Iron Warrior 4 and Technical Paper 21

John Tatom; A-P-T Research, Inc.; Huntsville, AL, USA

Shonn (Kevin) McNeill; Bureau of Alcohol, Tobacco, Firearms and Explosives; Huntsville, AL, USA

Robert Conway; NAVFAC EXWC; Port Hueneme, CA, USA

Keywords: testing, debris, TP-21, IMESAFR, collaboration, ATF

Abstract

When presented with the opportunity to "piggy-back" on the Iron Warrior IV test, the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) worked with Institute of Makers of Explosives (IME) to sponsor a debris recovery effort. This effort, which was intended to support the Institute of Makers of Explosives Safety Analysis for Risk (IMESAFR) model, was conducted in accordance with Department of Defense (DoD) recommended debris recovery practices, which are documented in Department of Defense Explosives Safety Board (DDESB) Technical Paper 21 (TP-21).

Iron Warrior IV was sponsored by the National Ground Intelligence Center (NGIC), conducted by the U.S. Army Corps of Engineers Engineer Research and Development Center (ERDC), and held at Dugway Proving Grounds (DPG). The debris recovery effort, which was supported by ATF, DoD, IME, and APT Research, Inc. (APT), lasted two weeks and cataloged tens of thousands of pieces of debris. This debris catalog can be used for multiple purposes, including anchoring the truck potential explosion site (PES) model in IMESAFR to higher charge weights than previously available.

IMESAFR was also used to predict the debris throw ranges ahead of the shot, which allowed the design of a debris collection grid, which was used by the debris recovery team after the shot.

Iron Warrior IV Debris Recovery: ATF's use of DDESB's Technical Paper 21

The Iron Warrior IV test was conducted in 2015 at DPG. The focus of this paper is not the purpose of the test or an overview all experiments, but instead looks at the collaborative effort undertaken to perform a post-test debris recovery. Of particular interest to DDESB was the promotion and use of their debris recovery methodology, as documented in TP-21 [Reference 1], in a test sponsored by other agencies.

1) Background

The NGIC held the initial kickoff meeting for the Iron Warrior project in Charlottesville, VA. Present were essential personnel from the NGIC, U.S. Army Corps of Engineers (USACE), DPG, and ATF. The initial meeting set the goals of the test and tasked each of the four principal members to solicit outside agencies for participation.

During the goal setting, ATF volunteered to conduct a partial TP-21 style debris recovery effort [Reference 1]. Data from such an effort would be valuable to DDESB, ATF, and IME in their on-going work on explosion effects and consequence algorithms used in quantitative risk assessment models.

Following the kickoff meeting, ATF reached out to IME and APT to solicit their participation in the Iron Warrior test. Both were immediately interested in supporting the test and the potential data from a debris recovery effort. The combined efforts of ATF, APT, and IME resulted in the following support for the debris recovery effort:

- IME supported the debris recovery with personnel,
- IME member company Dyno Nobel donated the explosives and a trailer for the test,
- ATF contracted APT to manage the overall debris recovery effort and provided debris recovery personnel,
- DDESB, the Naval Facilities Expeditionary Warfare Center (EXWC) and the U.S. Army Technical Center for Explosives Safety (USATCES) supported the test with debris recovery personnel and global positioning system (GPS) equipment.

a) Safety-vs-Security

Explosives safety is traditionally thought of as considering accidents with explosives intended to be used for legitimate purposes. The effects and consequences of such accidents must be well-understood in order to create quantitative risk assessment (QRA) models, such as IMESAFR.[1] Therefore, full-scale field tests are of great value to the explosives safety community.

Explosives physical security (or anti-terrorism), on the other hand, considers the use of explosives for nefarious purposes. Naturally, the goal for this community is to understand the threat from “the bad guys” and be prepared to deal with problem. Therefore, testing also provides vital information for modelers working on the security side.

