Ammonium Nitrate Modeling in the AN Module of IMESAFR

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Abstract

Worldwide, there have been several major accidents involving ammonium nitrate (AN) over the past decade. The Institute of Makers of Explosives (IME) recognized the need for explosives companies to be able to accurately model the risk from accidental explosions in AN stores and commissioned APT Research, Inc. (APT) to develop the models and software tool for this effort.

This paper touches on the following topics but concentrates on those that went into the development of the blast model:

- Background
- Assumptions that went into the model development
- Development of AN waveform
- Changes to the structural models in IMESAFR because the energetic material is assumed to be AN rather than TNT

Finally, the paper works through an example using both the current IMESAFR models as well as the AN Module and compares and contrasts the differences.

Background

AN is the main raw material used in the commercial explosives industry, accounting for roughly 75-80% by weight of the total explosives consumption--over 90% if one excludes water from the raw material list. As billions of pounds of explosives are used annually in the explosives industry globally, this means that very large amounts of AN are manufactured, stored, and transported on a regular basis. A large AN plant can manufacture more than a billion pounds per year. There are AN stores in remote areas of the world that contain millions of pounds of material; in more populous areas, there are stores of 1,000,000 pounds or more.

AN is classified as an oxidizer for purposes of transport; this classification has been extended in most jurisdictions to also cover storage. However, the United Nations (UN) definition explicitly recognizes AN and ammonium perchlorate (AP) as the two hazard division (HD) 5.1 substances that can explode under certain conditions. For instance, UN regulations change the classification of AN to HD 1.1 above an organic content of 0.3%. AN is an ideal raw material for explosives because it can be manufactured in very large quantities, is low cost, and is extremely stable in all normal conditions. It also has a very high energy density, especially when used in an oxygen-balanced explosive formulation, e.g., Ammonium Nitrate/Fuel Oil (ANFO) or Ammonium Nitrate Emulsion (ANE). However, “extremely stable” is not synonymous with “inert,” as there have been a significant number of AN explosions during manufacturing, transportation, and storage globally. High energy density is great when the release is controlled to time and place, but a significant risk when at least one of those is not controlled.

Except in those countries where AN is classified as a 1.5 or 1.1 material because of terrorism concerns, as an HD 5.1 substance, there are no quantity-distance (QD) requirements for the protection of populations. Accordingly, AN stores have historically been located based on operational requirements with a lesser consideration for any hazards or risks to the public. Since the West, TX, fire and explosion (2013) and the Toulouse incident (2001), both regulators and companies have had a greater focus on risks to the public from AN stores. When IMESAFR became available as a risk management tool for commercial explosives companies, many also used the software tool to estimate the risk from large AN stores. The availability of IMESAFR was very useful for explosives companies to determine evacuation circles, make siting decisions, etc. However, when it was used for siting AN, it was clearly a very conservative approach as AN explosions will be much less ideal than TNT explosions, on which the IMESAFR TNT engine is based and which was used for all calculations and algorithms, including HD 5.1 materials prior to the development of the AN Module. While some degree of conservatism is desirable in risk calculations, over-conservatism can cost money without adding safety value, i.e., meaningful risk reduction.

Because of this conservatism, there was a desire for a version of IMESAFR that would better model AN explosions. The IMESAFR Development Team[1] was tasked to look at whether this would be possible within the usual time and budget constraints. With significant input from APT, the team determined that an AN Module (i.e., IMESAFR running with an 'AN engine') was possible and, in the opinion of the team, highly desirable. There were concerns however, because of the relatively small amount of test data available to underpin the AN engine and new potential explosion site (PES) models. Despite these concerns, the decision was taken to develop the AN Module initially for release only to IME member companies, with full release pending an evaluation of the results with the use of the Module. Users found the AN Module to work well and provide generally – but not always – less conservative results than with the standard TNT engine in IMESAFR. The AN Module has been made fully available for all IMESAFR users who have completed the associated training.

AN Initiation Mechanisms, Frequencies, and Yields

The first thing that must be stressed with the AN engine vs. the TNT engine is that there is no TNT equivalency input or conversion to a TNT equivalence within the AN engine. There are two Net Explosive Weights/Net Explosive Quantities (NEWs/ NEQs) that are broadly quoted: 32% (Reference 1) and 42% (Reference 2). The latter is the absolute maximum chemical energy available relative to TNT and the former is the best scientific view of the maximum amount of energy likely to be released in an AN explosion, given the high non-ideality of pure AN explosions. (Note that these values assume a % contribution of 100%.) The standard IMESAFR software has the capability to run AN scenarios, but the program converts the AN with a fixed TNT equivalence and then treats it as a TNT explosion. Therefore, outside the AN Module,

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[1] Tatom, John W., *IMESAFR Overview*, Minutes of 2018 International Explosives Safety Symposium & Exposition, 6-10 August 2018, San Diego, CA 2018

IMESAFR treats AN as an ideal explosion with a low chemical equivalence. While this approach gets some things more or less correct in the calculation, other calculated values (e.g., pressure and impulse) could differ significantly from reality. The AN Module, on the other hand, treats a pound of AN as a pound of AN, not 5 ounces of TNT. How this model was developed and works is dealt with later in this paper. This section deals with how AN can be initiated and what this means for event frequencies and yields.

