**Lost Seoul?**
**Assessing Pyongyang's Other Deterrent**

**Appendix**

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This document contains a set of technical appendices, which accompany the article, "Lost Seoul? Assessing Pyongyang's Other Deterrent." The appendices cover the following topics:

- Appendix A: Sensitivity analysis
- Appendix B: Historical analysis of lethal radius
- Appendix C: Evacuation model
- Appendix D: Hardened Artillery Sites (HARTS)
- Appendix E: North Korean operations and effects
- Appendix F: CFC operations and effects

**Appendix A: Sensitivity Analysis**

This section presents the results of the sensitivity analysis conducted in the article. To conduct the sensitivity analysis, we set all of our input parameters to their baseline values for crisis/realistic scenario. We then varied the input values for 34 variables—one at a time—setting them to their lowest plausible value, and then to their highest plausible value. Table A1, below, presents the results.

**Table A1: Results of Sensitivity Analysis ("Realistic Crisis" Scenario)**

| Variable | Baseline value | Low value | High value | Baseline result | Low result | High result |
|---|---|---|---|---|---|---|
| *DPRK Variables* | | | | | | |
| 170mm Koksans available | 162 | 122 | 202 | 2,573 | 2,516 (-2%) | 2,629 (+2%) |
| 240mm MRLs available | 162 | 122 | 202 | | 1,994 (-23%) | 3,152 (+23%) |
| Share of 240mm MRLs in HARTS (%) | 50 | 30 | 70 | | 2,730 (+6%) | 2,429 (-6%) |
| HARTS within 60 km | 200 | 170 | 230 | | 2,573 (0%) | 2,573 (0%) |
| Lethal radius of artillery ($LR_{10}$) (m) | 10 | 4 | 12 | | 412 (-84%) | 3,704 (+44%) |
| 170mm Koksan setup time (mins) | 10 | 4 | 16 | | 2,573 (0%) | 2,573 (0%) |
| 170mm Koksan pack up time (mins) | 5 | 2 | 8 | | 2,573 (0%) | 2,573 (0%) |
| 240mm MRL setup time (mins) | 2 | 1 | 3 | | 2,574 (+0%) | 2,570 (-0%) |
| 240mm MRL pack up time (mins) | 2 | 1 | 3 | | 2,574 (+0%) | 2,570 (-0%) |
| Artillery shell dud rate (%) | 25 | 15 | 35 | | 2,916 (+13%) | 2,230 (-13%) |
| Breakpoint (%) | 75 | 60 | 90 | | 2,503 (-3%) | 2,631 (+2%) |
| Cycle time (%) | +50 | +25 | +75 | | 2,583 (+0%) | 2,566 (-0%) |
| Population density targeted (pop./km²) | 31,862 | 23,862 | 39,862 | | 1,927 (-25%) | 3,218 (+25%) |
| *Combined Forces Command Variables* | | | | | | |
| ROK GMLRS (K239 and M270A1) available | 152 | 122 | 182 | 2,573 | 2,573 (0%) | 2,573 (0%) |
| M270 MLRS available | 32 | 24 | 40 | | 2,573 (0%) | 2,573 (0%) |
| 155mm K-9 available | 867 | 667 | 1,067 | | 2,573 (0%) | 2,573 (0%) |
| (G)MLRS cycle time (min) | 35 | 25 | 45 | | 2,573 (0%) | 2,573 (0%) |
| (G)MLRS assignment to mission (%) | 90 | 80 | 100 | | 2,573 (0%) | 2,573 (0%) |
| Alert level (%) | 75 | 60 | 90 | | 2,573 (0%) | 2,573 (0%) |
| Mechanical readiness (%) | 80 | 60 | 100 | | 2,573 (0%) | 2,573 (0%) |
| GMLRS p(K) vs. HARTS (%) | 67 | 50 | 84 | | 2,573 (0%) | 2,573 (0%) |
| MLRS effectiveness vs. mobile targets (%) | 67 | 50 | 84 | | 2,637 (+2%) | 2,534 (-2%) |
| Mine suppression effectiveness (%) | 25 | 10 | 40 | | 2,573 (0%) | 2,573 (0%) |
| HARTS misidentification (%) | 10 | 0 | 20 | | 2,573 (0%) | 2,573 (+0%) |
| Radar effectiveness (%) | 50 | 25 | 75 | | 2,898 (+13%) | 2,460 (-4%) |
| Response time (min) | 10 | 5 | 15 | | 2,513 (-2%) | 2,574 (+0%) |
| *Evacuation Variables* | | | | | | |
| Population distribution (subway, outdoor, indoor) (%) | 3, 15, 82 | 0, 1, 99 | 5, 20, 75 | 2,573 | 2,635 (+2%) | 2,534 (-2%) |
| Shock delay before evacuating (min) | 2 | 1 | 3 | | 2,555 (-1%) | 2,578 (+0%) |
| Walk time to shelter (min) | 6 | 4 | 8 | | 2,566 (-0%) | 2,578 (+0%) |
| Shelter entry time (min) | 5 | 3 | 7 | | 2,566 (-0%) | 2,578 (+0%) |
| Time to clear floor (min) | 2 | 1 | 3 | | 2,567 (-0%) | 2,571 (-0%) |
| Descent time per floor (min) | 2 | 1 | 3 | | 2,559 (-1%) | 2,590 (+1%) |
| Stairwell protection (%) | 25 | 0 | 50 | | 2,599 (+1%) | 2,546 (-1%) |
| Population not seeking shelter (%) | 25 | 10 | 40 | | 2,357 (-8%) | 2,788 (+8%) |

***Simulations***

We ran Monte Carlo simulations using Microsoft Excel. Model results were simulated 10,000 times for each of the three scenarios, on both nominal and realistic settings, for a total of 60,000 sets of simulated aggregate fatalities. For the simulations, we used the same model parameters and ranges of input values that were used in the sensitivity testing.[1] The parameters that were varied and their ranges are presented in Table A2, below. The parameter ranges were all uniformly distributed. For each run of the model, Excel randomly selected values for each of these parameters from the defined ranges of values and put them into the model to produce results.[2]

[1] Because sensitivity analysis was only run for scenario 2 whereas simulations were run for all three scenarios, we add one variable to the simulations that is specific to scenario 3 and so wasn't in the sensitivity analysis: the JASSM/TLAM p(K) vs. HARTS (%).

[2] Simulations were run using the "Data Table" function in Excel. To run the simulations, we first made each of the chosen input parameters (on the "Key Inputs" spreadsheet) uniform statistical distributions using the =RANDBETWEEN() function. So, for instance, the "Dud Rate" input parameter (a percentage) was coded as =RANDBETWEEN(15,35)/100. Once each input parameter was defined as a distribution, the simulations were ready to be run (and could be run one at a time by pressing F9 or fn.+F9). To record the results of the simulations, we created a new spreadsheet ("Simulation"). With this spreadsheet, starting from Cell A2, we listed numbers 1 to 10,000 downward (ending in Cell A10001). Then, at the top of the spreadsheet, in Cell B1, we input the key output value of interest (total fatalities) using = and the location of that value ("Key Inputs" sheet, Cell I6). We then highlighted both columns A and B for each of the 10,000 rows (A1:B10001). With all of these cells highlighted, we clicked the "Data" tab and then clicked "What-If Analysis" under the "Forecast" group, and then clicked "Data Table…" in the drop-down menu. Then, in the Data Table dialog box, we left "Row input cell" blank, clicked the box beside "Column input cell," and then clicked a cell on the spreadsheet that wasn't one of the 20,000 highlighted cells. Then we clicked "OK" and a few minutes later, results were produced. A problem with running simulations with Excel is that there isn't a function that can be used to set a seed, so that the same random variables can be produced with each run of the simulation. This means that our results can't be precisely replicated. Though, with 10,000 runs of the simulation, replicated results should be very close.