Although physics-based modeling has made great strides in recent years to simulate the effects and consequences of explosions, it is still very difficult to model some aspects – especially debris. Given the need for anchoring data from tests, but realizing the expensive nature of full-scale testing, it is therefore imperative that communities with overlapping interests collaborate on testing whenever possible [Reference 2].

b) Test Details

As mentioned previously, this paper will not go into details of the test objectives, or even all of the test setup specifics. It is important to note that the test was 60K lb of ammonium nitrate fuel oil (ANFO) in a “hopper” truck; receptor experiments were present at various locations, but only one such experiment affected a potential debris recovery. That experiment was a large barricade

---

[1] Tatom, John W., *IMESAFR Overview*, Minutes of 2018 International Explosives Safety Symposium & Exposition, NDIA Paper No. 20720, 6-10 August 2018, San Diego, CA 2018

that would have compromised the debris pattern in that direction, therefore the debris recovery was conducted over 215° rather than a full 360°.

2) TP-21

A primary hazard in an explosives event is the generation of high-velocity fragments from the explosion location. These fragments can be generated from a variety of sources: munition casing, the packaging containing the explosive article, structural debris of the building or vehicle housing the explosives, crater ejecta, or any number of items in the near-field vicinity of the explosives event. In order to quantify the hazards from an explosives event, either accidental or intentional, it is paramount to fully characterize the hazards associated with this debris.

The fragments generated from the material directly housing the explosives, such as munition casing or metal boxes containing bulk material, are referred to as primary fragments. Due to their close proximity to the explosion event, primary fragments are typically broken into very small pieces that are launched with a very high initial velocity. In the case of munition casing, the vast majority of primary fragments will be less than half an ounce, and are launched with velocities in the 5,000 to 8,000 feet per second range. The debris generated from the facility or vehicle that contains the explosive article are referred to as secondary debris. The explosives are internal to the structure, but location of the explosives material is quite a bit further away than in the case of primary fragments. As such, secondary debris are typically launched with velocities in the hundreds to low thousands of feet per second, and are characterized by much larger debris sizes. Depending on the structure type, secondary debris will be in the range of ounces to pounds, with the larger debris in some structures weighing hundreds of pounds. Note that in other documentation, primary fragments are simply referred to as just “fragments” and secondary debris are just referred to as simply “debris”. This paper does not necessarily make that distinction and typically uses “debris” as a generic term to cover all sources of fragments and debris generated from an explosives event, but the reader should be aware of this distinction in other sources of information.

Proper quantification of the debris hazard is necessary for hazard characterization, whether for use in establishment of explosives safety criteria, performing quantitative risk assessments, or conducting security assessments of potential threats. The need for uniform procedures for the collection and analysis of debris was identified early on within the explosives safety community, and resulted in the NATO publication of guidelines for the collection and analysis of debris and fragments following an accident of test [Reference 3]. This was eventually converted into a DDESB technical paper in 2007 [Reference 4], with the most recent revision of this document, TP-21 Revision 2 being published in 2017 [Reference 1]. The ultimate objective of TP-21 is the standardization of both data collection and analysis procedures associated with the debris hazard from explosives events. Prior to the publication of References 1 and 2, a series of explosives tests generating debris had been conducted, but the lack of uniformity in which the manner the debris data was collected across the various tests made it quite difficult to compare results. Since the publication of TP-21, the majority of tests across the community have utilized the collection and analysis procedures prescribed within, resulting in the publication and generation of test results that can be compared across tests, and with established explosives safety criteria. Note that while the intent of TP-21 is focused on explosives safety, the procedures are general enough that they can be applied and used to the general quantification of debris hazards, regardless of the end use.

The debris collection of Iron Warrior IV utilized the procedures prescribed within TP-21 and are briefly described in the following paragraphs.

TP-21 provides significant detail with respect to the optimal way to set up a test given the desired collection parameters. However, that will not be discussed herein. Rather, the focus of this section shall be on the debris collection method employed during the Iron Warrior IV test. Prior to the test, the surrounding area was converted into a polar grid to establish a frame of reference to assist the debris collection. Markers were surveyed and staked at 200-foot, 1,400-foot, and 2,600-foot locations every 5°; survey markers on the three normals of interest were also placed at 3,800 feet and 5,000 feet. This grid is shown in Figure 1. The geometric centroid of the donor vehicle was used as the center of the grid.