The IMESAFR Development Team and APT reviewed the available information and decided that the SAFEX Good Practice Guidelines (GPG) for AN Storage (Reference 3) contained the best distillation of knowledge on the initiation of/yields from AN explosions. The GPG identified three accidental initiation mechanisms, with the maximum expected yields and event frequencies for each of those mechanisms:

- Shock/Projectile initiation – 100% of AN reacts; Event frequency = 1.17 E-06
- Contamination – 50% of AN reacts; Event frequency = 1.17 E-06
- Fire – 10% of AN reacts; Event frequency = 2.34 E-06

These initiation mechanisms and yields are based on analysis of data from accidents. Each of these ignition mechanisms has a default event frequency for risk calculations. These default event frequencies were derived by the SAFEX Workgroup in the same way that the default event probabilities were in the TNT engine version, i.e., historical accidents were used as the numerator and the number of AN storage sites was used as the denominator. This obviously valid approach is still somewhat problematic as the number of historical major accidents was very small (exactly one for contamination scenarios (Toulouse) and that one is still controversial) so relatively minor events were included. Also, the number of AN inventories was conservative, as only significant "AN piles" were included. The derived event frequencies appear to be very low but the methodology ensures they are conservative.

i) Shock/Projectile Initiation

This is the easy one. Most regulators have mandated that any AN inventory within the propagation distance to stores of explosives (different distances in the American Table of Distances (ATD) and NATO Tables, but treated the same) must be considered to be initiated at 50% NEW for QD calculations. The assumption is that this is shock or projectile initiation and that all the AN reacts. (Note that the maximum chemical energy available is 42% as discussed previously, so the mandated 50% equivalence is well above the total available energy.) There are no experimental data available to say that this is too conservative so the percent contribution of 100% was adopted directly. The AN Module will treat the AN as the actual weight of AN for risk calculations. Projectile initiation of AN piles has been shown to be valid (large, high velocity shaped charges), but there is some doubt that very large piles/stacks of AN will react fully when initiated by shock/ projectiles. However, projectile initiation of a 1,000,000 lb pile of AN, for example, is unlikely to be a viable experiment. The default frequency and yield are used when there is an AN inventory within the AN distance from an explosives inventory.

ii) Contamination

While many substances are known to sensitize AN and/or to cause local reactions, very few are capable of driving large quantities of AN directly to explosion. Toulouse is the only case where this has apparently happened, as terrorism has not been completely ruled out (or hadn't been at the time the GPG was written). The chemical in question was a chloro-organic swimming pool compound, manufactured on the Toulouse Site. It has been experimentally demonstrated to be possible to drive AN into an explosive decomposition through a contamination scenario. That experimental result required the AN to be ground, intimately mixed with a large quantity of the chloro-compound and some water added as the initial reaction with AN is ionic. This would be difficult to duplicate in a standard AN store but is certainly possible on large, complex chemical sites with poorly managed waste and effluent streams. Therefore, the default event frequency would be highly conservative for a normal AN store managed by an AN manufacturer or explosives company. At least one large explosives company has developed a flowchart to determine whether this scenario is credible for any site being reviewed. The yield of 50% is the estimate of the percent of AN that exploded in the Toulouse accident. As Toulouse was a worst-case contamination scenario, this may be a very conservative estimate.

iii) Fire

There have been many fire-initiated AN explosions; however, almost all have been in transportation (more later). The statistics supporting the default event frequency are better for fire scenarios because the numerator is larger. The yield is therefore also "more solid" as there are adequate historical data to support it. The low yield, both absolutely and relative to shock/ projectile and contamination, is credible because fire will initiate a low-order thermal decomposition/explosion of AN that is highly unlikely to propagate away from the initiation area. The unstated assumption in the GPG for both the event frequency and yield is that they are valid for large piles of AN (on the order of 500 tons) where fire engulfment is not credible and the fire and initiation are localized and propagation does not happen. In scenarios where fire engulfment is credible, then the event frequency may be valid (not for transport) but the yield is not. The yield should be increased to whatever percent of the AN inventory can be engulfed by fire.

For transport scenarios, it should be assumed that the entire load can be engulfed by fire. However, accident data suggest that about 50% of the AN load will not be involved in the explosion, having already decomposed or been thrown away from the incipient explosion. The event frequency may well be unconservative for transport accidents. There are excellent statistics on accidents and accident-fires (e.g., one IME member company determined that the Health and Science Executive (HSE)in the United Kingdom (UK) provided the most useful traffic/accident data), and there are adequate data to estimate the probability of such a fire initiating an explosion of the AN load. This will be determined by the location of the initial fire (e.g., engine, very unlikely; rear axle tires, quite likely) and various preventative and/or mitigative measures are in place. The AN Module handles the consequence calculations well, but the user needs to define both the event frequency and amount of AN involved.