**Table A2: Simulation Parameters and Values**

| Parameter | Baseline Model Value | Simulation Value Range |
|---|---|---|
| *DPRK Variables* | | |
| 170mm Koksans available | 162 | 122-202 |
| 240mm MRLs available | 162 | 122-202 |
| Share of 240mm MRLs in HARTS (%) | 50 | 30-70 |
| HARTS within 60 km of Seoul | 200 | 170-230 |
| Lethal radius of artillery ($LR_{10}$) (m) | 10 | 4.00-12.00 |
| 170mm Koksan setup time | 10 | 4-16 |
| 170mm Koksan pack up time | 5 | 2-8 |
| 240mm MRL setup time | 2 | 1-3 |
| 240mm MRL pack up time | 2 | 1-3 |
| Artillery shell dud rate (%)* | 25 | 15-35 |
| Breakpoint (%)* | 75 | 60-90 |
| Cycle time (%)* | +50 | +25-+75 |
| Population density targeted (pop./$km^2$) | 31,862 | 23,862-39,862 |
| *CFC Variables* | | |
| ROK GMLRS (K239 and M270A1) available | 152 | 122-182 |
| M270 MLRS available | 32 | 24-40 |
| 155mm K-9 available | 867 | 667-1,067 |
| (G)MLRS cycle time (min) | 35 | 25-45 |
| (G)MLRS assignment to mission (%) | 90 | 80-100 |
| Alert level (for Scenario 1) (%) | 25 | 10-40 |
| Alert level (for Scenarios 2, 3) (%) | 75 | 60-90 |
| Mechanical readiness (%) | 80 | 60-100 |
| GMLRS p(K) vs. HARTS (%) | 67 | 50-84 |
| MLRS effectiveness vs. mobile targets (%) | 67 | 50-84 |
| Mine suppression effectiveness (%) | 25 | 10-40 |
| HARTS misidentification (%) | 10 | 0-20 |
| Radar effectiveness (%) | 50 | 25-75 |
| Response time (for Scenario 1) (min) | 15 | 10-20 |
| Response time (for Scenario 2) (min) | 10 | 5-15 |
| JASSM/TLAM p(K) vs. HARTS (for Scenario 3) (%) | 67 | 50-84 |
| *Evacuation Variables* | | |
| Population distribution (subway, outdoor, indoor) (%) | 3, 15, 82 | See Table A3 |
| Shock delay before evacuating (min) | 2 | 1-3 |
| Walk time to shelter (min) | 6 | 4-8 |
| Shelter entry time (min) | 5 | 3-7 |
| Time to clear floor (min) | 2 | 1-3 |
| Descent time per floor (min) | 2 | 1-3 |
| Stairwell protection (%) | 25 | 0-50 |
| Population not seeking shelter (%) | 25 | 10-40 |

* These parameters only apply to "realistic" scenarios.

The population distribution range (one of the "Evacuation Variables") was defined by estimating the average distribution of the Seoul population for each hour of the day, based on Seoul city subway data as well as environmental health and science data.[3] Table A3, below, lists the estimated distribution of the population for each hour. The simulation randomly selected the hour of the day, which then input the associated distribution of the population for that run of the model.

**Table A3: Estimated Population Distribution by Hour in Seoul**

| Time | Metro | Outdoor | Indoor | Time | Metro | Outdoor | Indoor |
|---|---|---|---|---|---|---|---|
| **12:00 AM** | 0.00% | 0.92% | 99.08% | **12:00 PM** | 2.47% | 14.25% | 83.28% |
| **1:00 AM** | 0.00% | 0.92% | 99.08% | **1:00 PM** | 2.48% | 15.80% | 81.72% |
| **2:00 AM** | 0.00% | 0.68% | 99.32% | **2:00 PM** | 2.74% | 17.53% | 79.73% |
| **3:00 AM** | 0.00% | 1.06% | 98.94% | **3:00 PM** | 3.14% | 18.28% | 78.57% |
| **4:00 AM** | 0.64% | 2.47% | 96.89% | **4:00 PM** | 3.91% | 18.19% | 77.90% |
| **5:00 AM** | 1.21% | 5.77% | 93.02% | **5:00 PM** | 5.41% | 19.85% | 74.74% |
| **6:00 AM** | 3.32% | 13.69% | 82.98% | **6:00 PM** | 3.09% | 13.93% | 82.98% |
| **7:00 AM** | 4.25% | 19.99% | 75.76% | **7:00 PM** | 2.40% | 10.86% | 86.74% |
| **8:00 AM** | 2.72% | 14.37% | 82.92% | **8:00 PM** | 2.35% | 9.41% | 88.24% |
| **9:00 AM** | 2.05% | 13.24% | 84.71% | **9:00 PM** | 1.98% | 7.30% | 90.72% |
| **10:00 AM** | 2.09% | 13.61% | 84.29% | **10:00 PM** | 0.91% | 3.16% | 95.93% |
| **11:00 AM** | 2.31% | 13.55% | 84.14% | **11:00 PM** | 0.15% | 1.23% | 98.62% |

Table A4 presents key descriptive statistics for the simulation results.

**Table A4: Simulation Results – Descriptive Statistics**

| Scenario | Model Baseline | Mean | Min | Max | 5th percentile | 95th percentile |
|---|---|---|---|---|---|---|
| **Surprise (nominal)** | 4,555 | 3,539 | 402 | 18,848 | 869 | 7,813 |
| **Surprise (realistic)** | 2,961 | 2,184 | 259 | 11,832 | 551 | 4,728 |
| **Crisis (nominal)** | 3,642 | 2,626 | 336 | 9,563 | 675 | 5,564 |
| **Crisis (realistic)** | 2,573 | 1,828 | 246 | 7,655 | 470 | 3,887 |
| **Pre-emption (nominal)** | 1,085 | 851 | 33 | 7,094 | 171 | 2,127 |
| **Pre-emption (realistic)** | 697 | 549 | 29 | 4,593 | 107 | 1,372 |

[3] 서울교통공사 2019년 일별 역별 시간대별 승하차인원 (2022), http://data.seoul.go.kr/dataList/OA-12921/F/1/datasetView.do; Jinhyeon Park, et al., "Spatial and Temporal Exposure Assessment to $PM_{2.5}$ in a Community Using Sensor-Based Air Monitoring Instruments and Dynamic Population Distributions," *Atmosphere*, Vol. 11, No. 12 (2020), pp. 5-6.

**Appendix B: Historical Analysis of Lethal Radius**

The model operates with a concept of lethal radius that we refer to as "$LR_{10}$," or the radius within which 10 percent of people can be expected to be killed. In our baseline model, we set the value of this variable to 10 meters.

Coming up with an estimate of $LR_{10}$ in a dense urban environment was a laborious process. Accurate estimates of the lethal radius of various munitions under test conditions *in open terrain* exist, but modelling lethal radii in dense, urban environments is a challenge. We do so by drawing on historical cases as well as other experts' analyses of artillery attacks in urban areas.

For the historical cases, our selection criteria were as follows:

- Cases of aerial bombardment or artillery attacks against urban populations;[4]
- Good documentation of the number of shells fired or bombs dropped;
- Good documentation of the number of fatalities;
- The munitions being largely (or entirely) high explosive;
- The shelling/bombing being relatively well isolated from other fighting;
- Target population densities of at least 2,500 per square km;[5] and
- At least 500 shells fired or bombs dropped.

[4] We posit that the lethal effects of a standard air-delivered bomb (a high explosive charge, which creates lethal shrapnel) and a standard high explosive artillery shell are very similar—both fall from above and kill via fragments and overpressure. Both can be fuzed to detonate on contact, in proximity, or after penetrating a target.

[5] We can mathematically scale results from a case with a given population density to another case that has a different density; in fact, that is what we do here. But those adjustments have a logical limit. They account for the fact that more people are located per $km^2$ in a high-density location, but they don't mathematically account for the fact that more buildings, and walls, and cars are located in high density locations—each of those absorbs weapon fragments and deflects pressure waves. Artillery and bombs have a much smaller lethal radius within cities than in the open for precisely this reason: in cities there are many structures that shield the people therein, and therefore scaling from attacks in rural areas (below 2,500/$km^2$) up to Seoul-levels of density would make little sense because those low-density cases more closely resemble detonations in the open then they do detonations in a dense, built-up space.