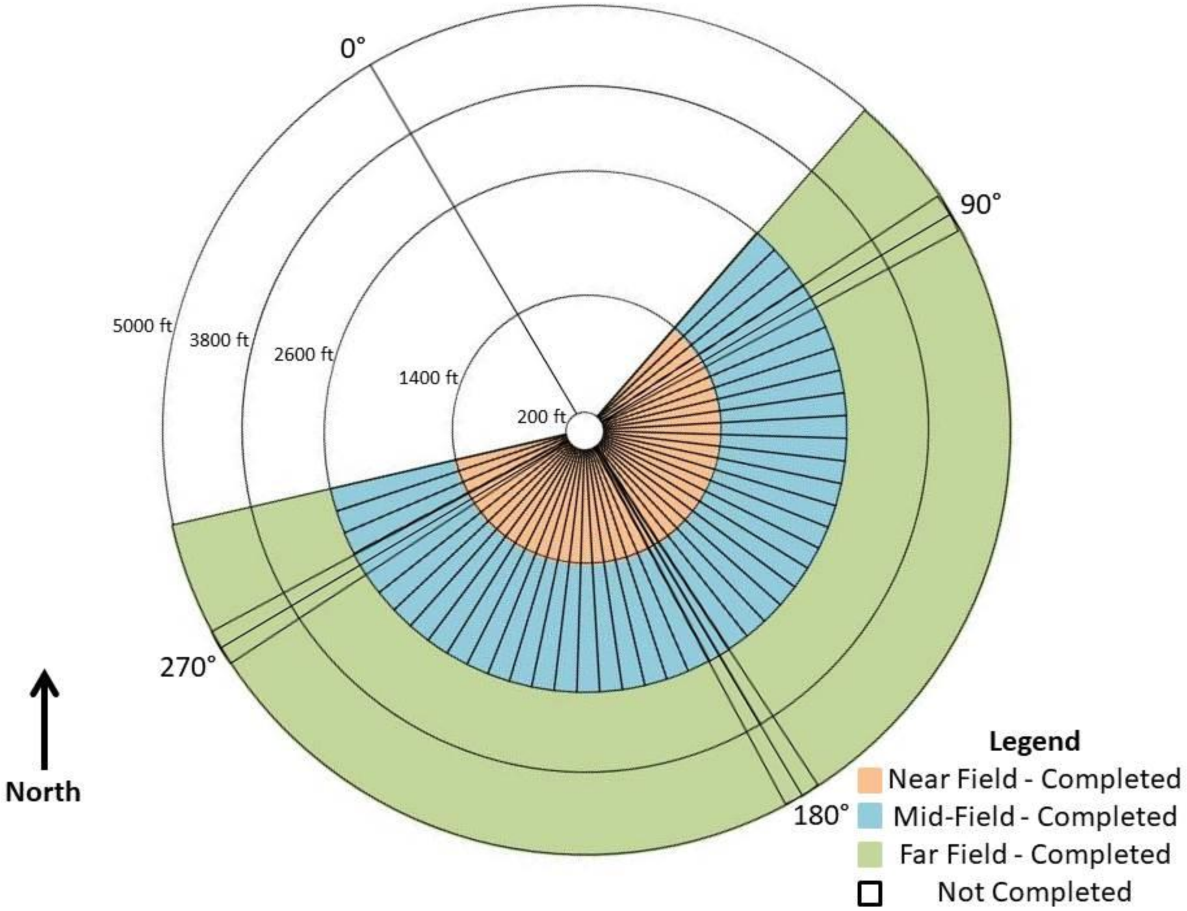

Figure 1. Debris Collection Grid

The markers at the inner ring (200 feet) and middle ring (1,400 feet) defined the *Near Field* collection area. The markers at the middle ring and the outer ring (2,600 feet) defined the boundary of the *Mid-Field* collection area. Beyond the outer ring (and thus beyond the Mid-Field) is the *Far Field*.