AN Airblast

An examination of the AN waveform would indicate that it is inherently different than a TNT wave form—at the same distance, the pressures are generally lower, the rise time of the shock front may be slower, the rate of energy release is different, and thus the durations and impulses of an AN event will be significantly different that a simple multiplicative factor times a TNT answer.

There are three possible levels of modeling that could be developed and used within the AN Module:

- Level 1 (lowest detail)
  - Scale to AN effects using a single value for TNT equivalence
  - TNT equivalence would be independent of explosive weight and distance
  - Same equivalent weight used to scale both pressure and impulse
- Level 2 (moderate detail)
  - Create curve fits of pressure vs. distance and impulse vs. distance for AN from available test data and modeling
  - Pressure and impulse models would not necessarily be the same
- Level 3 (highest detail)
  - This level would calculate the true AN pressure-time waveform at every required distance
  - Pressure and impulse would be calculated as functions of explosive weight and distance
  - Pressure and impulse models would be independent from each other

For this version of the AN Module, it was decided that a Level 2 model would be developed for predicting the airblast (peak pressure vs. scaled distance and scaled impulse vs. scaled distance) generated by AN detonating in the open. Such a model could be based on data from three sources:

- Previous testing programs
- Reverse-engineering from accidents and incidents
- Numerical simulations

Each of these sources have inherent strengths and weaknesses and the algorithms in the AN Module were developed from of a combination of these sources.

i) Previous Testing Programs

Data generated by defined tests are the most desirable. However, the tests that have looked at the airblast from detonating AN have been few in number. Further, although much testing has been carried out as part of restricted or classified programs, these data are not available for public release or distribution. There are other problems with much of the reported test data, as well:

1. The actual pressure measurements are not reported—only TNT equivalences derived from the measurements.
2. The shape of the container or stack of AN: shape has a dramatic effect on the measured airblast. This requires, as a minimum, that the dimensions and construction materials of the charge container be well-defined. If they are not, assumptions must be made which could lessen the validity of the data.

After a comprehensive literature survey, APT located and utilized data from five distinct sources. These sources (References 4-8) and a description of their data follow:

- *Kennedy, David, Detonics of Australian Technical Grade Ammonium Nitrate Prill: Phase I, 22 July 2010*. This report describes in great detail an Australian testing program. However, at the end of the discussion, the author discards almost all of the data collected because of problems with the instrumentation that were not discovered until after completion of the program.
- *Van den Hengel, E.I.V., Separation Distances and TNT Equivalences of Three Different Types of TGAN, TNO Report, Project Number 032.10829, January 2007*. This report provides data on three separate types of AN. The charge container is well defined (cylinder with diameter of 1.165 m and a length of 4 m) and the charge container is described in detail. Measurements were made at several distances.
- *Investigation of the Sensitivity of Ammonium Sulfate Nitrate, Interim Report Task 616, 22 May 2002*. Several pure AN charges were included in the test matrix. The charge container shape and composition were well defined.
- *Shatzer, D., Various Materials, (no title or report number information)*. Material was included as a copy of a presentation with no other identifying information. Assumptions were made regarding charge container shape and composition.
- *Material from Protected and/or Sensitive Sources*—no source identified. Assumptions were made regarding charge container shape and composition.

These five sources represent the extent of reported test data.

ii) Reverse-Engineering from Accidents and Incidents

Early thinking indicated that this could be a productive area. However, as the available information was examined more closely, it was soon discovered that the available information was often incomplete and assumptions were required to complete the required information. Did all of the AN detonate? If all of it did not detonate, how much reacted? What was the TNT equivalence of the material that did react? What was the shape of the AN just prior to reacting? In addition, the reported damage, from which the airblast estimates would be derived, was often faulty or incomplete. For these reasons, it was decided not to pursue this effort.

iii) Numerical Simulations

Two independent modeling efforts were utilized. The first was performed by Dr. David Dillehay utilizing the Vapor Cloud Explosion software VEXDAM (References 9-10). The second, performed by Karagozian & Case, Inc. (K&C), utilized a computational fluid dynamic (CFD) approach using the FEFLO (References 11-12) software.

For the VEXDAM runs, the following explosive weights were considered: 1,000,000 lb, 500,000 lb, 100,000 lb, 50,000 lb, 10,000 lb, 5,000 lb, and 1,000 lb. Distances were varied between 100 and 5,000 feet in 100-foot increments. The explosion strength (ES) parameter within VEXDAM was varied to simulate differing confinement levels provided by the inert mass. It should be noted that a limitation of the VEXDAM software is that it only calculates peak pressure and does not consider impulse.