These criteria led us to focus on five cases from the German "Blitz" on British cities (1940-41)—London, Liverpool, Manchester, Birmingham, and Coventry[6]—plus the Siege of Sarajevo (1991-92), and the Israeli shelling of Shuja'iya in July 2014 during the Israeli-Gaza conflict.

Despite its apparent relevance, we excluded the November 2010 North Korean shelling of Yeonpyeong Island when estimating lethal radius for a number of reasons. First, the population density on Yeonpyeong Island at the time of the shelling was about 381 people/km$^2$, making it a far less urban environment than the one under consideration.[7] Second, only approximately 60 shells detonated on the island itself.[8] Third, despite the fact that a number of shells detonated in the town of Yeonpyeong, all of the fatalities occurred on a South Korean Marine Corps base, well away from town.[9] Without any fatalities in the low-density populated area, we had no "numerator" that could be scaled up by the relative population density in Seoul—even if that made sense analytically.

We also excluded two recent cases of relevance from our analysis: the Russian shelling of Ukrainian cities during in the Russia-Ukraine War (2022- ) and Israeli airstrikes of populated areas of the Gaza Strip in the Israel-Hamas War (2023- ). While both conflicts provide potentially useful data for this question, the fact that they are ongoing presents issues of data availability and reliability. In the case of Russia in Ukraine, while we likely have fairly accurate Ukrainian fatality data from bombardments early in the war, the number of artillery shells fired by Russian forces is far less clear.

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[6] These Blitz cases partially violate the criterion that the munitions are largely high explosive, since incendiary bombs made up an important share of the ordnance dropped on the UK. In fact, it is difficult to uncover cases of strategic aerial bombardment that don't involve incendiaries—and none that we have discovered that are carefully documented (i.e., number of bombs, number of fatalities, etc.). To deal with this problem (the intermixing of incendiaries and high-explosive munitions), (1) we avoided cases in which the bombs dropped were primarily incendiary, such as Dresden or Tokyo, and (2) we only included the number high explosive bombs dropped, and we attribute *all fatalities* to those high explosives, thus exaggerating the estimated lethal radii for those high explosive bombs. The result is that our method exaggerates the $LR_{10}$ of North Korea's shells.

[7] Joseph S. Bermudez, "The Yonp'yong-do Incident, November 23, 2010," *38 North Special Report* 11-1 (11 January 2011), p. 3. See note 5 on the limits of scaling up results derived from very low population density areas to attacks on urban locations.

[8] Bermudez, "The Yonp'yong-do Incident," pp. 10-11.

[9] Two South Korean marines as well as two construction workers who were working on the base were killed in the attack. See: Nam Kim, "Korea on the Brink: Reading the Yŏnp'yŏng Shelling and its Aftermath," *The Journal of Asian Studies*, Vol. 70, No. 2 (May 2011), p. 346.

In the case of the Israel-Hamas War, while the numbers of Israeli airstrikes and Palestinian fatalities have been widely reported, the reliability of these numbers is difficult to determine.

For each of our historical cases, we collected data on the number of fatalities in the attack, the number of bombs dropped or shells fired, the type of shell(s) or bomb(s) used, the weight of its explosive fill in kilograms, and the population density of the targeted city. All of this information was then used to generate an estimated average $LR_{10}$ for that case. The formula used to generate $LR_{10}$ estimates is:[10]

$$LR_{10} = \sqrt{\frac{total\ fatalities}{\pi \times total\ shells \times population\ density \times (1/1{,}000{,}000)}} \times 10^{\frac{1}{2}}$$

This formula was then scaled to account for any difference between the explosive power of the shells in the historical case and the explosive power of the weapons that would be used in the hypothetical North Korean attack on Seoul. Scaling was conducted with the following formula:

$$Scaled\ LR_{10} = LR_{10} \times \left(\frac{North\ Korean\ explosive\ weight\ per\ shell\ (kg)}{historical\ case\ explosive\ weight\ per\ shell\ (kg)}\right)^{\frac{1}{3}}$$

As indicated in the formula, blast effects are scaled according to a 1/3 power rule.[11] In all historical cases the North Korean explosive weight per shell is set to the estimated weight of a 170mm "Koksan" shell's high explosive fill of 6.98 kg.[12] Table B1, below, includes all of the cases listed

[10] This is a rearranged version of the formula in the article, which we use to estimate fatalities in our model. This version solves for "lethal radius," given that the casualties are known. Multiplying the formula by $10^{½}$ increases the area of the circle ten-fold, to create the radius within which 10 percent fatalities are expected.

[11] Harold S. Morton, "Scaling the Effects of Air Blast on Typical Targets," *APL Technical Digest*, Vol. 7, No. 1 (September-October 1967), p. 4.

[12] The explosive weight of a Koksan 170mm shell is estimated from the German 17-cm Kanone Granate 39 170mm projectile; that German gun is believed to be an engineering inspiration for North Korea's Koksan. See, *German Explosive Ordnance (Projectiles and Projectile Fuzes)*, Departments of the Army and Air Force, TM 9-1985-3/TO 39B-1A-10 (Washington: United States Printing Office, March 1953), p. 517. On the links between the Koksan and the German Kanone Granate 39, see Joseph S. Bermudez, "The M-1978 and M-1989 170mm Self-Propelled Guns, Part I," *KPA Journal*, Vol. 2, No. 6 (June 2011), p. 1.

above, their associated estimates, detailed explanatory notes, and all the sources from which the information was derived.

The table also includes data from two hypothetical North Korean attacks on Seoul modelled by analysts at the RAND Corporation. We believe their analytic approach is different than ours (based on a conversation with the authors), but we back out the implied $LR_{10}$ from their model. The explosives for the two RAND scenarios are not scaled, since they model an attack using the same North Korean artillery we posit, and therefore no scaling is needed. In supplemental files, we include this table, along with all formulas and analysis, as part of an Excel workbook ("Historical Lethal Radius Data").

As the table indicates, the scaled $LR_{10}$ estimates, based on historical cases and RAND analyses, range from 3 to about 7.5 meters. In order to be conservative—i.e., to adopt an estimate of lethality for North Korean shells that is at the highest plausible value—we assume an $LR_{10}$ of 10 meters. Note that the lethal radius we use is approximately double what was observed in previous artillery attacks, such as Sarajevo and Shuja'iya, which means we assume *four times* as large a lethal area per shell as was experienced in those attacks. Our $LR_{10}$ is three times what was observed in the aerial attacks of the Blitz, so our model uses a lethal area *nine times* as large as was actually witnessed in those attacks.

A final point to note on the lethal radius is that we assume that the Koksan, with its 170mm shells, and North Korea's MRL, with its 240mm rockets, produce the same $LR_{10}$ of 10 meters. Despite a large difference in the explosive weight of these two munitions, estimates we found of their lethal radii in the open (i.e., not in built up, urban environments) are very similar—24 meters in the case of a 155mm shell, and about 22 meters in the case of a 240mm rocket.[13]

[13] The estimated explosive fill for a 170mm shell is 6.98 kg, whereas for a 240mm rocket it is 45 kg. For lethal radius estimates, see: Howard Champion, John B. Holcomb, and Lee Ann Young, "Injuries from Explosions: Physics,

Biophysics, Pathology, and Required Research Focus," *The Journal of Trauma*, Vol. 66, No. 5 (May 2009), p. 1470; Ove Dullum, *The Rocket Artillery Reference Book* (Norwegian Defence Research Establishment, June 2010), p. 64.

