	2×2	0	8	10.0	Critical distance: 2 m Recommendation: 3 m
4		3×3	0	0	9	11.25	Critical distance: 2 m Recommendation: 3 m
5		3×3	3×3	0	18	22.5	Critical distance: 3 m Recommendation: 4 m
6		4×4	0	0	16	20	Critical distance: 3 m Recommendation: 4 m

7		4×4	4×4	0	32	40	Critical distance: 5 m Recommendation: 6 m
8		5×5	0	0	25	31.25	Critical distance: 3 m Recommendation: 4 m
9		5×5	5×5	0	50	62.5	Critical distance: 5 m Recommendation: 6 m
Stack configurations having ½ bag set-back							
10		2×2	1	0	5	6.25	Critical distance: 1 m Recommendation: 2 m
11		3×3	2×2	1	14	17.5	Critical distance: 2 m Recommendation: 3 m
12		4×4	3×3	2×2	29	36.25	Critical distance: 3 m Recommendation: 4 m
13		5×5	4×4	3×3	50	62.5	Critical distance: 3 m Recommendation: 4 m

14		6×6	5×5	4×4	77	96.25	Critical distance: 4 m Recommendation: 5 m
15		7×7	6×6	5×5	110	137.5	Critical distance: 4 m Recommendation: 5 m
16		8×8	7×7	6×6	149	186.25	Critical distance: 6 m Recommendation: 8 m
17		9×9	8×8	7×7	194	242.5	Critical distance: 7 m Recommendation: 9 m
18		10×10	9×9	8×8	245	306.25	Critical distance: 10 m Recommendation: 12 m
Stack configurations having 1 ½ bag set-back							
19		4×4	1	0	17	21.25	Critical distance: 3 m Recommendation: 4 m
20		5×5	2×2	0	29	36.25	Critical distance: 3 m Recommendation: 4 m

21		6×6	3×3	0	45	56.25	Critical distance: 4 m Recommendation: 5 m
22		7×7	4×4	1	66	82.5	Critical distance: 5 m Recommendation: 6 m
23		8×8	5×5	2×2	93	116.25	Critical distance: 5 m Recommendation: 6 m
24		9×9	6×6	3×3	126	157.5	Critical distance: 5 m Recommendation: 6 m
25		10×10	7×7	4×4	165	206.25	Critical distance: 6 m Recommendation: 8 m
26		11×11	8×8	5×5	210	262.5	Critical distance: 7 m Recommendation: 9 m
27		12×12	9×9	6×6	261	326.25	Critical distance: 10 m Recommendation: 12 m

4.6 Determination of inter-stack separation distances for the most critical ammonium nitrate products – low bulk density (less than 0.75 g/cc)

In general, the shock sensitivity of AN increases with decreasing bulk density and decreases with increasing bulk density. While the Van Dolah experiments did not include AN materials having low density (<0.75 g/cc), the aforementioned TNO air-gap test series (see Section 4.4) did include prilled AN materials of such density. Low-density prills were found to be more shock sensitive. Does this indicate that increased separation distances are necessitated?

As pointed out earlier, the donor-acceptor relation is usually asymmetric in AN air-gap testing, with the donor charge holding ANFO and the acceptor charge containing the AN product to be tested. By contrast, the sympathetic detonation of stacks of bagged AN products is symmetric. Both the donor charge and the acceptor charge are there filled with the same AN material.

The TNO-Yara tests demonstrated that sympathetic detonation occurred at greater separation distances when AN products having low density were tested, as compared to standard material of medium density. However, in sympathetic detonation of AN stacks, the donor charge holds AN product, not ANFO, and products with low density will have less volumetric energy content and a decreased detonation pressure. The donor charge becomes weaker with less dense AN.[*]

We therefore have two factors opposing one another in sympathetic detonation of AN stacks. When the density of the AN product is lowered, the pressure developed by the donor stack is diminished, compared to material of higher density, but the shock sensitivity of the acceptor stack is increased. Low-density AN is a less powerful explosive, but it is more sensitive.

To determine if low-density AN products do require separation distances that differ from those for medium-density products, we have conducted simulations of selected stack configurations with low-density product. The results do not indicate that such AN materials require increased separation relative to medium-density material. Nor do the results indicate reduced distances. The two factors – reduced detonation pressure and increased sensitivity – mostly cancel out.

Consequently, we believe that among the most critical AN products, meaning those that belong to the most stringent (red) category (Table 2.3), the AN products having low bulk density do not necessitate intra-stack separation distances that deviate from those calculated for AN products having medium density and previously presented herein in Table 4.2.

<u>A precondition for our conclusion is the quality of the AN material</u>. Products containing undue amounts of fines, dust, etc. can have increased shock sensitivity. Increased separation distances for low-density AN have been included in the SAFEX guidelines for TGAN storage [11].[†]

---

[*] The detonation pressure of an explosive is in fact proportional to the square of its loading density.

[†] According to SAFEX, stacks having ½ bag set-back and weighing 500 tonnes should have a separation distance of 16 meter (low density) or 9 meter (medium density). Stacks with 1 ½ bag set-back should have a separation distance of 9 meter (low density) or 7 meter (medium density) [11]. Our recommendations are given in Table 4.2.

4.7 Determination of inter-stack separation distances for the most critical ammonium nitrate products – high bulk density (greater than 0.85 g/cc)

The explosion hazards of AN are significantly diminished as the bulk density increases, because the critical diameter of AN materials increases with density, reducing its detonability. As part of the 2005 EFMA study, mentioned earlier in Section 4.4, large-scale air-gap testing of granulated fertilizer grade AN (FGAN) having density 0.92 g/cc was reported [30]. The critical gap length was found to be between 0.35 m and 0.75 m, compared to 3.5–4.5 m for TGAN [30].[*]

Based on the air-gap testing of FGAN and succeeding CFD simulation studies, TNO determined the critical inter-stack separation distance for FGAN to be 0.1–0.7 m. These results are reflected in the SAFEX guidelines and Australian code of practice for safe storage of solid AN materials, where the recommended separation distance between stacks of high-density AN products (greater than 0.85 g/cc) is 1 meter, even for stacks as large as 500 tonnes [11,17].

We have conducted our own CFD simulations at FFI of the TNO-EFMA air-gap tests of FGAN, and our results substantiate those obtained from TNO. Simulated under the same conditions that provided the critical initiation pressures listed in Table 4.1, we obtained an initiation pressure of 2.05–2.75 GPa for the granulated FGAN tested in the 2005 EFMA study, pressure levels that are somewhat less than twice those for the typical TGAN products given in Table 4.1.[†]

While the shock sensitivity of AN is substantially lowered as density increases, the detonability of AN increases with temperature. This was methodically investigated and reported during the mid-1960s by Van Dolah and coworkers, who found that higher charge temperatures lead to a lower critical diameter [31]. Moreover, extensive studies conducted during the late 1970s at the Department of Mining Engineering, Queen's University at Kingston in Ontario, Canada, found that even high-density AN prills could be made to detonate completely in large charges [32].

As reported by TNO, the investigations done at Queen's University in Canada functioned as a starting point also for the 2005 EFMA study, but lower critical diameters were established in the latter study, and the variation of the critical diameter with density was found to be less [30]. The large-scale behavior of FGAN (density = 0.92 g/cc) was probed by initiating a double-layered, rectangular pile of FGAN big-bags,[‡] with the bags stacked at no set-back (three bags in width), using a large ANFO booster charge – a set-up involving about 28 tonnes of test material [30].