Table 1 shows the inputs that were used for the FEFLO runs:

Table 1. FEFLO Inputs

Energetic Material	Properties	JWL Equation of State	Container	Initiation
TGAN	Mass: 3,496 kg Density: 0.82 g/cm^3 Heat of Detonation: 1712 KJ/Kg Detonation Velocity: 3.0 km/s Detonation Pressure: 1.845 Gpa	A: 49.46 Gpa B: 1.891 Gpa R1: 3.907 R2: 1.118 ω: 0.33	Shape: Cylinder Material: Cardboard Wall thickness: 3cm Height: 4m Diameter: 1.165m	Plane Wave across upper surface

<u>Charge Shape</u>. For the purposes of airblast generation, IMESAFR assumes that the charge shape is hemispherical. All of the data (both from the testing programs and computational effort) are for 4:1 right circular cylinders. Therefore, an additional factor must be applied to these data to convert them into the airblast from a hemisphere before they can be used in IMESAFR. Figure 1 shows these conversion factors for both pressure and impulse as a function of scaled distance.

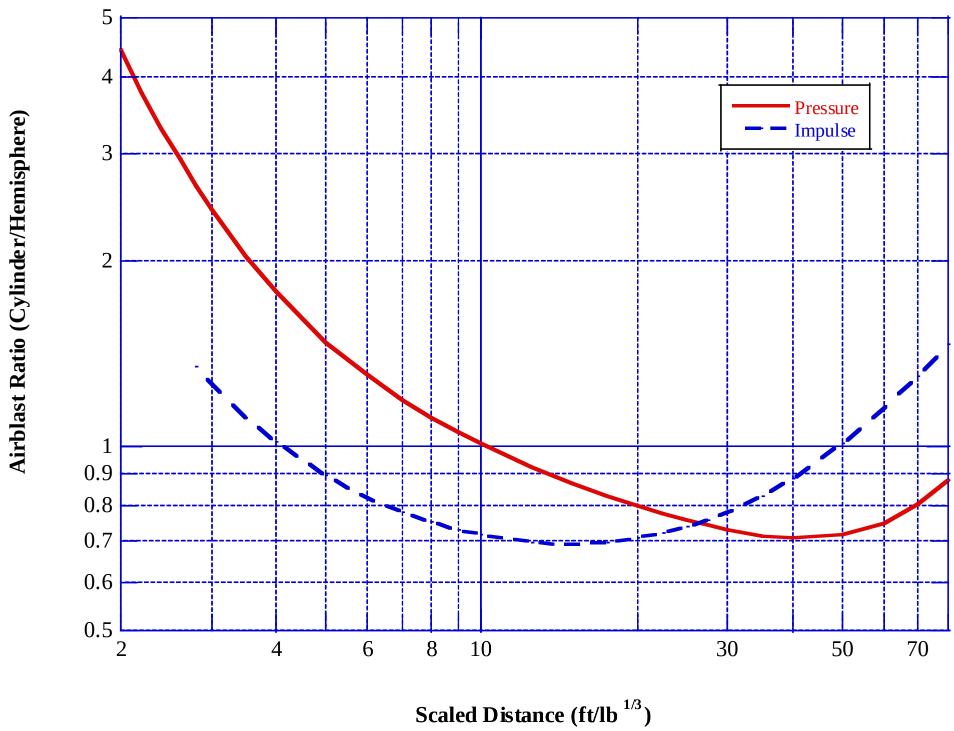

Figure 1. 4:1 Cylinder-to-Hemisphere Airblast Conversion

<u>Composite AN Airblast</u>. The airblast information from both the testing and computational sources were converted from cylindrical to hemispherical shape and then combined to form

composite airblast curves. These curves were then used to generate the open-air AN airblast functions. Figure 2 and Figure 3 present the composite airblast information that was used to generate the AN airblast functions.