**Table B1: Historical and Analytical Cases of Civilian Bombardment**

| Case | Fatalities | Shots | Weapons | Explosive (kg) | Pop. density | Implied $LR_{10}$ (m) | Scaled $LR_{10}$ (m) |
|---|---|---|---|---|---|---|---|
| The Blitz, London (1940-41) | 19,868[a] | 225,600[b] | SC50 & SC250[c] | 77.5[d] | 5,480.3[e] | 7.15 | 3.21 |
| London, Day One (7 Sept. 1940) | 430[h] | 3,960[i] | SC50 & SC250 | 77.5 | 5,480.3 | 7.94 | 3.55 |
| Liverpool (20-22 Dec. 1940) | 702[j] | 5,820[k] | SC50 & SC250 | 77.5 | 8,338.0[l] | 6.79 | 3.04 |
| Manchester (22-24 Dec. 1940) | 684[m] | 5,604[n] | SC50 & SC250 | 77.5 | 6,677.2[o] | 7.63 | 3.42 |
| Birmingham (19-20 Nov. 1940) | 450[p] | 4,800[q] | SC50 & SC250 | 77.5 | 4,974[r] | 7.75 | 3.47 |
| Coventry (Aug.-Oct. 1940) | 176[s] | 2,376[t] | SC50 & SC250 | 77.5 | 3,944.1[u] | 7.73 | 3.47 |
| Siege of Sarajevo (1992-94)[v] | 803 | 52,140 | 120mm mortar[w] | 2.99[x] | 2,685.5[y] | 4.27 | 5.67 |
| Shuja'iya (July 2014)[z] | 55 | 600 | 155mm shell | 6.99[aa] | 15,333.3[bb] | 4.36 | 4.36 |
| RAND Scenario 3[cc] | 1,500 | 1,188 | 240mm rocket | 45[dd] | 70,165.4[ee] | 7.57 | 7.57 |
| RAND Scenario 5[ff] | 10,120 | 14,000 | 170mm shell / 140mm rocket | 25.99[gg] | 55,200.0[hh] | 6.46 | 6.46 |

[a] Michael Clodfelter, *Warfare and Armed Conflicts: A Statistical Encyclopedia of Casualty and Other Figures* (Jefferson: McFarland, 2008), p. 471.
[b] This is based on 18,800 tons (18,800,000 kg) being dropped on London and assuming that half are 50 kg and half are 250 kg bombs. Clodfelter, *Warfare and Armed Conflicts*, p. 471.
[c] Germany dropped many different sizes and types of bombs during the Blitz, from 1 kg incendiaries to 50 kg high explosives to 1,000 kg parachute mines. The most common high explosive dropped was of the SC (*Sprengcylindrische*, cylindrical general purpose) class. For the purpose of analysis, we assume that half of the high explosive bombs dropped were SC50 (50 kg) and that half were SC250 (250 kg), and we attribute all fatalities to high explosives.
[d] This is the average of the explosive weight of the SC-50 (25 kg) and the explosive weight of the SC-250 (130 kg). See: *German Explosive Ordnance (Bombs, Fuzes, Rockets, Land Mines, Grenades, and Igniters*, Departments of the Army and Air Force, TM 9-1985-2/TO 11A-1-26 (Washington: United States Printing Office, March 1953), pp. 6, 8.
[e] This is based on London's 1939 population of 8,615,000 (See: "Population Change, 1939-2015," Greater London Authority, London Datastore (2021), https://data.london.gov.uk/dataset/population-change-1939-2015) and an area of 1,572 km² ("London," in *Encyclopaedia Britannica* (2021), https://www.britannica.com/place/London).
[h] John Ray, *The Night Blitz, 1940-1941* (London: Arms and Armour, 1996), p. 20.
[i] This is based on 330 tons (330,000 kg) being dropped on London and assuming that half are 50 kg and half are 250 kg bombs. See: Ray, *The Night Blitz*, p. 18.
[j] Ray, *The Night Blitz*, pp. 170-171.
[k] This is based on 485 tons (485,000 kg) being dropped on Liverpool and assuming that half are 50 kg and half are 250 kg bombs. Ray, *The Night Blitz*, pp. 170-171.
[l] This is based on Liverpool's estimated 1937 population of 836,300 and an area of 100.3 km². See: M. Epstein, ed., *The Statesman's Yearbook, 1940* (London: MacMillan & Co., 1940), p. 16.
[m] "The Manchester Blitz," Imperial War Museum (2021), https://www.iwm.org.uk/history/the-manchester-blitz.
[n] This is based on 467 tons (467,000 kg) being dropped on Manchester and assuming that half are 50 kg and half are 250 kg bombs. "The Manchester Blitz."
[o] This is based on Manchester's estimated 1937 population of 736,500 and an area of 110.3 km². See: *The Statesman's Yearbook, 1940*, p. 16.
[p] Ray, *The Night Blitz*, p. 165.
[q] This is based on 400 tons (400,000 kg) being dropped on Birmingham and assuming that half are 50 kg and half are 250 kg bombs. "The Blitz Around Britain," Imperial War Museum (2021), https://www.iwm.org.uk/history/the-blitz-around-britain.
[r] This is based on Birmingham's estimated 1937 population of 1,029,700 and an area of 207.0 km². See: *The Statesman's Yearbook, 1940*, p. 15.
[s] Ray, *The Night Blitz*, pp. 151-152.
[t] This is based on 198 tons (198,000 kg) being dropped on Coventry and assuming that half are 50 kg and half are 250 kg bombs. Ray, *The Night Blitz*, pp. 151-152.
[u] This is based on Coventry's estimated 1937 population of 204,700 and an area of 51.9 km². See: *The Statesman's Yearbook, 1940*, p. 15.

[v] The Sarajevo data count those shots and deaths that occurred between October 1992 and February 1994, the period in which the UN gathered daily shells and fatality data. We only include data for dates on which both artillery activity and fatalities are reported (a total of 141 days). The data were collected from*: Final Report of the United Nations Commission of Experts Established Pursuant to Security Council Resolution 780* (1992), Annex VI: Study of the Battle and Siege of Sarajevo, Appendix 2: Statistics, S/1994/647/Add.2 (Vol. II) (28 December 1994), pp. 29-35.

[w] The shelling in Sarajevo involved all calibers of indirect fire weapons, from 60 mm mortars up to 152 mm howitzers. We assumed each shot was a 120 mm mortar, to provide a rough average.

[x] This is an estimate based on the ubiquitous U.S. M933 high explosive mortar cartridge. See: *Army Ammunition Data Sheets, Artillery Ammunition: Guns, Howitzers, Mortars, Recoilless Rifles, Grenade Launchers, and Artillery Fuzes*, TM 43-0001-28 (Washington, DC: Department of the Army, April 1994), p. 4-103.

[y] This is based on an assumed population of 380,000 and an area of 141.5 $km^2$. According to the UN, Sarajevo had an estimated population of 435,000 prior to the siege, and in December 1994, after the siege, an estimated population between 300,000 and 380,000. See: *Final Report of the UN Commission of Experts*, p. 7.

[z] Unless otherwise noted, data in this row are from: *Report of the detailed findings of the Commission of Inquiry on the 2014 Gaza Conflict*, A/HRC/29/CRP.4 (24 June 2015), pp. 70 (para. 255), 73 (para. 271), 76 (para. 282). Available at: https://ohchr.org/en/hrbodies/hrc/coigazaconflict/pages/reportcoigaza.aspx.

[aa] This is based on the U.S. M107 155mm projectile. See: *Army Ammunition Data Sheets*, p. 3-78.

[bb] This is based on a population of 92,000 in an area of 6 $km^2$.

[cc] Unless otherwise noted, data in this row are from: D. Sean Barnett, et al., *North Korean Conventional Artillery: A Means to Retaliate, Coerce, Deter, or Terrorize Populations* (Santa Monica: RAND Corporation, 2020), pp. 12-13.

[dd] See "Notes" in "M-1985 North Korean 240mm Multiple Rocket Launcher," OE Data Integration Network (ODIN), Worldwide Equipment Guide (WEG), Department of the Army (2021), https://odin.tradoc.army.mil/WEG.

[ee] This is based on an envisioned area targeted of 2.4 $km^2$ and a population targeted of 168,397.

[ff] Unless otherwise noted, data in this row are from: Barnett, et al., *North Korean Conventional Artillery*, pp. 16-17.