The collection grid was not intended to be a definitive discretization of debris collection zones. Rather, it was to be used as a frame of reference during the collection process with the assistance of ropes running from the 200-foot to 2,600-foot markers, allowing the collection team to move on to the next adjacent sectors in the Near Field and Mid-Field collection areas once collection was complete. The organized search in a given sector was conducted primarily using the width-walk technique. Some portions of the debris recovery were conducted using the length-walk technique, if a pressing need dictated that requirement. Both collection techniques are illustrated in Figure 2 and Figure 3.

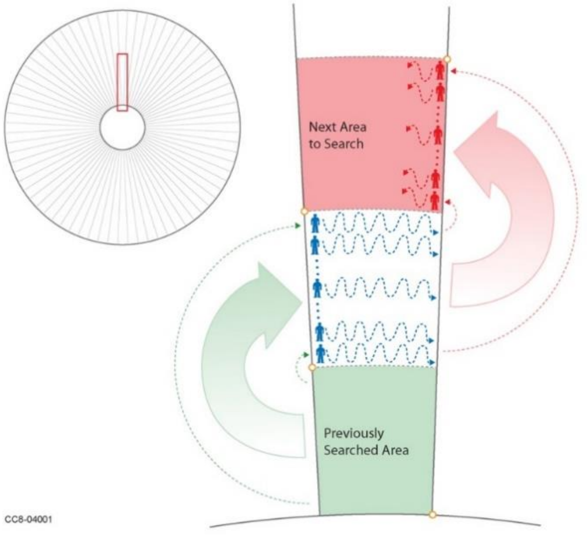

Figure 2. Width-Walk Search Technique (left)

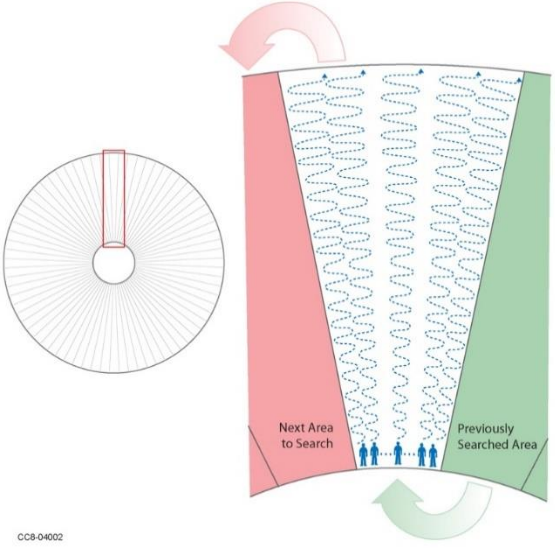

Figure 3. Length-Walk Search Technique

The Far Field beyond 2,600 feet was searched as well, but in a less rigorous manner known as the Far Field Walk. The team was lined up along a radial using logarithmic spacing (i.e., spacing between personnel was minimal at 2,600 feet and quite large at 5,000 feet), and slowly performed a circular walk around the collection grid. Each individual walked in a serpentine manner in order to cover all ground in their area. This technique was employed for practical (time) considerations, as well as with the knowledge that the debris that could make it out to the Far Field tend to be quite large and easier to see from a distance.

An important decision at the onset of a test is what debris to collect. For Iron Warrior IV, the source of debris was from the vehicle itself. TP-21 defines a series of mass bins as a convenient way to discretize debris mass into a finite number of categories, but actual debris masses in Iron Warrior IV were recorded. One aspect of the TP-21 mass bins that did affect the Iron Warrior IV collection was the definition of the lower limit of mass collected during the test. Mass Bin 10 is the smallest mass bin defined in TP-21, and it has a lower limit of 0.21 ounces (6 grams). This was defined as the lower limit of vehicle debris collected. The collection crew was instructed to err on the side of caution and to flag pieces they estimated to be 5 grams and larger in an effort to minimize omitted data.