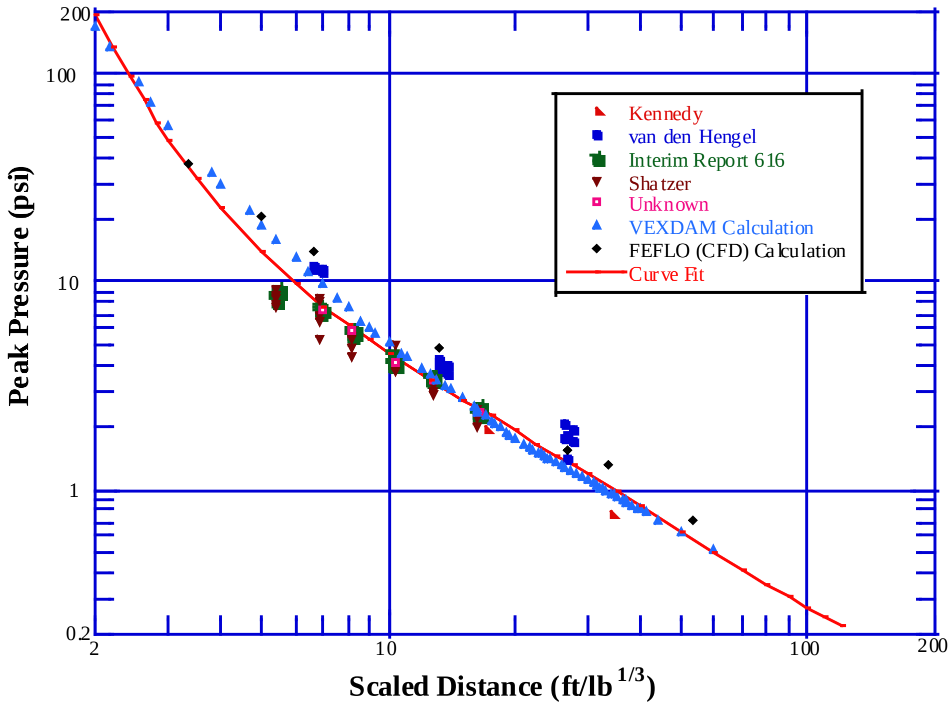

Figure 2. AN Composite Peak Pressure vs. Scaled Distance

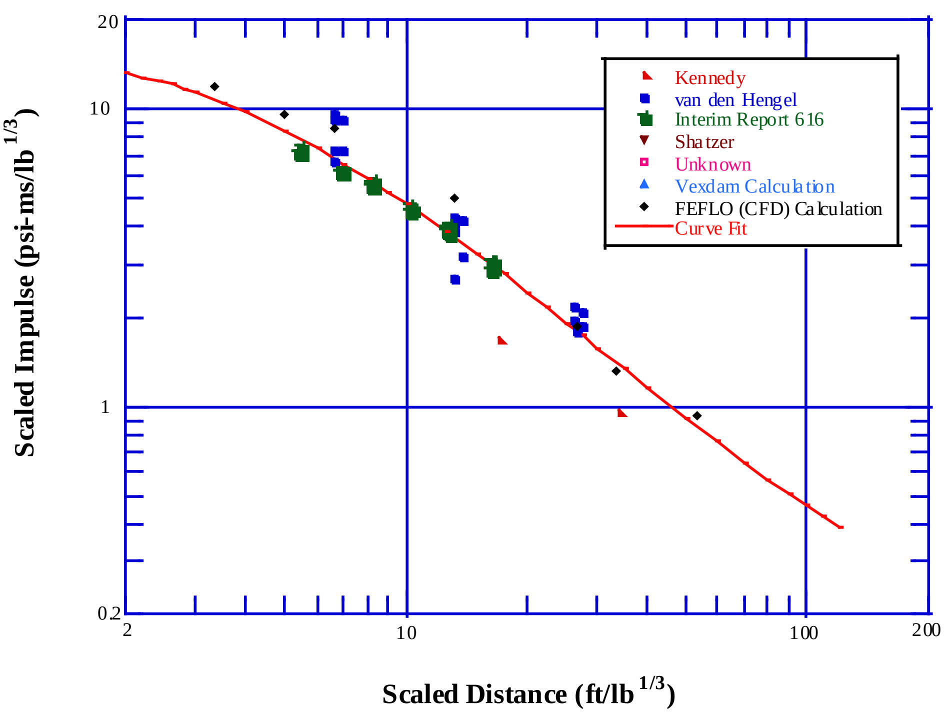

Figure 3. AN Composite Scaled Impulse vs. Scaled Distance

Something that is fairly unique to detonating AN is the potential presence of large amounts of unreacted material that could be entrained in the blast wave. The effect of the presence of unreacted material entrained in the flow of the blast wave was described and discussed in several papers by Porzel (References 13-14). As described by Porzel, the effect of the unreacted mass is to depress the peak pressure at scaled distances less than about 10 ft/lb$^{1/3}$ and to enhance or increase the peak pressure at scaled distances greater than 10 ft/lb$^{1/3}$. Porzel did not provide a lot of information on the effects of inert mass on positive impulse. For conservatism, it was assumed that the inert mass has the effect of increasing the impulse at all scaled ranges, with the amount of increase being proportional to the amount of increase of the peak pressure.

Three inert mass loading regimes were identified and are associated with the three initiation mechanisms discussed previously. These three mass loading regimes are:

- Unloaded: Associated with a projectile/shock initiation mechanism. This regime corresponds to a reaction of 70-100% of the AN available. The default value is 100% of the material reacts.
- Moderately Loaded: Associated with a contamination-initiation mechanism. It corresponds to a reaction of 30-70% of the AN available. The default value is 50% of the material reacts.
- Heavily Loaded: Associated with a fire-initiation mechanism. It corresponds to a reaction of < 30% of the AN available. The default value is 10% of the material reacts.

Figure 4 and Figure 5 show the expected airblast for these three regimes. Figure 4 shows the expected effect on peak pressure while Figure 5 shows the corresponding information for positive impulse.