[gg] This is the average of the explosive weight of the 240mm rocket (45 kg) and the estimated explosive weight of the 170mm shell (6.98 kg).

[hh] This is based on an envisioned area targeted of 25 $km^2$ and a population targeted of 1,380,000.

**Appendix C: Evacuation Model**

In the case of an attack on Seoul, the South Korean government instructs the public to evacuate to civil defense shelters.[14] We assume that 75% of the people do so (the rest forego shelter, presumably to seek family members or friends who are scattered around the city). As a result, the percentage of the Seoul population that is sheltered never exceeds 75%.[15]

Within the population, there are three distinct groups to consider: 1) those who are underground when the attack begins; 2) those who are outside; and (3) those who are inside buildings when the first shells detonate.

Underground. According to Seoul city government data, an average of 285,000 people enter the Seoul city subway system each hour between 7:00AM and 11:00PM daily, representing 3 percent of the city's population.[16] Assuming that an average ride is 1 hour long, roughly 3% of Seoul residents are underground at any given time during those hours. Many subway stations are civil defense shelters, so for a war that erupts during these hours, 3 percent of the population is protected at the outset; those who follow government instructions and remain sheltered (75% of the 3%) are protected throughout the attack.[17]

Inside a building. An average of 82 percent of the South Korean public are inside buildings at any given time between 7:00AM and 11:00PM.[18] The ROK government publishes detailed data on the size and number of buildings throughout the country, allowing us to estimate the location of the

[14] "Emergency Procedures Manual," National Disaster and Safety Portal, Government of the Republic of Korea (2019), http://eng.safekorea.go.kr/safeguide/selectSafeguidelist.do?searchLrgeclCd=COMM_01_04.
[15] This is a conservative assumption, because many of the people who decide to disobey instructions and seek out their family / loved ones will be sheltered some of the time (going down or upstairs), and others will find their family and shelter with them.
[16] Note that during peak hours (6:00-7:00PM), this figure will be as high as 5.6 percent. 서울교통공사 2019년 일별 역별 시간대별 승하차인원 (2022), http://data.seoul.go.kr/dataList/OA-12921/F/1/datasetView.do.
[17] This is a somewhat conservative assumption, given that we ignore other reasons that people may be underground at the time of an attack: e.g., living or working in a basement or parking their vehicle in an underground parking facility.
[18] We thank Jinhyeon Park and co-authors for sharing their data with us. See: Park, et al., "Spatial and Temporal Exposure Assessment to $PM_{2.5}$," pp. 5-6.

population in Seoul by floor (i.e., ground floor, second floor, etc.), and estimate evacuation times accordingly.[19] For instance, 27% of all building floors in Seoul are ground floors; 22% are second floors; 17% are third floors, and so on.[20] We assume that people located in buildings are distributed across the various floors proportionately.

The model tracks peoples' movement from inside buildings, down the stairs, outside to a shelter, and inside to protection, using the following assumptions:

1. Shock: 2 minutes delay from initial impacts until civilians begin to move toward shelter;[21]
2. Evacuating floors: Up to 2 minutes for the people on a floor to move into the stairwell;[22]
3. Descending stairs: Up to 2 minutes to descend each flight of stairs;[23]
4. Walking to shelter: Up to 6 minutes to walk from one's building to a shelter;[24]

[19] "Buildings by Floor," KOrean Statistical Information Service (KOSIS), Statistics Korea (2022), https://kosis.kr/eng/index/index.do.

[20] The data include the number of buildings within a few categories of sizes, including "1 Floor," "2-4 Floor," "5 Floor," "6-10 Floor," "11-20 Floor," "21-30 Floor," and "Over 31 Floor." For the purpose of the model, we assume an equal number of building sizes within each category (i.e., we assume an equal number of two floor, three floor, and four floor buildings for that category, as well as all other categories). For the "Over 31" category, we disaggregate and evenly distribute the data for buildings from 31 to 45 floors, given how few buildings in Seoul are over 45.

[21] A two-minute delay before people begin to move toward safety seems conservative; it is intended to account for panic and confusion at the outset of an attack—a phenomenon known as "pre-evacuation" in evacuation research.

[22] Given that many stairwells are in the interior of buildings and are encased in concrete, we assume that the stairwells offer 25 percent protection to those that are inside them.

[23] Data from 62 evacuations of buildings ranging from 2 to 31 floors show that it takes an average of 80 seconds per floor for people to evacuate buildings. Two minutes is the 80$^{th}$ percentile value in these data. Note that the data are collected from drills, and people move more quickly in an actual emergency. See: Guylène Proulx, "Evacuation Time and Movement in Apartment Buildings," *Fire Safety Journal*, Vol. 24, No. 3 (1995), p. 237; R.D. Peacock, et al., "Overall and Local Movement Speeds During Fire Drill Evacuations in Buildings," *Safety Science*, Vol. 50, No. 8 (October 2012), p. 1659; Erica D. Kuligowski, et al., "Movement on Stairs During Building Evacuations," *NIST Technical Note*, No. 1839 (2015), p. 115; Maria Miñambres, et al., "Study of Historical Evacuation Drill Data Combining Regression Analysis and Dimensionless Numbers," *PLoS ONE*, Vol. 15, No. 5 (2020), p. 7.

[24] Seoul has 3,224 civil defense shelters; given the city's area (606 km$^2$), that is one civil defense shelter per 0.19 km$^2$. If we assume the shelters are evenly distributed, and if a circle with an area of 0.19 km$^2$ (190,000 m$^2$) were placed around each one, the radii of each circle (and therefore the point at which an individual is farthest away from any shelter) would be 246 meters. Thus, the maximum distance from any given point in the city to a shelter is, therefore, approximately 250 meters. At a slow speed of 0.82 meters per second, this suggests 5 minutes, 5 seconds walking time to the nearest shelter, which we round up to 6 minutes to account for any crowding and confusion. Shelter data from 민방위대피시설, LocalData, 행정안전부, 대한민국 정부 (2022), https://www.localdata.go.kr/devcenter/dataDown.do?menuNo=20001. Note that in an emergency situation, most people would be traveling much faster than a "slow walking speed." On walking speed, see: Elaine M. Murtagh, et al., "Outdoor Walking Speeds of Apparently Healthy Adults: A Systematic Review and Meta-Analysis," *Sports Medicine*, Vol. 51, No. 1 (2021), p. 125.

5. Entering the shelter: Up to 5 minutes to queue and enter the shelter.[25]

The model assigns 0% protection to people who are frozen by the initial shock of the attack (stage 1), or moving from their floor to the stairs (stage 2). It assigns 25% protection to people inside stairwells (stage 3), and 0% protection to those walking to the shelter (stage 4) or queueing for entry (stage 5). People inside a shelter are 100% protected.

Outside. An average of 15 percent of the South Korean public are outdoors at any given moment between 7:00AM and 11:00PM.[26] When an attack begins, we assume that people who are outside go through the following stages:

1. Shock: 2 minutes delay from initial impacts until civilians begin to move toward shelters;
2. Walking to shelter: Up to 6 minutes to walk from one's position on the street to a shelter;
3. Entering the shelter: Up to 5 minutes to queue and enter the shelter.

Two minutes of delay before civilians on the street start to move to a shelter is conservative (i.e., overstates the delay), but people may be overcome by shock and initially seek cover rather than move toward a shelter. As noted above, walking to a shelter should take no more than 6 minutes. There is likely to be crowding at some shelter entrances in dense areas of the city. In order to account for such crowding, we assume it takes up to 5 minutes to enter the shelters. Putting these figures together, we estimate that the people who are at street level when the conflict begins, and follow orders and proceed to a shelter, will start to arrive at the shelters 2 minutes after the attack begins, and all of them will be sheltered 13 minutes after the attack commences.

[25] Note that we assume that all groups enter shelters at a constant rate, so, for those on ground floors, it would be (82% (those indoors) * 27% (those on ground floors) * 75% (those evacuating)) / 11 (6 minutes walking + 5 minutes entering) = 1.5% per minute for 11 minutes.