The large-scale test verified that propagation of detonation was achieved in the FGAN pile [30]. Moreover, high-density AN products have been involved in recent accidents (see Section 2.3).

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[*] The experimental set-up for these TNO-EFMA air-gap tests were detailed in footnotes in Section 4.4.

[†] Interestingly, the critical initiation pressure values for TGAN listed in Table 4.1 correspond to roughly 50–60% of the theoretical Chapman-Jouguet detonation pressure for AN with density 0.80 g/cc ($P_{CJ} \sim 2.63$ GPa), while those for the FGAN above correspond to approximately 55–75% of that for AN with density 0.92 g/cc ($P_{CJ} \sim 3.70$ GPa).

[‡] FGAN, unlike TGAN, is typically shipped in big-bags holding 600 kg product. Crystalline AN grades, another type of high-density AN products, are in Europe typically shipped in big-bags holding 1000 kg product.

For the most critical AN products, belonging to the most stringent (red) category of Table 2.3, with high bulk densities (greater than 0.85 g/cc), we find a uniform critical separation distance of only 1 meter – regardless of stack or pile size – to be unsound. While it probably will all but remove the likelihood of a detonation event in one stack from propagating to an adjacent stack, such a small separation distance may not block a "thermal event" from spreading further.

By a thermal event, we here mean an escalating and exothermic mass decomposition of solid AN material(s), taking place during storage as result of fire exposure or other undue heat loads. In such a scenario, the thermal decomposition may possibly reach a level of violent deflagration, and sufficient separation distances should be applied to prevent a thermal event directly linking piles together, even though the decomposition may not develop into full-fledged detonation.

To address the possible spreading of a thermal event, we here suggest what can be referred to as an approximate "order of magnitude" principle, as in Table 4.3, where the separation distance is doubled when going from a stack size of 1–10 to 10–100 tonnes (an "order of magnitude") and doubled again when going from a stack size of 10–100 to 100–500 tonnes.

Table 4.3 Recommended intra-stack separation distances for critical AN products having high bulk density (greater than 0.85 g/cc) according to an "order of magnitude" principle. The AN product stack size is here limited to 500 tonnes.

Quantity of AN product in stack [metric tonnes]	**Moderate intra-stack separation distances**	**Conservative intra-stack separation distances**
1–10	1 m	2 m
10–100	2 m	4 m
100–500	4 m	8 m

Stacks larger than 500 tonnes have not been included in Table 4.3, and such stacks are usually not recommended, as encouraged by the SAFEX guidelines and the Australian code of practice [11,17]. The system in Table 4.3 has been arranged in two tiers, having one class of moderate separation distances and one class of conservative separation distances, both following the same principle of "order of magnitude" with stepwise doublings of separation distance.

The potential for violent (but non-detonative) decomposition sets the high-density AN products belonging to the most stringent (red) category of Table 2.3 apart from products belonging to the mildest (yellow) category or those that are not covered at all by the hazard classification system, such as the CAN fertilizer materials.* We therefore recommend that separation distances be introduced in order to prevent the transfer of thermal mass decomposition events.

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* Please see Section 2.3 for arrangement of the three-tier hazard classification system for AN products.

4.8 Inter-tank separation distances for ammonium nitrate fluid products

AN fluid products (ANSOLs, ANEs and AN suspensions/gels) are stored in tanks, usually made from either metal (steel or aluminium) or plastic materials (with fiber reinforcement). Though the previous discussion in Section 3.8 focused on metal tanks, guidelines in certain countries encourage use of tanks made from plastic materials (co-combustible with the AN product).

Although the likelihood of a detonation event in a storage tank holding AN fluid product must be regarded as very low (see discussion in Section 3.8), such an occurrence cannot, most likely, be ruled out altogether. In order to prevent detonative transfer from one storage tank to another, adequate inter-tank separation distances must be upheld. In order to use CFD simulations to assess such separation distances, the following four-step approach has been used at FFI:

1. A critical initiation pressure criterion for a representative AN fluid product was established by CFD modeling of the ANE gap test prescribed in Test Series 8, part of Section 18, in the *Manual of Tests and Criteria* [6]. The specific AN fluid product used was the generic ANE used earlier in Table 3.5 (76.0% AN, 17.0% water, 5.6% paraffin, 1.4% polyisobutylene).

2. A generic, representative tank for storage of AN fluid product (~35 tonnes) was defined based on input from relevant commercial explosives manufacturers (Figure 4.5).

3. CFD simulations of detonating AN fluid product storage tanks were carried out, with the cylindrical storage tanks placed side by side. The effect of fragments was not included.

4. Inter-tank separation distances were evaluated based on the mentioned CFD simulations of AN fluid product storage tanks in combination with the critical initiation pressure criterion of the AN fluid product concerned (as determined by the simulations of the ANE gap test).

The ANE gap test given in the *Manual of Tests and Criteria* is different from the air-gap tests treated previously (Section 4.2 to 4.4), both with regard to scale and the inert barrier material employed. In the said ANE gap test, a cylindrical donor pellet* (95×95 mm) is used to initiate a cylindrical acceptor charge (steel tubing, 280 mm in length, 95.0 ± 7.0 mm outer diameter) containing the ANE, using a rod of polymethyl methacrylate (PMMA) as the inert barrier [6].

Contrasting air and other gases, PMMA is almost incompressible, making the shock dynamics of this gap test much simpler than those for air-gap tests. Also, the density of PMMA (a solid) is comparable to the materials making up the donor and acceptor charges. As a result, PMMA gap tests result in a single shock-compression of the acceptor material. The maximum pressure induced by this shock wave was interpreted as the critical initiation pressure of the ANE.

The generic AN fluid product storage tank chosen for use in our simulation work is presented in Figure 4.5. The dimensions of the tank were selected based on input from relevant industry.

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* Consisting of either pentolite (≥50% PETN), Composition B (≥50% RDX) or RDX/wax (≥95% RDX) and having a density of 1600 kg/m^3 ± 50 kg/m^3. A sketch of the coaxially aligned gap test set-up is included in the UN manual [6].

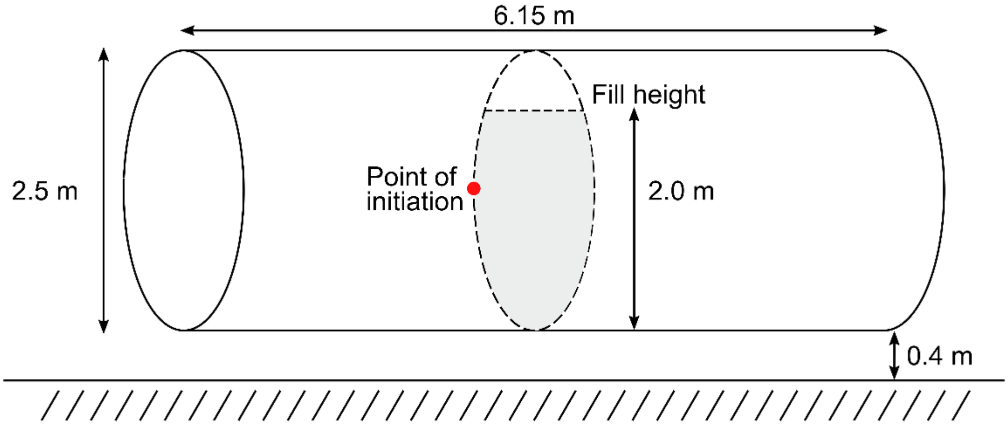

Figure 4.5 Generic tank for storage of AN fluid product, with indicated spatial dimensions. Indicated fill height of generic AN emulsion with density 1.35 g/cc (see Table 3.5) corresponds to a total tank content of just under 35 tonnes. This model tank has been used in the simulation work herein, and its dimensions were chosen based on representative storage tanks in use by explosives manufacturers in Europe.