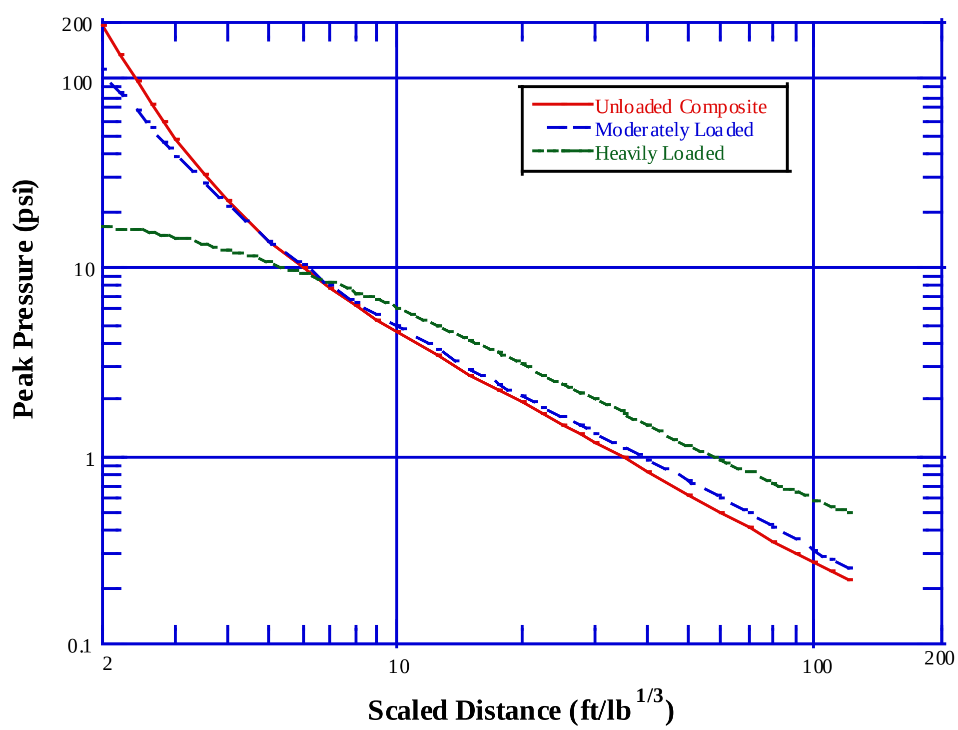

Figure 4. Effect of Entrained Unreacted Material on Peak Pressure

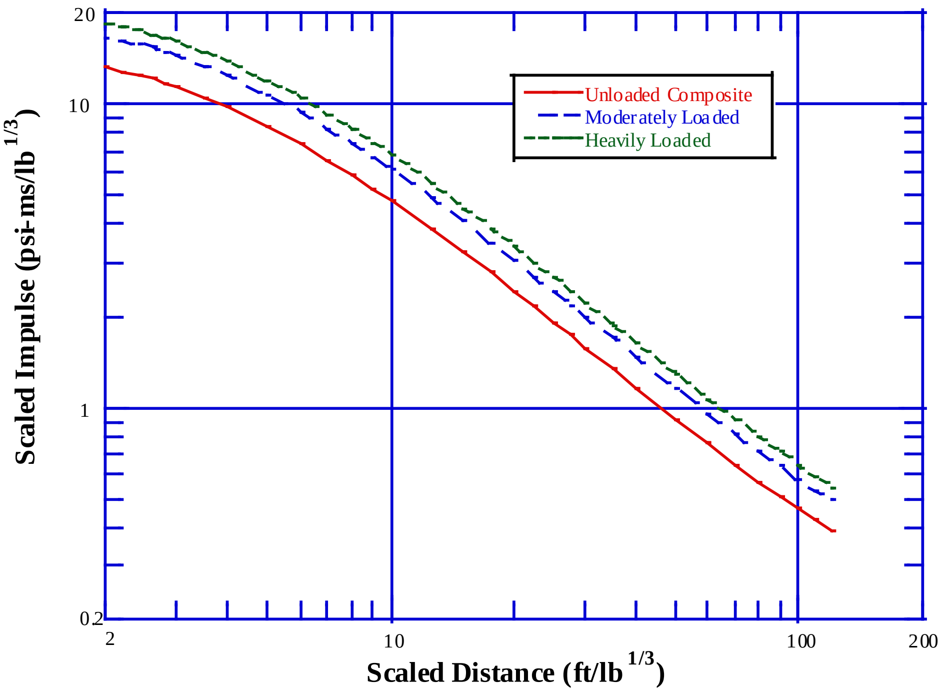

Figure 5. Effect of Entrained Unreacted Material on Scaled Positive Impulse

<u>Other IMESAFR Changes in the AN Module</u>

The building response to a blast wave was not altered in the AN Engine. This decision was made as a result of a discussion with the IMESAFR Development Team. Since the building response was not changed, the algorithms to calculate the probability of fatality, major injury, and minor injury due to building collapse were not altered either. It is important to note, however, that while the response logic was not changed, the "answers" will be different since the AN Engine will generate different pressure, impulse, etc., terms than the TNT Engine.

The development of the AN Engine led to the addition of two new PES types in IMESAFR—a railcar and overhead silo. Both of these PES types are available in the regular IMESAFR as well as in the AN Module.