[26] Park, et al., "Spatial and Temporal Exposure Assessment to $PM_{2.5}$," pp. 5-6.

**Appendix D: Hardened Artillery Sites (HARTS)**

Many North Korean artillery batteries operate from hardened artillery sites, known as "HARTS." These HARTS vary considerably in terms of their sophistication and the protection they offer, but they come in two basic types—shed-type and underground-type. Shed-type HARTS are groups of simple gun positions protected by a berm, with a nearby shed that provides cover, concealment, and some protection. Two images of shed-type HARTS are included in Figure D1, below. Shed-type HARTS typically have between four and six firing positions to accommodate the associated artillery forces. In some satellite images, such as in Figure D2 (below), Koksan barrels can be seen protruding from artillery sheds, and batteries can be observed parked outside the sheds.

**Figure D1: Shed-Type HARTS**

Note: These images were generated by the authors using Google Earth Pro. The upper HARTS (HARTS_id: 141) image was captured in November 2017, and the lower HARTS (HARTS_id: 167) was captured in November 2020.

Underground-type HARTS generally comprise an underground barracks with six gun positions dug into north- or northwest-facing hillsides. These structures are protected by several feet of earth and stones, a reinforced concrete roof, and a metal door. Underground-type HARTS typically have firing positions that are placed directly outside their entrances, allowing artillery batteries to pull out a few meters, set up, fire, pack up, and quickly re-enter the HARTS to take advantage of cover, concealment, and protection. Images of underground HARTS entrances are included in Figure D3, below. Often the entrances are arrayed linearly, though this is not always the case, and they are periodically interspersed with other local infrastructure, as shown in Figure D4 (below). Satellite images have also captured underground-type HARTS over the course of their construction (see Figure D5, below), which gives a good sense of the kind of protection they offer.

*HARTS Data*

In conducting the analysis, we compiled data on 171 HARTS locations that are within 60 kilometers of the northernmost populated areas of Seoul.[27] We chose 60 kilometers[28] as our scope, because this is the maximum range of North Korea's longest-range artillery piece, the 240mm multiple rocket launch (MRL) system.[29] In supplemental files, we include the following:

- "HARTS Data" sheet in "Supplementary Data" (Excel Workbook, *xlsx)
- "HARTS Data" (Google Earth Pro file, *kmz)

[27] All HARTS locations were identified and individually catalogued based on: "AccessDPRK 2021 Map – Free Version," My North Korea (31 January 2021), https://mynorthkorea.blogspot.com/2021/01/accessdprk-2021-map-free-version.html.

[28] The coordinates for the northernmost populated areas of Seoul are the following: 37.603110565, 126.800834227; 37.6495352794, 126.905242882; and 37.6939314545, 127.048940346. Using the "Ruler" tool in Google Earth Pro, we measured circles with 60-kilometre radii from these three points, and catalogued all HARTS that fell within these circles as relevant to the analysis.

[29] "M-1991 North Korean 240mm MRLS," OE Data Integration Network (ODIN), Worldwide Equipment Guide (WEG), Department of the Army (2021), https://odin.tradoc.army.mil/WEG.

**Figure D2: Shed-Type HARTS with Koksans**

Note: These images were generated by the authors using Google Earth Pro. The two upper images (HARTS_id: 22) appear to show a HARTS with a Koksan battery parked outside of a shed that is under construction. The two lower images (HARTS_id: 22 & 32) appear to show two different HARTS, each with the barrels of a Koksan battery protruding from the structures.

**Figure D3: Underground-Type HARTS**

Note: These images were generated by the authors using Google Earth Pro. Both the upper HARTS image (HARTS_id: 92) and the lower HARTS image (HARTS_id: 112) were captured in March 2021.

**Figure D4: Underground-Type HARTS (Non-Linear Entrances)**

Note: These images were generated by the authors using Google Earth Pro. The upper HARTS image (HARTS_id: 105) was captured in March 2021, and the lower HARTS image (HARTS_id: 111) was captured in February 2021.

**Figure D5: Underground HARTS (Under Construction)**

Note: These images were generated by the authors using Google Earth Pro. The images show the same HARTS location (HARTS_id: 11) in April 2011 (top-left), December 2012 (top-right), October 2013 (bottom-left), and February 2015 (bottom-right).

The Excel workbook contains three relevant tabs. The first tab ("HARTS Data") contains a list of each of the 171 HARTS within 60 km of Seoul that we've identified as relevant to the analysis. Each individual HARTS in the data has its own unique identifier (HARTS_id), an indicator of whether it is on a south or southeast slope (southeast_facing) or a north or northwest slope (northwest_facing),[30] and an indicator of whether it is a shed-type (shed) or an underground-type (underground) HARTS. We've also included the approximate area in square meters for each HARTS,[31] as well as its distance in kilometers from Seoul (along with the coordinates in Seoul from which this distance was measured).[32]

The second tab ("HARTS Entrance Measurements") includes measurements of a number of exposed underground HARTS entrances (such as those pictured above, in Figure D5), which help inform how we model CFC counterbattery targeting (more on this below).[33] The third tab ("HARTS Travel Dist. Measurements") includes measurements of the distances North Korean artillery would have to travel to get into position to fire. For shed-type, it includes the distances from probable artillery sheds to the firing positions of a sample of 21 HARTS.[34] For underground-type, it includes the distances from the entrances to the firing positions of a sample of 13 underground-type

[30] The slope of surrounding terrain was measured using the "Elevation" indicator on Google Earth Pro.
[31] The area of each HARTS was measured using the "Ruler" tool in Google Earth Pro. For shed-type HARTS, the tool was used to draw a polygon around the firing positions and nearby buildings that appear to potentially be artillery sheds. For underground-type HARTS, the tool was used to draw a polygon around the door entrances as well as their firing positions. The exact area figure for each HARTS should be interpreted with caution, since the results are sensitive to minor changes in the placement of the polygon. It is likely that the overall average areas will be most useful.
[32] The distance from Seoul was measured using the "Ruler" tool in Google Earth Pro. For each HARTS, the tool was used to draw a line from the HARTS location to the closest populated area within the boundaries of Seoul.
[33] The length, width, and area in meters for each of the HARTS entrances were measured using the "Ruler" tool in Google Earth Pro. HARTS entrances were measured and are listed in order from north-to-south and/or east-to-west
[34] The distance from probable artillery sheds to the firing positions was measured using the "Ruler" tool in Google Earth Pro. The "path" setting was used to measure the distance from the probable shelter, along existing roads, to the approximate center of the arrays of firing positions.

HARTS.[35] These measurements inform how we model North Korea's artillery operations (more on this below).

The Google Earth Pro file (.kmz) contains the locations of all 171 individual HARTS in the data set.

[35] The distance from entrances to the firing positions was measured using the "Ruler" tool in Google Earth Pro. The "line" setting was used to measure the distance from the underground HARTS entrances to the far end of their individual firing positions.

## Appendix E: North Korean Forces & Operations

Our baseline scenarios envision a North Korean attack with 162 170mm "Koksan" guns and 162 240mm multiple rocket launchers (MRLs).[36] We assume that all Koksans operate in batteries of six guns from hardened artillery sites (HARTS, see above), since their rates of fire and emplacement and displacement times are too slow to support mobile, "shoot-and-scoot" operations.[37] We also assume that all long-range artillery operating from HARTS, to include Koksans, must pull out of their shelters to fire.[38] Finally, we assume that the HARTS contain adequate ammunition and fuel. For "nominal" scenarios, we model Koksans operating on the following, 27-minute cycle:

- Exit HARTS and drive to position (1 min.)[39]
- Emplace and prepare to fire (10 min.)[40]
- Fire two rounds (5 min.)