A complication arises in using the results from the abovementioned ANE gap tests, prescribed in the *Manual of Tests and Criteria*, because the gap length corresponding to the 50% estimate (for initiation of the acceptor) is not available, only positive/negative test results for given gap lengths (typically 35 and 70 mm). For the generic ANE selected for this work, a negative test result is obtained at 35 mm PMMA when it is in a non-sensitized condition, while a positive test result is obtained at both 35 and 70 mm when the ANE is in a sensitized condition [6].*

The term "non-sensitized condition" refers to the ANE as stored. One may foresee a situation where a storage tank holding ANE in such unaffected condition is subjected to a shock wave from a detonating, neighboring storage tank, regardless of the condition of the ANE that gave rise to the detonation (even though a fire scenario could, or will, affect both tanks similarly).

The phrase "sensitized condition" here refers to the ANE in a gassed state with reduced density. This condition may arise because of prolonged heating of the ANE tank during a fire scenario, something that may cause decomposition, boiling, etc. In this state, the ANE is considerably more shock sensitive than when in a non-sensitized condition. While the actual state of such ANE, under accidental circumstances, is unknown, a heightened sensitivity must be assumed.

The 35 mm gap test result was used to establish a conservative initiation pressure criterion for non-sensitized ANE. For the sensitized ANE, a critical (minimum) gap length could in fact not be established with certainty, but the positive result at 70 mm gap length, when taken together with gap test results obtained with comparable ANEs, did provide some indications [6].

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* These numbers have been extracted from the *Examples of results* on p. 204 in the *Manual of Tests and Criteria*, with the ANE designated ANE-1/ANE-2 and consisting of 76.0% AN, 17.0% water and 7.0% fuel/emulsifier [6]. Parameters derived for this ANE are provided in Appendix C (non-sensitized) and Appendix E (sensitized).

For non-sensitized ANE, CFD simulations of the ANE gap test gave a critical initiation pressure that is approximately on the level of the theoretical Chapman-Jouguet detonation pressure of the ANE, that is, about 14–15 GPa. These simulations therefore substantiate the common notion of non-sensitized ANEs having a very low degree of shock sensitivity. For non-sensitized ANEs, an inter-tank separation distance of 1 meter should be adequate – based on shock pressure.

In the case of sensitized ANE, the situation is much less clear-cut, because a negative gap test result for the material was not available for the present work. Yet, simulation of detonation in the storage tank of Figure 4.5 – with its content being sensitized ANE of bulk density 1.30 g/cc, and starting at the indicated point of initiation – has been used to assess separation distances, by comparison with the shock sensitivity of porous TGAN (which should be equally sensitive).

The simulations show that the pressure developed by the detonating storage tank on an adjacent storage tank, when they are positioned side by side in parallel, reaches a level of around half the theoretical Chapman-Jouguet detonation pressure at an inter-tank separation distance of roughly 6–7 meter.[*] Shock reflections at the ground level make it difficult to make precise estimates. In addition, the details of these shock dynamics will vary somewhat with the exact tank layout.

On the basis of shock initiation alone, a conservative inter-tank separation distance of 7 meter should probably suffice to prevent sympathetic detonation, also when the tank at the receiving end holds ANE in sensitized condition.[†] However, a hugely complicating factor is the effect of any high-velocity fragments thrown out by a detonating tank with AN fluid product, at least in those cases where the tank material is constituted (mainly) by metals (steel or aluminium).

Initiation of detonation by high-velocity fragments is well established, and barricades can be very effective in preventing sympathetic detonation. During the 1960s Van Dolah experiments, the air-gap tests conducted included donor charges where the downstream end closure was made from 1/16-inch sheet steel plating, thereby giving rise to dense, high-velocity fragments [27-29]. Use of such metal-ended donors resulted in markedly increased distances for 50% initiation.

Compared to soft-ended donors made from thin plastic sheeting,[‡] use of metal-ended donors gave estimated distances for initiation of prilled AN that increased roughly by a factor of two. For analogous air-gap tests with acceptors containing ANFO or dynamite, use of metal-ended donors gave an increase in the 50% estimate as high as a factor of approximately three [29]. Sensitive explosives were thus more susceptible to initiation by high-velocity fragments.

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[*] It should be emphasized that this distance estimate applies only to the specific storage tank outlined in Figure 4.5, holding the specified ANE to the level indicated (~35 tonnes ANE). As commonly practiced at many sites in Europe, the total amount of AN fluid product stored at one location, in one or more tanks, is kept within the 50-tonne limit (lower-tier requirement) mandated by the Seveso-III Directive for AN fluid products (UN 3375 products) [3].

[†] Whereas a negative gap test result for the ANE was not available for this work, we have previously detailed how our estimated critical initiation pressures for TGAN, listed in Table 4.1, correspond to ca. 50–60% of the theoretical Chapman-Jouguet detonation pressure for AN with density 0.80 g/cc. Because such porous prilled AN is considered to be rather shock sensitive, we have used a pressure value of 50% of the theoretical Chapman-Jouguet detonation pressure as a simplified proxy criterion for sensitized ANE. Additional margin was added on top, as detailed later.

[‡] Please see Figure 4.1 in Section 4.2 for the detailed experimental design of the Van Dolah experiments.

Consequently, to include the effect of high-velocity fragments ejected from a metal storage tank holding an AN fluid product, in a worst-case scenario entailing an all-inclusive detonation of the tank contents, the inter-tank separation distance then ought to be doubled – from 7 to 14 meter. Some additional margin of safety can be added on top, giving a recommendation of 16 meter.

The effect of sand/soil-filled barricades were studied as part of the Van Dolah experiments, and these apparently proved "remarkably effective in preventing sympathetic detonation" [29]. The ratio between the unbarricaded and barricaded separation distances was found to be in the range of three to five for prilled AN (and as high as seven for acceptors holding ANFO) [29].*

According to Van Dolah, separation of unbarricaded charges compared to barricaded charges entailed, according to the state of knowledge at the time of the Van Dolah field experiments, a doubling of the separation distance. These guidelines indicated an effect of the barrier that was noticeably smaller than the 3–5 ratio subsequently found during the large-scale air-gap tests on acceptors holding prilled AN material [29]. We have used the estimates found by Van Dolah.

Concerning inter-tank separation distances for the generic storage tank outlined in Figure 4.5, the recommended unbarricaded distance for such tanks, when constructed of metal and holding AN fluid product, was determined to be 16 meter, taking into account the effect of fragments. The barricaded distance may then be reduced by a factor of 3 to 5 to give 3–6 meter.†

For AN fluid product storage tanks made from fiber-reinforced plastic, fragment hazards are significantly reduced, so an inter-tank separation distance of 8 meter – based on shock pressure alone, and with 1 meter of added margin on top – seems adequate. This translates to half of the 16-meter separation distance above that apply to metal storage tanks of equivalent design.

Due to the obvious impracticality of introducing a 16-meter inter-tank separation distance for AN fluid product storage tanks, the use of barricades between such storage tanks to filter out, and/or reducing the velocity of, metal fragments, will probably be rather prevalent. However, we will not here provide any detailed guidelines for the construction of adequate barricades, referring instead to those that can be found in regulations applying to high-explosives.