Once a piece of debris was identified as part of the collection process, a flag was placed next to the debris and the search was continued. In areas where there was a large amount of debris, particularly in the Near Field normal to the orientation of the vehicle, the debris (and flag) density might be as high as a piece of debris per square foot. In the Mid-Field off-normal and the Far Field, the debris density was much more sparse. The second step of the collection process involved the cataloguing team. The cataloguing team would locate each piece of debris via the flags and using a programmable GPS system, note the location with the GPS, record the actual mass of the debris with a scale, assign any applicable pre-programmed category codes further describing the source of debris (e.g., engine, aluminum, etc.), and take photographs of any interesting pieces of debris. Upon completion of the test, all of this information was consolidated into a spreadsheet that becomes the official test dataset.

Finally, upon completion of debris collection associated with a test or accident, TP-21 prescribes methods to interpret this debris data via multiple analysis methods. In explosives safety, the debris hazardous fragment distance (HFD), also known as the debris Inhabited Building Distance (IBD), is the range at which the density of hazardous fragments falls below a value of 1 per 600 ft^2. For an individual in the open, this equates to approximately a 1% chance of getting hit. A hazardous fragment is currently defined as a fragment that has an impact kinetic energy of 58 ft-lb or greater. The 58 ft-lb is essentially a historical value with minimal traceability as to what the initial intended representation is, but the fact is that a blunt impact of this kinetic energy against a person will almost surely case a minor injury, likely cause a major injury, and has a small chance of causing a fatality. The debris analysis procedures in TP-21 prescribe multiple methods to define the debris density at a given location as a function of range and azimuth. The decision as to what debris should be included in that density is left up to the user. TP-21 provides guidance on relating mass to kinetic energy for various material types falling at terminal velocity.

Given that a minimal debris mass has been chosen in the generation of debris density plots, TP-21 provides multiple methodologies to represent the debris hazard. Analysts attempt to represent measure debris densities as trajectory-normal, i.e., a density measured in a plane perpendicular to the trajectory at any point. This is an attempt to represent the actual hazard to targets such as people and structures, but the issue is that the trajectory information for each piece of debris is unknown. In order to approximate trajectory-normal densities, a conservative methodology used is to define the pseudo-trajectory-normal (PTN) density. At a given location, this density is computed by defining the number of debris pieces to be considered as all hazardous debris material at that location plus all hazardous material that had to pass through that location to reach a greater range. One of the following two formulae can be used to compute these densities:

$$PTN_{r\theta}(i) = [360/(\pi\ \Delta r \Delta\theta\{2r + \Delta r\})] \sum_{i}^{i\,\max} N_{r\theta}(i) \tag{1}$$

$$PTN_{r\theta}(i) = [180\ /\ (\pi\ r_c \Delta\theta \Delta r)] \sum_{i}^{i\,\max} N_{r\theta}(i) \tag{2}$$

where

$PTN_{r\theta}(i)$ is the PTN zonal debris density for the i-th zone
r_c = radial distance from ground zero to the center of the zone
r = radial distance from ground zero to the inner boundary of zone
θ = polar angle of the center of zone in degrees with respect to a coordinate system centered at ground zero
Δr = incremental zone depth
$\Delta\theta$ = angular width of zone in degrees

i max is the number of the zone that contains the furthest debris hazard.

During the debris dispersion process, many pieces are thrown well above the ground surface at a given distance and, hence, would not interact with persons or structures in that zone. In order to make a more realistic estimate of the true trajectory normal density, a study on the topic found that only about a third of such debris contributes to the hazard within the zone. This nominal value of one third seemed to adequately represent an average of the scenarios considered; however, this estimation would be conservative for roof or other vertically launched debris.