In the TNT Engine, the mass distribution logic is anchored by test data augmented by several theoretical points. At run-time the mass distribution is calculated based on the loading density (NEW divided by the volume of PES). The forward and reverse models are hinged at a nominal data point based on the ISO-4 test (Reference 15). This nominal point represents the best available data and is, hence, a good average. Within the AN Module, the mass distribution process takes into account the lower energy with in AN available to break-up the PES. In addition, the range of potential loading densities was also considered. TNT loading densities generally vary between 0.00162 lb/ft^3 to 21.3 lb/ft^3. AN could have loading densities up to 50 lb/ft^3 for fully loaded railcars and overhead silos. AN loading densities are mapped onto the TNT Table as shown in Table 2. Once the mapping is made, the mass distribution algorithms behave in a similar manner.

Table 2. Dynamic Mass Distribution by Bin for an Example PES Component

AN loading density (lb/ft³)	TNT loading density (lb/ft³)	Source data	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
0.5	0.00162	Theoretical	94.30%	2.40%	1.70%	1.00%	0.50%	0.30%	0.00%	0.00%	0.00%	0.00%
2	0.0162	Theoretical	93.80%	2.40%	1.70%	1.10%	0.60%	0.30%	0.00%	0.00%	0.00%	0.00%
5	0.162	KG ISO	63.30%	8.70%	5.90%	5.50%	4.50%	3.70%	3.30%	2.50%	1.30%	1.30%
10	0.97	Theoretical	39.60%	13.60%	9.10%	9.00%	7.60%	6.30%	5.80%	4.50%	2.20%	2.20%
20	1.6	ISO-4	33.00%	15.00%	10.00%	10.00%	8.50%	7.00%	6.50%	5.00%	2.50%	2.50%
50	6.5	ISO-2	14.20%	8.30%	7.00%	9.50%	10.30%	14.50%	9.80%	8.50%	8.10%	10.00%
Not used	11.3	Theoretical	7.10%	3.20%	4.70%	5.90%	9.00%	11.20%	18.50%	12.90%	12.10%	15.40%
Not used	16.2	Theoretical	2.50%	1.20%	0.80%	3.80%	5.70%	10.50%	14.10%	23.50%	17.80%	20.10%
Not used	21.1	Theoretical	0.00%	0.00%	0.80%	1.90%	3.60%	5.30%	7.00%	15.80%	27.90%	37.90%

The initial velocity of secondary fragments is scaled in the AN Engine to represent the potential of AN to throw fragments at lower initial velocities than TNT. As a result of APT discussions and meetings with the IME AN Module Working Group, two reduction factors were developed. The first, based on a ratio of detonation velocities of AN and TNT, was 0.59. The second, based on the ratio of the impulse close to the charge surface, was 0.77. The default in the AN Engine is 0.77, as it is the more conservative option. There is an option for the user to select the 0.59 scaling factor. The scaling factor will also apply to the initial velocity cut-off values.

In IMESAFR, the maximum throw range of secondary debris is a function of the initial velocity. The maximum throw range in the AN Engine is calculated in a similar manner. Since the maximum throw range is a function of the initial velocity, it was decided that the maximum throw ranges would not be scaled separately. In other words, the reduction in initial velocities directly affects the maximum throw ranges, so further scaling the maximum throw ranges would be redundant.

The AN Engine includes updates to the maximum throw ranges for three PES types: vehicle-van/truck, vehicle-tractor-trailer, and pre-engineered metal building (PEMB). For these PES types, the maximum throw range cut-offs were mapped to the cut-off values of primary fragments in the TNT Engine. In the AN Engine, these PES types have the same maximum throw range cut-offs as the other metal PES types, since primary fragments are never involved with AN Engine runs.

Example

The PES is a standard AN Shed that contains a total NEW of 88,000 lb of HD 5.1 material. It is being used to store AN. A residence located 2,300 feet away has one occupant who is unrelated to the AN storage operation. Table 3, generated using IMESAFR V2.1, compares the risks associated with the operation using both the TNT Engine and the AN Engine in IMESAFR (Note many of the required inputs are the same in both cases and have not been shown or discussed in this example). There is only one set of results for the TNT Engine but six sets for the AN Engine, which correspond to the three potential initiation modes/yields each with the unreacted mass considered/not considered. Several of the columns show the same value for all scenarios. This is the floor value, i.e., the lowest value that test data underpinning IMESAFR can support.