A weakness of our analysis is the fact that it strictly applies to only a single type of storage tank, holding a specified ANE product, though we believe these choices are somewhat representative of practices and situations in many places. Our framework can certainly be extended to similar circumstances. The guiding principle in this section has been the lower-tier requirement limit of 50 tonnes mandated by the Seveso-III Directive for UN 3375 AN fluid products [3].

AN liquid solutions (UN 2426 products) do not contain fuel components and have higher quantity limits than other AN fluid products. They will be treated separately in Section 4.10.

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* The thickness of the barricade, constructed of ½-inch plywood without metal fasteners and filled with sandy soil taken from the test site in Wisconsin in the upper Midwestern USA, was scaled to ¼ the charge diameter [29].

† We have chosen to use 16 meter, a number containing an additional margin of safety of 2 meter on top of values obtained from CFD simulations, as basis. This margin of safety is similar to that applied previously in Table 4.2.

4.9 Separation distances for co-storage of AN products belonging to different hazard categories

One final point to be addressed is the co-storage of AN products belonging to different hazard categories. The treatment in this section will be limited to co-storage of AN products covered by the classification system in Table 2.3. Co-storage of AN products with either high-explosives or pyrotechnic articles, or both of these sorts of materials, is outside the scope of the present work.

Because AN products belonging to the mildest (yellow) category of Table 2.3 are not believed to pose any probable explosion hazard (see Section 3.7), co-storage of these AN products with AN products belonging to any of the other two hazard categories (red, orange) is believed to be uncomplicated. However, as even the least critical AN products in Table 2.3 pose a fire hazard, their inclusion in a store can heighten the overall probability of a fire event occurring there.[*]

Co-storage of AN products belonging to the most stringent (red) category with AN products belonging to the intermediate (orange) category (AN fluid products) is the main issue that needs to be addressed. Once more, CFD simulations were taken into use, and representative conditions were modeled by simulation of detonation of the generic storage tank shown in in Figure 4.5, positioned in the vicinity of a stack of bagged AN product belonging to the red category.

The specific AN product stack chosen for simulation was stack no. 9 in Table 4.2, with two layers of 5×5 big-bags, each weighing 1250 kg and containing prilled AN product of medium bulk density (see Section 4.5). The detailed arrangement is shown schematically in Figure 4.6. The point of initiation is located on the side of the tank situated opposite to the stack, hence giving a worst-case scenario with regard to the shock pressure applied to the big-bag stack.

It is here worth pointing out that in the co-storage of AN products belonging to red and orange categories, it is actually the AN fluid product in the orange category, the least critical category of the two, that has the greatest detonative performance. As such, the AN fluid product is in fact the dimensioning factor, at least in those instances where the amount of AN material is similar in the storage tank and the big-bag stack. As mentioned earlier (Section 3.8), this is due to the fact that AN fluid products in the UN 3375 class contain fuel components in addition to AN.[†]

Our CFD simulations of the storage layout in Figure 4.6 indicate a critical tank-stack separation distance of approximately 6 meter if the stack holds prilled AN of medium bulk density, using the critical initiation pressure criterion for prilled AN developed in Section 4.4. This is similar to the inter-tank separation distance of roughly 6–7 meter determined in the previous section.

In analogy with the evaluations in the immediately foregoing section, this separation distance is increased from 6 meter to either 8 meter (plastic tanks) or 16 meter (metal tanks), depending on the fragment hazard (and with the same added margin on top). This simplifies our framework.

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[*] We have not attempted to quantify this hazard, but a uniform separation distance of 1 meter will be recommended.

[†] Additionally, they have much higher densities, giving considerably higher detonation pressure than solid AN.

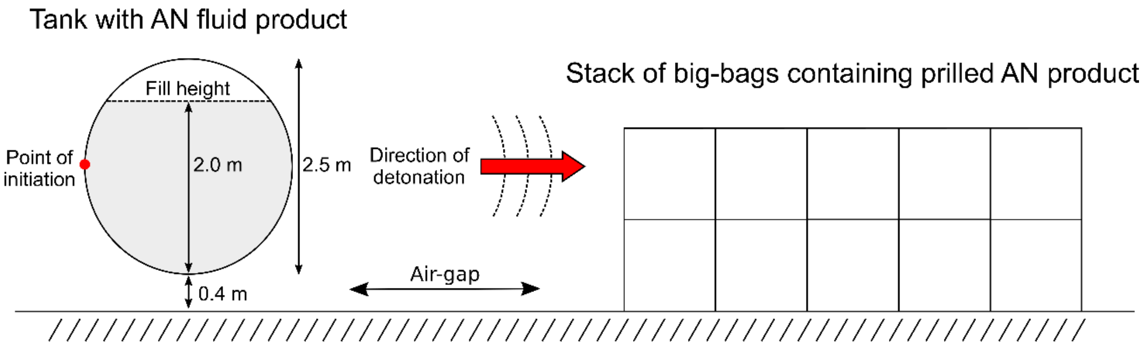

Figure 4.6 Layout for CFD simulation of detonating storage tank holding AN fluid product, positioned near a big-bag stack with prilled AN product of medium bulk density. The tank is identical to that in Figure 4.5 and holds the same generic ANE of density 1.35 g/cc. The stack has two layers, with 5×5 big-bags in each layer.

With regard to unbarricaded versus barricaded separation distances, we recommend applying a reduction based on the same 3–5 ratio as argued previously. Accordingly, a separation distance of 16 meter will be reduced to 3–6 meter. We will refine the separation distances determined in this section, as well as the ones in the preceding section, and forward all of these in our final recommendations summarized toward the end of the present chapter in Section 4.11.

4.10 Separation distances for ammonium nitrate liquid solutions

A complication relevant for the AN fluid products belonging to the intermediate (orange) category of Table 2.3 is the fact that they are constituted by two major types of fluid products: UN 2426 products (AN liquid solutions) and UN 3375 products (ANEs, AN suspensions/gels). Of these, only the UN 3375 products have been treated in Section 4.8 and 4.9 above.

The AN liquid solutions of the UN 2426 products are associated with a 350 tonne lower-tier requirement in the Seveso-III Directive, compared to 50 tonnes for the UN 3375 products [3].[*] They do not contain fuel components and are therefore less critical. In the case of separation distances to protected places in the previous chapter (Section 3.8), we argued for treating the AN liquid solutions in the same way as pure AN, using the separation distances for the latter.

However, with regard to separation distances for sympathetic detonation,[†] AN liquid solutions must be considered significantly less hazardous than solid AN, ANEs or AN suspensions/gels. The likelihood of a tank of AN liquid solution serving either as a donor or as an acceptor are almost certainly very low. Serving both roles are even less likely. Accordingly, we propose uniform separation distances of 5 meter (unbarricaded) and 3 meter (barricaded).

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[*] These liquid solutions are concentrated (80–93% AN in water, see Table 2.2), and must be stored in hot condition, something that may preclude storage of very large quantities in a single tank.

[†] Unlike separation distances to protected places, sympathetic detonation entails both donor and acceptor abilities.

4.11 Summary of recommendations for the internal arrangement of storage facilities holding the critical ammonium nitrate products covered by the three-tier hazard classification system (red/orange/yellow)

Our final recommendations for the internal arrangement of storage facilities holding the critical AN products integrated into the three-tier classification system of Table 2.3 (red/orange/yellow) have been summarized in Table 4.4 for the AN products belonging to the same hazard category, and in Table 4.5 for co-storage of AN products belonging to two different hazard categories.

When all AN products belong to the red category, we advise applying Table 4.2 for products having either medium or low bulk density and Table 4.3 for products having high bulk density. We also forward some tentative recommendations regarding the maximum product stack size.