Based on this analysis, it was decided that a Modified Pseudo-Trajectory-Normal (MPTN) density could be defined and used. This was defined for a particular location by considering all appropriate debris material at that location plus one third of all material that had to pass through that point to reach a greater range. The appropriate modifications to Equations (1) and (2) are shown as Equations (3) and (4):

$$MPTN_{r\theta}(i) = [360/(\pi\,\Delta r\Delta\theta\{2r+\Delta r\})][N_{r\theta}(i) + (1/3)\sum_{i}^{\mathrm{imax\text{-}1}} N_{r\theta}(i+1)] \qquad (3)$$

$$MPTN_{r\theta}(i) = [180/(\pi\, r_c\Delta\theta\Delta r)][N_{r\theta}(i) + (1/3)\sum_{i}^{i\max-1} N_{r\theta}(i+1)] \qquad (4)$$

TP-21 has the ultimate goal of generating uniformity in the debris collection process following an explosives event, as well as with the interpretation of that debris data. TP-21 is not entirely prescriptive, but rather it provides guidance for test set-up, minimal information that should be acquired, and best practices both before, during, and after the test. Though initially written for explosives safety purpose, the debris collection and analysis methodologies within have a wide range of applications, and provide methods to quantify the debris hazard for multiple locations and targets regardless of the source of event. The procedures, methodologies, and general suggestions within TP-21 were successfully implemented in the Iron Warrior IV debris collection.

Test Execution

The test was successfully conducted by ERDC at DPG and the debris recovery commenced immediately afterwards.

1) Debris recovery effort

The crew size varied daily, but a total of 48 people participated in the debris recovery. A total of 1.944 manhours were involved, not counting DPG personnel that were present to allow site access or otherwise support the test (but not actively involved in the debris recovery). Table 1 lists the manhours and Section Heads (team leads) by organization.

Table 1. Debris Recovery Team

Organization	Total Manhours	Section Heads
ATF	744	1
IME (including students)	592	1
Dyno	176	-
APT	168	4
USATCES	168	1
NAVFAC EXWC	24	1
DDESB	16	-
Orica	16	-

Figure 4 shows the crew present on the first full debris recovery day, posing at the edge of the crater.

Figure 4. Crew Picture

Approximately 12,600 debris pieces were cataloged, which means about 6.5 points were found, weighed, GPS-located, and recorded per manhour.

The Near Field zone (200-1,400 feet) was established based on a prediction where ~80% of fragments would be found. Most of the remaining pieces were expected to land in the Mid-Field zone (1,400-2,600 feet). The predicted 95% confidence maximum throw range was 4,200 feet. All predictions were made with IMESAFR.

After the debris collection was completed, statistics showed that in fact 75% of the recovered fragments were in the Near Field, and only five fragments were in the Far Field. The farthest fragment was at approximately 4,300 feet.

Figure 5 is a scatter plot of the debris recovered.

Figure 5. Scatter Plot

Figure 6 shows a zoomed-in view of the near-field debris.