Table 3. Risk Comparisons TNT Engine vs AN Engine

	TNT Engine	AN Engine					
		Projectile/Shock Initiation		Contamination		Fire	
		Unreacted Mass Considered	Unreacted Mass Not Considered	Unreacted Mass Considered	Unreacted Mass Not Considered	Unreacted Mass Considered	Unreacted Mass Not Considered
Public Probability of Fatality (E_f)	3.41E-08	1.11E-09	1.11E-09	6.02E-10	6.01E-10	6.30E-10	6.30E-10
Individual probability of Fatality (P_f)	3.41E-08	1.11E-09	1.11E-09	6.02E-10	6.01E-10	6.30E-10	6.30E-10
Adjusted Probability of Event (P_e)	4.99E-06	1.25E-06	1.25E-06	1.20E-06	1.20E-06	2.34E-06	2.34E-06
P_f Overall--Given Event	4.16E-03	5.43E-04	5.43E-04	3.06E-04	3.06E-04	1.65E-04	1.65E-04
Risk: Overpressure	2.07E-09	2.07E-09	2.07E-09	2.07E-09	2.07E-09	2.07E-09	2.07E-09
Risk: Glass	6.98E-06	4.46E-06	4.46E-06	6.47E-07	3.32E-07	1.00E-10	1.00E-10
Risk: Building Collapse	1.16E-10	1.16E-10	1.16E-10	1.16E-10	1.16E-10	1.16E-10	1.16E-10
Risk: Horizontal Debris	4.16E-03	5.37E-04	5.37E-04	3.04E-04	3.04E-04	1.64E-04	1.64E-04
Risk: Vertical Debris	8.11E-06	1.36E-06	1.36E-06	1.36E-06	1.36E-06	1.19E-06	1.19E-06

As shown in this example, the AN Engine gives results that are less conservative and believed to be more realistic than using the TNT engine for the same scenario. That the AN Engine will return lower consequence values will be generally, but not universally, true. The AN Engine will "always" generate lower risk values given the always lower event frequencies and generally lower consequences.

Summary and Conclusions

The AN Module is a novel advance in the modelling of AN events. To the best the authors are aware, this is the first non-TNT based model for AN explosions due to fire, shock, or contamination. It is a particular step out as the change is from a fairly ideal/molecular explosive to a highly non-ideal energetic material. This is, of course, the driver for the development of the model as an ideal explosion model that will be very conservative for AN explosions. The development of an AN engine and addition of two ES types, railcars and overhead silos, which are typical stores for AN manufacturers and explosives companies, are major additions to the risk management capabilities of these industries.

To the extent possible, the current AN Engine is based on experimental and test data, with state-of-the-art modelling used to fill in the gaps. IME and APT are working to address these gaps and to further validate the modelling. This is especially true for the new PES models, for which there are no test data. For this reason, the IME has agreed to a test program with the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) as the co-sponsor. This test program will provide meaningful data on both the AN waveform and behavior of the two new PES models. In addition, IME and APT personnel participated in the debris collection associated with a recent railcar test[2]. It is likely that these data will result in improvements to both the PES models and AN Engine algorithms (Reference 16).

While the AN Engine will continue to be improved from this point, it has already proven to be very successful from the perspective of the customer base. Risk management for large AN

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[2] Hoffman, Joshua, *IME Derailed Debris Collection*, Minutes of 2018 International Explosives Safety Symposium & Exposition, 6-10 August 2018, San Diego, CA 2018

inventories has become much more important for AN manufacturers and the explosives industry, and the AN Module has proven to be an excellent tool in that risk management.

References

1. Nygarrd, E., *Storage of Technical (Porous) Ammonium Nitrate*, ISEE Conference 2008.
2. Braithwaite, Martin, *Ammonium Nitrate: Fertilizer, Oxidizer, and Tertiary Explosive*, UKELG, Loughborough, Sept 2008.
3. Good Practice Guide: Storage of Solid Technical Grade Ammonium Nitrate, International Industry Working Group on Ammonium Nitrate, SAFEX, rev 1 July 5, 2011.
4. Kennedy, David, *Detonics of Australian Technical Grade Ammonium Nitrate Prill: Phase I*, 22 July 2010.
5. van den Hengel, E.I.V., *Separation Distances and TNT Equivalences of Three Different Types of TGAN*, TNO Report, Project Number 032.10829, January 2007.
6. *Investigation of the Sensitivity of Ammonium Sulfate Nitrate*, Interim Report Task 616, 22 May 2002.
7. Shatzer, D., *Various Materials, no title or report number information*.
8. *Material from Unknown Sources.*
9. Dillehay, D.R., *VEXDAM and Pyrotechnic Safety Hazard Classification*, 20th International Pyrotechnics Seminar, 1994.
10. Dillehay, David, *VEXDAM Analysis of Ammonium Nitrate*, project deliverable to APT, 16 July 2015.
11. Lohner, Rainald, et. al., *Advances in FEFLO*, AIAA-02-1024, 2002.
12. Karagozian and Case (K&C), AN Modeling (presentation), project deliverable to APT, 10 July 2015.
13. Porzel, F. B., *Introduction to A Unified Theory of Explosions*, NOL TR 72-209, 4 September 1972.
14. Porzel, F. B., *Damage Potential From Real Explosions: Total Head and Prompt Energy*, Minutes of 16th Explosive Safety Seminar, August 1974.
15. Swisdak, Michael M., Conway, Robert T., and Tatom, John W., *ISO-4: Program Description and Test Results*, APT Research Technical Report CDES-AL011-00600, January 2018.
16. Swisdak, Michael M., et. al., *A Proposed Test Program to Improve Explosive Risk Management*, 2012 ISEE Symposium, February 2018.