When all AN products belong to the orange category, the situation is more complicated due to differentiation on the use of plastic versus metal tanks, unbarricaded versus barricaded distances and formulation of guidelines relevant for emulsions/suspensions/gels versus liquid solutions. For AN liquid solutions, we propose uniform and simplified separation distances (Table 4.4).

For AN emulsions/suspensions/gels, we recommend the 16-/8-meter unbarricaded inter-tank separation distances discussed in Section 4.8, applying to storage tanks that can be reasonably represented by the one in Figure 4.5. For the accompanying barricaded distances, a reduction using the 3–5 ratio was argued in Section 4.8 and 4.9 (based on the Van Dolah experiments). We have reduced the 16- and 8-meter distances conservatively to 5 and 3 meter, respectively.[*]

In the case of AN products belonging to the yellow category, we recommend introducing only a uniform separation distance of 1 meter for all product stacks larger than 100 tonnes, in order to avoid any self-sustaining decomposition from spreading directly from one stack to another.

For co-storage of AN products belonging to different hazard categories, co-storage of products from either the red or orange category together with any from the yellow category is regarded as uncomplicated. Nevertheless, we encourage the use of a uniform separation distance of 1 meter.

In the case of co-storage of AN products from the red and orange categories, as delimited by the tank and stack sizes in the table, we advise different regimes depending on the specific products involved. Generally, the AN liquid solutions lead to more favorable separation distances than the AN emulsions/suspensions/gels, and products in the red category having medium or low bulk densities lead to greater separation distances than products having high bulk density.

For all AN products in Table 4.5, the dimensioning factor for any separation distance comprises both the “donor side” (product explosive capability) and “acceptor side” (product sensitivity).

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[*] While not discussed here, it is obvious that the application of a plastic tank for storage of any AN fluid product will, notwithstanding a more beneficial separation distance, in the event of a fire scenario occurring, lead to the release and subsequent open combustion of the fluid product involved. To what extent such circumstances should be regarded as more, or less, hazardous than allowing the fire to heat the fluid product in a sufficiently ventilated metal storage tank, we will not attempt to answer here. Probably, the explosion hazard will be low in both cases.

Table 4.4 Summary of recommendations for inter-stack/inter-tank separation distances for storage of AN products belonging to the same hazard category in Table 2.3.[*]

Seveso-III Directive AN products	**ADR treaty UN No.**	**Summary of recommendations for inter-stack/inter-tank separation distances**
Ammonium nitrate technical grade	1942	• *Medium bulk density (0.75–0.85 g/cc)* Apply the recommendations in Table 4.2 for a given (big-bag) stack configuration. Stacks different from, or larger than, the stacks in Table 4.2 are discouraged. • *Low bulk density (<0.75 g/cc)* Same recommendations as for analogous products having medium bulk density. • *High bulk density (>0.85 g/cc)* Apply the recommendations in Table 4.3. Products stacks larger than 500 tonnes are discouraged.
Ammonium nitrate fertiliser grade	1942	
Ammonium nitrate fertiliser grade containing more than 80% AN	2067	
Ammonium nitrate 'off-specs' material and fertilisers	Not applicable	
Ammonium nitrate technical grade AN liquid solutions	2426	• *AN liquid solutions* Apply a uniform separation distance of either 5 meter (unbarricaded) or 3 meter (barricaded) between all tanks. • *AN emulsions, suspensions and gels* For tanks similar to the one in Figure 4.5: 16 meter (unbarricaded metal tank) 8 meter (unbarricaded plastic tank) 5 meter (barricaded metal tank) 3 meter (barricaded plastic tank)
Oxidizing liquids AN emulsions, suspensions and gels	3375	
Ammonium nitrate fertiliser grade containing less than 80% AN	2067	• *All AN products in this category* Apply a uniform separation distance of 1 meter for all product stacks larger than 100 tonnes in order to avoid self-sustaining decomposition from spreading directly from one stack to another.
Ammonium nitrate fertilisers capable of self-sustaining decomposition	2071	

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[*] For co-storage of different type/kind/variety of AN products that belong to the same hazard category in Table 2.3, please see our concluding remarks at the end of the present section, immediately after the conclusion of Table 4.5.

Table 4.5 Summary of recommendations for stack-tank/stack-stack separation distances for co-storage of AN products belonging to different hazard categories in Table 2.3.[*]

Hazard category combination (red/orange/yellow)		**Summary of recommendations for stack-tank/stack-stack separation distances**
Red Medium bulk density (0.75–0.85 g/cc)	**Orange** AN liquid solutions (UN 2426)	• Unbarricaded separation distance: 5 meter (stack to plastic or metal tank) • Barricaded separation distance: 3 meter (stack to plastic or metal tank)
Red Low bulk density (<0.75 g/cc)	**Orange** AN liquid solutions (UN 2426)	• Unbarricaded separation distance: 5 meter (stack to plastic or metal tank) • Barricaded separation distance: 3 meter (stack to plastic or metal tank)
Red High bulk density (>0.85 g/cc)	**Orange** AN liquid solutions (UN 2426)	• Unbarricaded separation distance: 3 meter (stack to plastic or metal tank) • Barricaded separation distance: 2 meter (stack to plastic or metal tank)
Red Medium bulk density (0.75–0.85 g/cc)	**Orange** AN emulsions, suspensions and gels (UN 3375)	• Unbarricaded separation distance: 16 meter (stack to metal tank) 8 meter (stack to plastic tank) • Barricaded separation distance: 5 meter (stack to plastic or metal tank)
Red Low bulk density (<0.75 g/cc)	**Orange** AN emulsions, suspensions and gels (UN 3375)	• Unbarricaded separation distance: 20 meter (stack to metal tank) 10 meter (stack to plastic tank) • Barricaded separation distance: 6 meter (stack to plastic or metal tank)
Red High bulk density (>0.85 g/cc)	**Orange** AN emulsions, suspensions and gels (UN 3375)	• Unbarricaded separation distance: 5 meter (stack to plastic or metal tank) • Barricaded separation distance: 3 meter (stack to plastic or metal tank)

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[*] In this table, the storage tank for the AN fluid product should be roughly similar to the ~35 tonne tank in Figure 4.5. For co-storage of AN products belonging to the red and orange categories, stack size has been limited to 100 tonnes. Discussion of unbarricaded versus barricaded separation in this text has not included the (usually) very large stacks making up most of Table 4.2, as it is difficult to assess and address adequate barricades for stacks of such size.

Red All products	**Yellow** All products	- Apply a uniform separation distance of 1 meter (stack to stack).
Orange All products	**Yellow** All products	- Apply a uniform separation distance of 1 meter (stack to plastic or metal tank).

To conclude, we will elaborate on some of the special cases covered by Table 4.4 and 4.5.

Because AN products belonging to the same hazard category in Table 2.3 are not necessarily treated uniformly with regard to separation distances, the concept of co-storage will now and then apply also to different AN products fitting within the same hazard category. In particular, this will apply to products in the red and orange categories (density or fluid types/varieties).

Upon such co-storage of different types of AN products belonging to the same hazard category, we recommend using the separation distances that apply to the most critical AN product variety. This is because donor and acceptor abilities are both crucial in sympathetic detonation events.