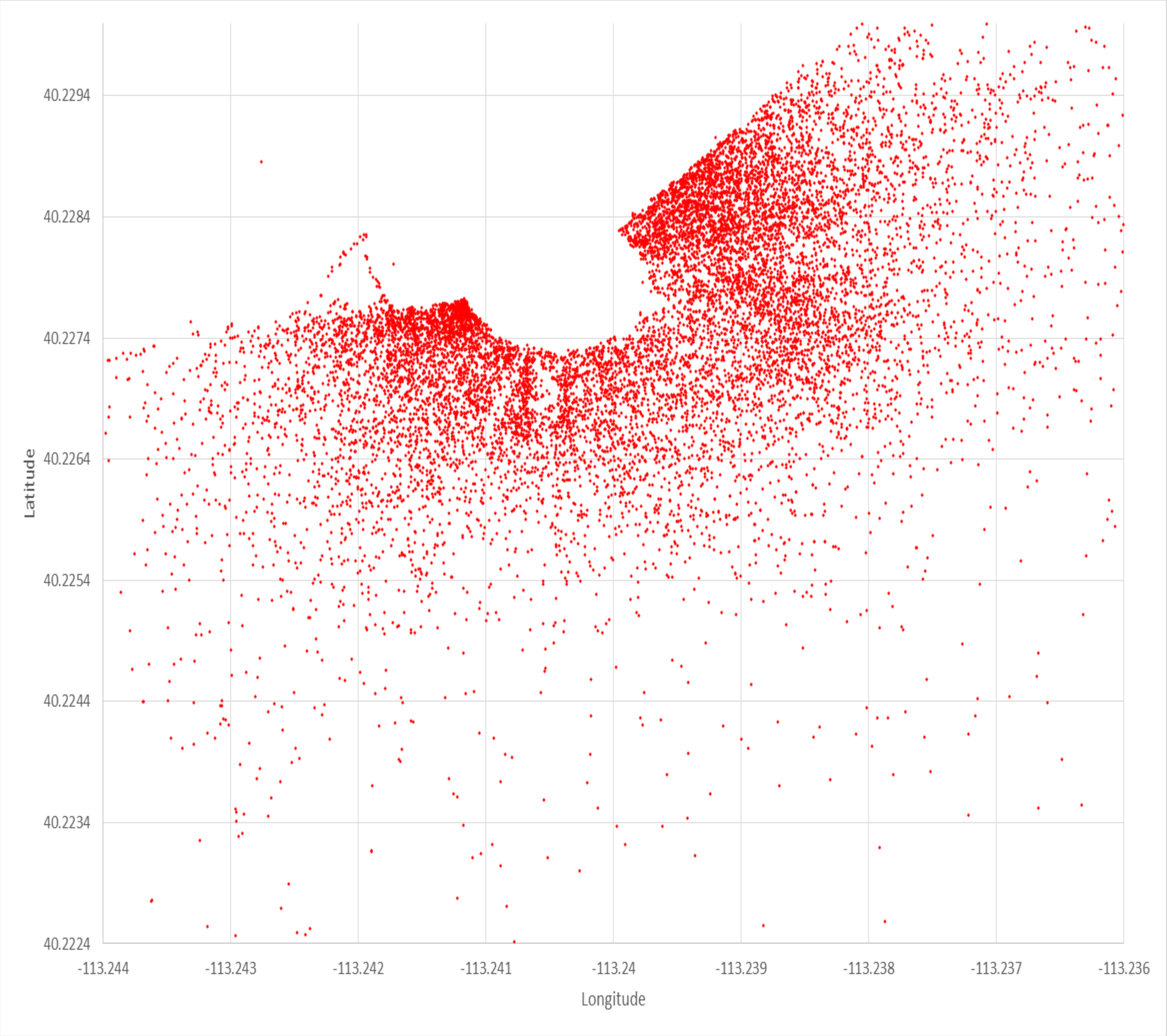

Figure 6. Zoomed Scatter Plot

USATCES finished the debris catalog and provided it to DDESB, EXWC, ATF, and IME in 2017. With this catalog, interested parties will be able to establish mass distribution and debris density as a function of range and bearing for the test.

2) Future Plans

With the debris catalog now available, comparisons can be made between the IMESAFR model predictions and the test results. If appropriate, the IMESAFR debris logic will be modified to include this new anchor data to improve the model. DoD may also perform the same sort of comparison with their new TP-14 Revision 5 debris logic.[2]

References

1. Swisdak, Michael M., Tatom, John W. and Conway, Robert T., “Procedures for the Collection, Analysis, and Interpretation of Explosion Produced Debris—Revision 2,” DDESB Technical Paper 21, October 2017.
2. “A Proposal for International Government/Industry Explosives Safety Testing Collaboration and Coordination,” Minutes of the Eighth Annual Australian Explosive Ordnance Symposium, Melbourne, Australia, November 2007; J. Tatom, M. Swisdak, D. Shatzer, D. Kennedy.
3. NATO AC/258-D/462, PFF (CPG/TS)D(99)3, “Measurement and Analysis of Explosion Produced Debris and Fragments Following an Accident or a Test Representative of an Accident,” 5 July 1999.
4. Swisdak, Michael M., Tatom, John W. and Hoing, Craig A., “Procedures for the Collection, Analysis, and Interpretation of Explosion Produced Debris—Revision 1,” DDESB Technical Paper 21, 22 October 2007.

---

[2] Conway, Robert T., *Updated Blast Effects and Consequence Models in DDESB Technical Paper 14*, Minutes of 2018 International Explosives Safety Symposium & Exposition, NDIA Paper No. 21244, 6-10 August 2018, San Diego, CA 2018