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[36] This is in line with a recent RAND Corporation analysis, and it is consistent with our assumptions that of North Korea's 432 of each type of artillery weapon, 70% are deployed near the DMZ, two-thirds being deployed in the west (north of Seoul), and 80% being mechanically ready. See: Gian Gentile, et al., *Four Problems on the Korean Peninsula: North Korea's Expanding Nuclear Capabilities Drive a Complex Set of Problems* (Santa Monica: RAND Corporation, 2019), p. 7; D. Sean Barnett, et al., *North Korean Conventional Artillery: A Means to Retaliate, Coerce, Deter, or Terrorize Populations* (Santa Monica: RAND Corporation, 2020), pp. 14, 16-17.

[37] The 170mm Koksan's sustained rate of fire is 1-2 rounds every 5 minutes, its emplacement time is roughly 20 minutes, and its displacement time is approximately 10 minutes. "M-1978 Koksan North Korean 170mm Self-Propelled Gun (SPG)," OE Data Integration Network (ODIN), Worldwide Equipment Guide (WEG), Department of the Army (2021), https://odin.tradoc.army.mil/WEG.

[38] In the case of the Koksan, the large size of these vehicles (15 meters in length) and the need to elevate their 10-meter barrels to approximately 45 degrees to maximize their range make underground operations difficult. Additionally, the deafening sound and concussive effects of 170mm gun firing in a confined space risks incapacitating the crew. See: "M1978/M1989 – Schematics," Global Security (2021), https://www.globalsecurity.org/military/world/dprk/m-1978-170-schem.htm; "M-1978 Koksan," ODIN, WEG.

[39] Measurements of a sample of 13 underground-type HARTS found that the average distance from a HARTS entrance to the far end of its associated firing position was 22.7 meters. Measurements of a sample of 21 shed-type HARTS found that the average distance from a probable shed to the middle of the array of firing positions is 257.2 meters (see "HARTS Data" section, above, for a description of the data). The Koksan's maximum road travel speed is 40 km/h and its maximum off-road travel speed is 10 km/h. Given the short distances and rudimentary infrastructure involved (see Figures D1-D5, above), we assume that Koksans entering and exiting HARTS travel at 10 km/h (2.78 m/s), meaning that it takes approximately 8 seconds (22.7/2.78 = 8.2) to traverse the distance required to exit and enter underground-type HARTS and approximately 93 seconds (257.2/2.78 = 92.5) to traverse the distance required to exit and enter shed-type HARTS before and after firing. Since, according to data we collected (see: "HARTS Data"), 69 percent of all relevant HARTS are of the shed type, and about 32 percent are underground type, 60 seconds is a good assumed average travel time for Koksans operating from HARTS ((8.2*0.32)+(92.5*0.69) =66.4). For Koksan road travel speeds, see: "M-1978 Koksan," ODIN, WEG.

[40] Note that we halve the emplacement and displacement times for North Korean Koksans in our model as compared to publicly available sources.

- Displace and prepare to return to HARTS (5 min.)
- Drive to and enter HARTS (1 min.)
- Reload, shelter, and rest (5 min.)

What this means is that each Koksan in the model is able to fire two rounds into Seoul every 27 minutes, at least until it or its HARTS is destroyed by counterbattery fire.

In our baseline scenarios, we model 240mm MRL operations a little differently. First, we assume that half of North Korea's MRLs are the M-1985 version, which fires volleys of 12 rockets, and the other half are the M-1991 version, which fires volleys of 22.[41] Second, while we again assume that the 240mms operate in batteries of six, we envision half of these batteries as operating from HARTS and half of them conducting mobile, shoot-and-scoot operations. For 240mms operating from HARTS, we again assume that they must pull out from the HARTS in order to fire.[42] For both HARTS-based and mobile 240mms, we assume that they have adequate fuel and ammunition. For "nominal" scenarios (more on this below), we model HARTS-based 240mm MRLs operating on the following, 17-minute cycle:

- Exit HARTS and drive to position (1 min.)[43]

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[41] In the actual model, we take the average of these two and model all MRLs as firing volleys of 17 rockets ((12+22)/2 = 17). "M-1985 North Korean 240mm Multiple Rocket Launcher" and "M-1991 North Korean 240mm MRLS," both in OE Data Integration Network (ODIN), Worldwide Equipment Guide (WEG), Department of the Army (2021), https://odin.tradoc.army.mil/WEG.

[42] Rocket artillery, particularly of this large caliber, generate significant backblast, which makes underground operations dangerous. See: Roger Cavazos, "Mind the Gap Between Rhetoric and Reality," *NAPSNet Special Reports* (26 June 2012), https://nautilus.org/napsnet/napsnet-special-reports/mind-the-gap-between-rhetoric-and-reality/.

[43] North Korea's 240mm MRLs' maximum off-road speed is unknown, though their maximum road speed is 60 km/h, 50 percent faster than the Koksan. This may imply that their maximum off-road speed is approximately 15 km/h, given that the Koksan's is 10 km/h. Given the short distance and rudimentary infrastructure involved (see Figures D1-D5, above), we assume that 240mm MRLs entering and exiting HARTS travel at 15 km/h (4.17 m/s), meaning that it takes approximately 5 seconds (22.7/4.17 = 5.4) to traverse the distance required to exit and enter underground-type HARTS and approximately 62 seconds (257.2/4.17 = 61.7) to traverse the distance required to exit and enter shed-type HARTS before and after firing. Since 69 percent of all relevant HARTS are shed type, and 32 percent are underground type, 60 seconds is not a bad assumed average travel time for 240mm MRLs operating from HARTS ((5.4*0.32)+(61.7*0.69) = 44.8). For 240mm MRL road travel speeds, see: "M-1985 North Korean 240mm MRL" and "M-1991 North Korean 240mm MRLS," both in ODIN, WEG.

- Emplace and prepare to fire (2 min.)[44]
- Fire a volley of 12 or 22 rockets (1 min.)[45]
- Displace and prepare to return to HARTS (2 min.)
- Drive to and enter HARTS (1 min.)
- Reload, shelter, and rest (10 min.)[46]

What this means is that each 240mm MRL operating from a HARTS in the model is able to fire 12 or 22 rockets into Seoul every 17 minutes, at least until it or its HARTS is destroyed by counterbattery fire.

For "nominal" scenarios, we model mobile, shoot-and-scoot 240mm MRLs operating on the following, 25-minute cycle:

- Drive to firing position (5 min.)
- Emplace and prepare to fire (2 min.)
- Fire a volley of 12 or 22 rockets (1 min.)
- Displace and prepare to move to a new position for reload (2 min.)
- Move to a new position for reload (5 min.)
- Reload and rest (10 min.)

What this means is that each 240mm MRL conducting mobile, shoot-and-scoot operations in the model is able to fire 12 or 22 rockets into Seoul every 25 minutes, at least until it is destroyed by counterbattery fire.

*"Nominal" vs. "Realistic" North Korean Operations*

[44] At 2 minutes, respectively, emplacement and displacement times are much faster for the 240mm MRLs than for the Koksan. See: "M-1985 North Korean 240mm MRL," ODIN, WEG.
[45] The 240mm MRL can fire a full volley of rockets in between 48 and 96 seconds. See: "M-1985 North Korean 240mm MRL" and "M-1991 North Korean 240mm MRLS," both in ODIN, WEG.
[46] Reload time for the M-1991 is 10 minutes. See: "M-1991 North Korean 240mm MRLS," ODIN, WEG.