In co-storage of AN products in the red category, medium and low-density products have the same separation distances (given in Table 4.2), but high-density products have less restrictive separations (given in Table 4.3). Now then, if medium and/or low-density products are stored together with high-density products, we therefore suggest taking use of the separation distances applying to the former products, between two stacks of such differing AN product varieties.[*]

In co-storage of AN products in the orange category, AN liquid solutions have less restrictive separation distances than AN emulsions/suspensions/gels. If these two AN fluid product types are then to be stored together, we suggest using the separation distances applying to the latter, between two storage tanks when they contain these two different AN product varieties.[†]

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[*] Although high-density AN is an unlikely donor material, necessitating a strong impulse for initiation of detonation, it makes a strong donor material because of its high density. Hence, explosive decomposition of high-density AN can therefore affect neighboring medium/low-density AN strongly, e.g. in a fire scenario. On the other hand, high-density AN is a very insensitive acceptor material, making propagation of detonation from medium/low-density AN to high-density AN unfeasible. For co-storage of high-density AN together with medium/low-density AN, the dimensioning factor will be propagation from the former to the latter, putting the separation distances of the latter in effect. Also, we have not attempted to introduce any compensation for now having high-density AN as donor yet actually using the separation distances in Table 4.2, which were calculated using medium/low-density AN as the donor material.

[†] AN emulsions/suspensions/gels are stronger donors than AN liquid solutions in the event of sympathetic detonation, and the former are also more sensitive as acceptor materials. Propagation of detonation from the former to the latter is the dimensioning factor, also because the sensitivity of AN liquid solutions is unknown, but may be significant when gassed during decomposition. For these reasons, the separation distances applying to AN emulsions/suspensions/gels should be put into effect upon such co-storage with AN liquid solutions. No compensation for the asymmetry of the donor/acceptor relation has been introduced, but all of our separation distances already contain some safety margin.

Turning now to co-storage of AN products from different hazard categories. For co-storage of the least critical members of the orange category, AN liquid solutions, with AN products from the red category, our recommended separation distances (Table 4.5) are similar to the distances applying to AN liquid solutions in Table 4.4, but high-density AN gives reduced distances.[*]

Co-storage involving AN emulsions/suspensions/gels, which make powerful donor materials, with the AN products belonging to the red category gives rise to a more complicated evaluation. The specific case concerning high-density AN gives the smallest separation distances. However, for medium/low-density AN, these products' higher sensitivity must be taken into consideration.

Situations where AN emulsions/suspensions/gels are stored together with prilled AN having medium bulk density were treated specifically in Section 4.9. The reader is encouraged to seek out the discussion in that section to understand how the recommended separation distances in Table 4.5, for co-storage of these AN fluid products with medium density AN, were determined.

When low-density AN of the red category is stored with AN emulsions/suspensions/gels of the orange category, a special situation arises. As the reader might recall, our reasoning for treating medium and low-density AN, both part of the red category, equally with regard to inter-stack separation distances, was because a lowered density makes the AN product a less powerful donor material, weighing up for low-density product being a more sensitive acceptor.[†]

However, for the asymmetric donor-acceptor relation relevant for co-storage of low-density AN with AN emulsions/suspensions/gels, our previous arguments in Section 4.6 are invalid. What is more, this storage scenario is particularly delicate because AN emulsions/suspensions/gels are strong donor materials while low-density AN is a rather sensitive acceptor material.

Our recommended separation distances in Table 4.5 for co-storage of AN with low bulk density and AN emulsions/suspensions/gels were calculated by taking distances for the equivalent state involving AN with medium bulk density and adding an additional safety margin of 25% on top, increasing the 8-meter and 16-meter distances to 10 meter and 20 meter, respectively.

The 25% safety margin for low-density AN, relative to material having medium bulk density, was estimated from our CFD simulations of detonating stacks of low-density AN, previously applied in establishing the inter-stack separation distances in Section 4.6. We first assessed the shock sensitivity of medium and low-density AN and then transferred this criterion to the storage layout in Figure 4.6, involving a storage tank positioned near a big-bag stack.

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[*] We have previously pointed out, on several occasions, our belief that AN with high bulk density must be considered a considerable hazard in a fire scenario. Regarding co-storage, they must therefore be treated as quite powerful donor materials. However, they are very insensitive acceptor materials. In this particular instance, since AN liquid solutions are poor donor materials and insensitive acceptor materials, co-storage of high-density AN with AN liquid solutions give reduced separation distances compared to analogous co-storage involving medium or low-density AN.

[†] Please see Section 4.6 for our detailed arguments.

4.12 Suggestions for future studies

We would like to remark that the Van Dolah experiments indicate a square root scaling law for sympathetic detonation involving charges of prilled AN. It might be that inter-stack separation distances for such AN products could be based on such a simple scaling law, instead of having to resort to tables such as Table 4.2 herein, where the exact configuration of each product stack has been specified. This could potentially simplify our framework for government regulations. We suggest that future work address such simplified scaling laws for assessment of adequate inter-stack separation distances for storage of the most critical AN products.

Appendix

A Parameters derived for AN of density 0.80 g/cc by computerized thermochemical calculations

The tabulated parameters below were derived for 100% AN of density 0.80 g/cc by application of the thermochemical computer code EXPLO5 (Version 6.06), using the Exp-6 EOS and setting the freezing of chemical equilibrium to 1800 K:

Jones-Wilkins-Lee (JWL) EOS coefficients	
A [GPa]	101.87
B [GPa]	1.5839
R_1	5.53
R_2	1.47
ω	0.356
ρ_0 [kg/m^3]	800

Parameters at Chapman-Jouguet (CJ) state	
P_{CJ} [GPa]	2.6277
ρ_{CJ} [kg/m^3]	1055.9
γ_{CJ}	3.13
D [m/s]	3682

B Tables with calculated separation distances for AN storage facilities when attenuated by explosive yields/efficiencies

The tables with calculated separation distances on the following pages have been prepared from Table 3.1 in the main text by applying the scaling law of Table 3.2. Like for values in Table 3.1, all distances have been rounded to the nearest multiple of 10 meter. It is important to note that the AN product quantities given in these tables correspond to the ones in the largest product stack or pile that fulfills the requirements of inter-stack separation as prescribed in Chapter 4.

B.1 Table with separation distances for AN storage facilities (Table 3.1) when attenuated by an explosive yield/efficiency of 75%

Quantity of AN [metric tonnes]	Distances for AN air blast overpressure thresholds [m]					
	2 kPa	**5 kPa**	**7 kPa**	**14 kPa**	**21 kPa**	**40 kPa**
1	260	120	90	60	40	30
2	320	150	120	70	60	40
5	440	210	160	100	70	50
10	550	260	200	120	90	60
15	630	300	230	140	110	70
20	690	330	260	160	120	80
25	750	360	280	170	130	80
30	790	380	300	180	140	90
40	870	420	320	200	150	100
50	940	450	350	210	160	110
75	1080	520	400	240	180	120
100	1180	570	440	270	200	140
125	1280	610	470	290	220	140
150	1360	650	500	300	230	160
175	1430	690	530	320	240	160
200	1490	720	560	340	260	170
250	1610	770	600	360	280	180
300	1710	820	640	380	290	200
350	1800	860	670	400	310	200
400	1880	900	700	420	320	220
450	1960	940	730	440	330	220
500	2020	970	750	460	350	230
750	2320	1120	860	520	400	260
1000	2550	1230	950	570	440	290
1250	2750	1320	1020	620	470	310
1500	2920	1400	1090	660	500	330
2000	3220	1550	1200	720	550	370
2500	3460	1670	1290	780	590	400

B.2 Table with separation distances for AN storage facilities (Table 3.1) when attenuated by an explosive yield/efficiency of 50%

Quantity of AN [metric tonnes]	Distances for AN air blast overpressure thresholds [m]					
	2 kPa	**5 kPa**	**7 kPa**	**14 kPa**	**21 kPa**	**40 kPa**
1	220	110	80	50	40	20
2	280	140	100	60	50	30
5	380	180	140	80	60	40
10	480	230	180	110	80	50
15	550	260	200	120	90	60
20	600	290	220	140	100	70
25	650	310	240	150	110	70
30	690	330	260	160	120	80
40	760	370	280	170	130	90
50	820	400	300	180	140	90
75	940	450	350	210	160	110
100	1030	500	380	230	180	120
125	1110	540	410	250	190	130
150	1180	570	440	270	200	140
175	1250	600	460	280	210	140
200	1300	630	480	290	220	150
250	1400	680	520	320	240	160
300	1490	720	560	340	260	170
350	1570	760	580	350	270	180
400	1640	790	610	370	280	190
450	1710	820	640	380	290	200
500	1770	850	660	400	300	200
750	2020	970	750	460	350	230
1000	2230	1070	830	500	380	250
1250	2400	1160	890	540	410	270
1500	2550	1230	950	570	440	290
2000	2810	1350	1040	630	480	320
2500	3030	1460	1130	680	520	350

B.3 Table with separation distances for AN storage facilities (Table 3.1) when attenuated by an explosive yield/efficiency of 30%

Quantity of AN [metric tonnes]	Distances for AN air blast overpressure thresholds [m]					
	2 kPa	5 kPa	7 kPa	14 kPa	21 kPa	40 kPa
1	190	90	70	40	30	20
2	240	110	90	50	40	30
5	320	150	120	70	60	40
10	400	190	150	90	70	50
15	460	220	170	100	80	50
20	510	240	190	110	90	60
25	550	260	200	120	90	60
30	580	280	220	130	100	70
40	640	310	240	140	110	70
50	690	330	260	160	120	80
75	790	380	300	180	140	90
100	870	420	320	200	150	100
125	940	450	350	210	160	110
150	1000	480	370	220	170	110
175	1050	510	390	240	180	120
200	1100	530	410	250	190	120
250	1180	570	440	270	200	140
300	1260	600	470	280	220	140
350	1320	640	490	300	230	150
400	1380	670	520	310	240	160
450	1440	690	540	320	250	160
500	1490	720	560	340	260	170
750	1710	820	640	380	290	200
1000	1880	900	700	420	320	220
1250	2020	970	750	460	350	230
1500	2150	1040	800	480	370	250
2000	2370	1140	880	530	400	270
2500	2550	1230	950	570	440	290

B.4 Table with separation distances for AN storage facilities (Table 3.1) when attenuated by an explosive yield/efficiency of 25%

Quantity of AN [metric tonnes]	Distances for AN air blast overpressure thresholds [m]					
	2 kPa	**5 kPa**	**7 kPa**	**14 kPa**	**21 kPa**	**40 kPa**
1	180	80	60	40	30	20
2	220	110	80	50	40	20
5	300	140	110	70	50	30
10	380	180	140	80	60	40
15	440	210	160	100	70	50
20	480	230	180	110	80	50
25	520	250	190	120	90	60
30	550	260	200	120	90	60
40	600	290	220	140	100	70
50	650	310	240	150	110	70
75	750	360	280	170	130	80
100	820	400	300	180	140	90
125	880	420	330	200	150	100
150	940	450	350	210	160	110
175	990	480	370	220	170	110
200	1030	500	380	230	180	120
250	1110	540	410	250	190	130
300	1180	570	440	270	200	140
350	1250	600	460	280	210	140
400	1300	630	480	290	220	150
450	1360	650	500	300	230	160
500	1400	680	520	320	240	160
750	1610	770	600	360	280	180
1000	1770	850	660	400	300	200
1250	1910	920	710	430	330	220
1500	2020	970	750	460	350	230
2000	2230	1070	830	500	380	250
2500	2400	1160	890	540	410	270

B.5 Table with separation distances for AN storage facilities (Table 3.1) when attenuated by an explosive yield/efficiency of 20%

Quantity of AN [metric tonnes]	Distances for AN air blast overpressure thresholds [m]					
	2 kPa	5 kPa	7 kPa	14 kPa	21 kPa	40 kPa
1	160	80	60	40	30	20
2	210	100	80	50	40	20
5	280	140	100	60	50	30
10	350	170	130	80	60	40
15	400	190	150	90	70	50
20	440	210	160	100	80	50
25	480	230	180	110	80	50
30	510	240	190	110	90	60
40	560	270	210	130	100	60
50	600	290	220	140	100	70
75	690	330	260	160	120	80
100	760	370	280	170	130	90
125	820	400	300	180	140	90
150	870	420	320	200	150	100
175	920	440	340	210	160	100
200	960	460	360	220	160	110
250	1030	500	380	230	180	120
300	1100	530	410	250	190	120
350	1160	560	430	260	200	130
400	1210	580	450	270	210	140
450	1260	600	470	280	220	140
500	1300	630	480	290	220	150
750	1490	720	560	340	260	170
1000	1640	790	610	370	280	190
1250	1770	850	660	400	300	200
1500	1880	900	700	420	320	220
2000	2070	1000	770	470	350	240
2500	2230	1070	830	500	380	250

B.6 Table with separation distances for AN storage facilities (Table 3.1) when attenuated by an explosive yield/efficiency of 15%

Quantity of AN [metric tonnes]	Distances for AN air blast overpressure thresholds [m]					
	2 kPa	**5 kPa**	**7 kPa**	**14 kPa**	**21 kPa**	**40 kPa**
1	150	70	60	30	20	20
2	190	90	70	40	30	20
5	260	120	90	60	40	30
10	320	150	120	70	60	40
15	370	180	140	80	60	40
20	400	190	150	90	70	50
25	440	210	160	100	70	50
30	460	220	170	100	80	50
40	510	240	190	110	90	60
50	550	260	200	120	90	60
75	630	300	230	140	110	70
100	690	330	260	160	120	80
125	750	360	280	170	130	80
150	790	380	300	180	140	90
175	830	400	310	190	140	100
200	870	420	320	200	150	100
250	940	450	350	210	160	110
300	1000	480	370	220	170	110
350	1050	510	390	240	180	120
400	1100	530	410	250	190	120
450	1140	550	420	260	200	130
500	1180	570	440	270	200	140
750	1360	650	500	300	230	160
1000	1490	720	560	340	260	170
1250	1610	770	600	360	280	180
1500	1710	820	640	380	290	200
2000	1880	900	700	420	320	220
2500	2020	970	750	460	350	230

B.7 Table with separation distances for AN storage facilities (Table 3.1) when attenuated by an explosive yield/efficiency of 10%

Quantity of AN [metric tonnes]	**Distances for AN air blast overpressure thresholds [m]**					
	2 kPa	**5 kPa**	**7 kPa**	**14 kPa**	**21 kPa**	**40 kPa**
1	130	60	50	30	20	10
2	160	80	60	40	30	20
5	220	110	80	50	40	20
10	280	140	100	60	50	30
15	320	150	120	70	60	40
20	350	170	130	80	60	40
25	380	180	140	80	60	40
30	400	190	150	90	70	50
40	440	210	160	100	80	50
50	480	230	180	110	80	50
75	550	260	200	120	90	60
100	600	290	220	140	100	70
125	650	310	240	150	110	70
150	690	330	260	160	120	80
175	730	350	270	160	120	80
200	760	370	280	170	130	90
250	820	400	300	180	140	90
300	870	420	320	200	150	100
350	920	440	340	210	160	100
400	960	460	360	220	160	110
450	1000	480	370	220	170	110
500	1030	500	380	230	180	120
750	1180	570	440	270	200	140
1000	1300	630	480	290	220	150
1250	1400	680	520	320	240	160
1500	1490	720	560	340	260	170
2000	1640	790	610	370	280	190
2500	1770	850	660	400	300	200

B.8 Table with separation distances for AN storage facilities (Table 3.1) when attenuated by an explosive yield/efficiency of 5%

Quantity of AN [metric tonnes]	Distances for AN air blast overpressure thresholds [m]					
	2 kPa	**5 kPa**	**7 kPa**	**14 kPa**	**21 kPa**	**40 kPa**
1	100	50	40	20	20	10
2	130	60	50	30	20	10
5	180	80	60	40	30	20
10	220	110	80	50	40	20
15	260	120	90	60	40	30
20	280	140	100	60	50	30
25	300	140	110	70	50	30
30	320	150	120	70	60	40
40	350	170	130	80	60	40
50	380	180	140	80	60	40
75	440	210	160	100	70	50
100	480	230	180	110	80	50
125	520	250	190	120	90	60
150	550	260	200	120	90	60
175	580	280	220	130	100	70
200	600	290	220	140	100	70
250	650	310	240	150	110	70
300	690	330	260	160	120	80
350	730	350	270	160	120	80
400	760	370	280	170	130	90
450	790	380	300	180	140	90
500	820	400	300	180	140	90
750	940	450	350	210	160	110
1000	1030	500	380	230	180	120
1250	1110	540	410	250	190	130
1500	1180	570	440	270	200	140
2000	1300	630	480	290	220	150
2500	1400	680	520	320	240	160

B.9 Table with recommended separation distances for AN storage facilities (see Section 3.6) by combining Table B.1 (in grey) and B.4 (in blue)

Quantity of AN [metric tonnes]	Distances for AN air blast overpressure thresholds [m]					
	2 kPa	5 kPa	7 kPa	14 kPa	21 kPa	40 kPa
1–2	200	100	75	50	35	20
2–10	350	150	125	75	50	35
15	630	300	230	140	110	70
20	690	330	260	160	120	80
25	750	360	280	170	130	80
30	790	380	300	180	140	90
40	870	420	320	200	150	100
50	940	450	350	210	160	110
75	1080	520	400	240	180	120
100	1180	570	440	270	200	140
125	1280	610	470	290	220	140
150	1360	650	500	300	230	160
175	1430	690	530	320	240	160
200	1490	720	560	340	260	170
250	1610	770	600	360	280	180
300	1710	820	640	380	290	200
350	1800	860	670	400	310	200
400	1880	900	700	420	320	220
450	1960	940	730	440	330	220
500	2020	970	750	460	350	230
750	2320	1120	860	520	400	260
1000	2550	1230	950	570	440	290
1250	2750	1320	1020	620	470	310
1500	2920	1400	1090	660	500	330
2000	3220	1550	1200	720	550	370
2500	3460	1670	1290	780	590	400

C Parameters derived for generic AN emulsion of density 1.35 g/cc (non-sensitized condition) by computerized thermochemical calculations

The tabulated parameters below were derived for generic AN emulsion of density 1.35 g/cc (76.0% AN, 17.0% water, 5.6% paraffin and 1.4% polyisobutylene) by application of the thermochemical computer code EXPLO5 (Version 6.06), using the Exp-6 EOS and setting the freezing of chemical equilibrium to 1800 K:

Jones-Wilkins-Lee (JWL) EOS coefficients	
A [GPa]	704.90
B [GPa]	9.4917
R_1	5.38
R_2	1.57
ω	0.335
ρ_0 [kg/m^3]	1350

Parameters at Chapman-Jouguet (CJ) state	
P_{CJ} [GPa]	14.4052
ρ_{CJ} [kg/m^3]	1736.0
γ_{CJ}	3.50
D [m/s]	6927

D Parameters derived for ANFO of density 0.85 g/cc by computerized thermochemical calculations

The tabulated parameters below were derived for ANFO of density 0.85 g/cc by application of the thermochemical computer code EXPLO5 (Version 6.06), using the BKW EOS and setting the freezing of chemical equilibrium to 1800 K:

Jones-Wilkins-Lee (JWL) EOS coefficients	
A [GPa]	107.17
B [GPa]	2.3819
R_1	4.78
R_2	1.11
ω	0.331
ρ_0 [kg/m^3]	850

Parameters at Chapman-Jouguet (CJ) state	
P_{CJ} [GPa]	5.7214
ρ_{CJ} [kg/m^3]	1169.6
γ_{CJ}	2.66
D [m/s]	4963

E Parameters derived for generic AN emulsion of density 1.30 g/cc (sensitized condition) by computerized thermochemical calculations

The tabulated parameters below were derived for generic AN emulsion of density 1.30 g/cc (76.0% AN, 17.0% water, 5.6% paraffin and 1.4% polyisobutylene) by application of the thermochemical computer code EXPLO5 (Version 6.06), using the Exp-6 EOS and setting the freezing of chemical equilibrium to 1800 K:

Jones-Wilkins-Lee (JWL) EOS coefficients	
A [GPa]	622.13
B [GPa]	8.2936
R_1	5.39
R_2	1.55
ω	0.332
ρ_0 [kg/m^3]	1300

Parameters at Chapman-Jouguet (CJ) state	
P_{CJ} [GPa]	12.5432
ρ_{CJ} [kg/m^3]	1661.8
γ_{CJ}	3.59
D [m/s]	6657

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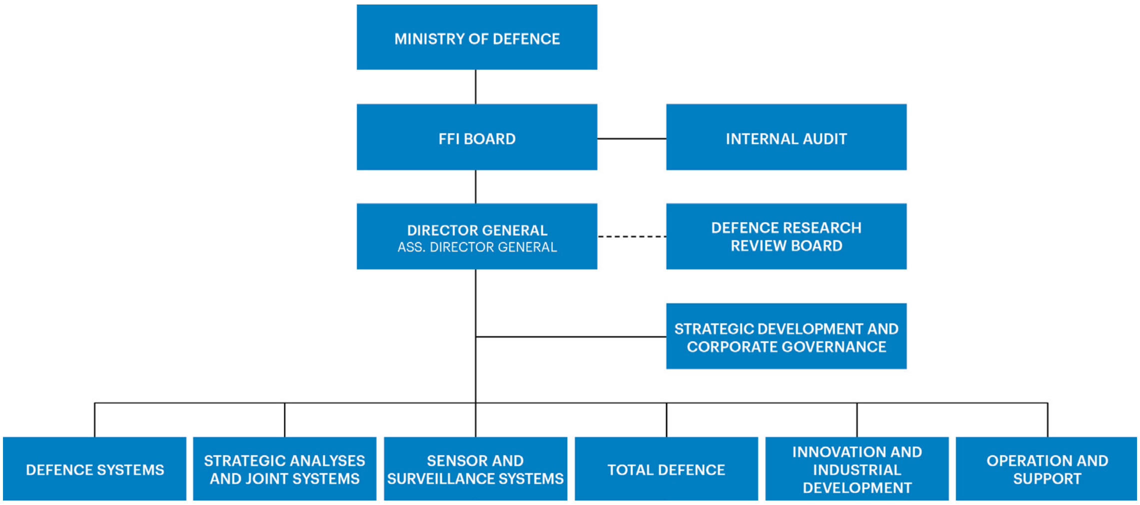

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