We model North Korean operations two ways, which we refer to as "nominal" and "realistic." In the "nominal" case we treat North Korean artillery like a normal, adequately equipped, well-trained ground force. We assume that their weapons work as expected; that their soldiers sustain a normal pace of operations; and that the North Korean units fight until they have lost essentially all of their combat power. In the "realistic" case, we take into consideration the poor state of the North Korean military. Many of their weapons are old; their maintenance is poor; they rarely conduct large-scale or realistic exercises; and their troops appear to be ill-fed and unhealthy. Under these "realistic" conditions, we assume:

- 25% of North Korea's shells and rockets fail to detonate.[47]
- The operational cycle for artillery fire takes 50% more time.[48]
- North Korean units will collapse after taking 75% losses.[49]

[47] This matches what was observed in the 2010 shelling of Yeonpyeong Island. See: Joseph S. Bermudez, "The Yonp'yong-do Incident, November 23, 2010," *38 North Special Report* 11-1 (11 January 2011), p. 11.
[48] For the times of these cycles, see the previous section of this appendix.
[49] This 75% figure is quite conservative—meaning that for a unit to fight until 75% of its personnel are incapacitated, it would need high levels of morale and cohesion. For instance, the Center for Army Analysis Wargaming Analysis Model (C-WAM) rule 5.7.2 states that the "attacker must establish a minimum strength percentage for component BCTs/BDEs [(Brigade Combat Teams/Brigades)] at which they will break contact and withdraw from the engagement. The default is 50%... defending BCTs/BDEs are eliminated if they fall below 30% strength." See: Dan Mahoney, *The CAA Wargaming Analysis Model (C-WAM)*, 29 July 2016, Version 7 (Center for Army Analysis), p. 59, available at Christopher A. Lawrence, "C-WAM 2," Mystics & Statistics Blog, Dupuy Institute (28 March 2018), http://www.dupuyinstitute.org/blog/2018/03/28/c-wam-2/. For critiques of the idea of using casualties to predict a "breakpoint" in combat, see: Robert McQuie, "Battle Outcomes: Casualty Rates as a Measure of Defeat," *Army*, Vol. 37, No. 11 (November 1987), pp. 30-35; Christopher A. Lawrence, *War by the Numbers: Understanding Conventional Combat* (Lincoln: Potomac Press, 2018), pp. 288-289. It is plausible that North Korean units would break after suffering much lower losses. One might compare the North Korean forces to Iraq's front-line infantry divisions in the 1991 Persian Gulf War. Those divisions—armed with old, poorly-maintained weapons, starved for realistic training or exercises, short of food, and brutalized by their own regime—surrendered *en masse* upon first contact with U.S. forces. The problem was not common to all Iraqi forces—Iraq's Republican Guard maneuvered and fought bravely during the ground war—but revealed the consequences of denying the front-line infantry divisions the weapons, maintenance, training, and food they needed. If the same dynamics play out in Korea, the KPA artillery units will collapse when they experience any significant counterbattery fire. On the morale of the various units of the Iraqi military during the 1991 war, see: Daryl G. Press, "The Myth of Airpower in the Persian Gulf War and the Future of Warfare," *International Security* Vol. 26, No. 2 (Fall 2001), pp. 5-44.

Table E1 summarizes these assumptions across the two cases.

**Table E1: How Nominal and Realistic Cases Differ for North Korean Artillery**

| | **"Dud rate"**[a] | **Operational Efficiency**[b] | **Break point**[c] |
|---|---|---|---|
| **Nominal** | 0% | Normal | 100% |
| **Realistic** | 25% | Reduced | 75% |

[a] Dud rate: the number of shells fired that fail to detonate, and therefore produce no fatalities.
[b] Operational efficiency: For nominal scenarios, the tasks associated with firing artillery take "nominal" amounts of time (as described in the appendix text above). For realistic cases, the time required for each task is multiplied by 1.5.
[c] Break point: the percentage of losses at which the force stops fighting.

## Appendix F: Combined Forces Command (CFC) Forces and Operations

We model the CFC counterbattery mission with the forces listed in Table F1, below. Just as we assumed that 2/3 of North Korean long-range artillery near the DMZ are in the west near Seoul, we assume that 2/3 of South Korea's artillery—including its MLRS and 155mm howitzers—are near Seoul. The figures in Table F1, therefore, count 2/3 of the ROK artillery (and 100% of US artillery on the peninsula, given that the U.S. 210th artillery regiment's location puts it in position to support the counterbattery operation we model in this paper).

**Table F1: Combined Forces Command's Counterbattery Artillery**

| Type | Country | Model | Quantity[b] |
|---|---|---|---|
| Multiple Launch Rocket Systems (MLRS) | U.S. | M270A1[a] (227mm) | 48 |
| | ROK | K239 "Cheonmu"[a] (239mm) | 145 |
| | | M270 (227mm) | 32 |
| | | M270A1[a] (227mm) | 7 |
| Self-Propelled Howitzer | | K-9 "Thunder" (155mm) | 867 |

[a] Capable of firing GPS-guided rockets.
[b] We assume that two-thirds of the ROK's artillery are deployed in the vicinity of Seoul; the same assumption we make with respect to North Korean artillery along the DMZ.
Source: *The Military Balance 2024*, pp. 51, 286-287.

In total, the CFC has approximately 200 GPS-guided MLRS (GMLRS), 32 unguided MLRS, and 867 155mm howitzers at its disposal. The availability and readiness of these forces is dependent upon which of three distinct scenarios is being modelled.

*The Scenarios*

Our model considers three alternative pathways to war, which determine how much of the CFC force is available to fight and how quickly it can do so. The first is a surprise attack. Under this scenario, very few CFC forces are on alert,[50] and they are slow to respond. The second scenario envisions war erupting during an intense crisis. Under this scenario, most CFC forces are on alert,

[50] Alert levels prescribe how much of the force is available for a given scenario. We assume that only the portion of the force that is "on alert" is available to fight in the battle.

and they are quicker to begin firing. The third scenario envisions a CFC pre-emptive strike on the North during a crisis. Under this scenario, most CFC forces are on alert, and they can begin firing at the same time as the North Korean forces (so no lag time in the CFC artillery response).[51] Table F2 summarizes these scenarios and their implications for force readiness and availability.

**Table F2: Summarizing the Three Scenarios**

| Scenario | Mechanical Readiness | On Alert | Counterfires Mission | Time to Respond | Cumulative Available |
|---|---|---|---|---|---|
| 1. Surprise | 80% | 25% | MLRS: 90%<br>K-9: 67% | 15 min. | MLRS: 42[a]<br>K-9: 116 |
| 2. Crisis | | 75% | | 10 min. | MLRS: 119[b]<br>K-9: 347 |
| 3. Pre-emption | | | | 0 min. | MLRS: 119<br>K-9: 347 |

[a] 36 GPS-guided MLRS (GMLRS), 6 MLRS.
[b] 108 GMLRS, 17 MLRS.

A few things are worth noting about the scenarios. First, under all scenarios we assume that only 80% of the CFC's artillery force is mechanically ready.[52] Second, in the "surprise" scenario, only 25% of the force is on alert and therefore available for use, whereas in both the "crisis" and "pre-emption" scenarios, 75% of the force is on alert. Third, in all scenarios 90% of available MLRS are assigned the mission of striking North Korean artillery, whereas just 67% of the K-9 Thunders are assigned to this mission. And fourth, the time required for alert forces to respond—the number of minutes before they begin returning fire to North Korean artillery—varies across the scenarios, being the greatest in the surprise attack scenario, and the least in the pre-emption scenario. What this

[51] In other words, in the pre-emptive scenario, CFC artillery forces begins firing on North Korean HARTS, and responding to fire from North Korean mobile artillery, at the same time that their North Korean counterparts begin to fire (which can be defined as minute 1). We assume that CFC ground forces are *not* told of the planned pre-emptive strike, and therefore their alert posture is the same as the posture in the "crisis" scenario. Once U.S. cruise missiles begin to strike North Korean targets, DPRK artillery begin to ready themselves to fire, as do CFC artillery. Giving North Korea the benefit of the doubt—that they can move from "alerted" to "firing" (even while under attack) as quickly as CFC artillery—we assume both sides are ready to fire at minute 1.
[52] Our assumption of 80% readiness is identical for CFC and DPRK forces—which is conservative given the poor state of maintenance among North Korean forces.

all amounts to is that the number of artillery pieces available will vary depending on the scenario modelled and that, in all cases, it is only a fraction of the total force.

*CFC Counterbattery Fire Concept*

The different parts of the CFC artillery force are modelled as having distinct roles and missions. The primary role of the GMLRS (the M270A1s and the K239s) in each of the scenarios is to destroy the hardened artillery sites (HARTS) housing much of North Korea's long-range artillery. As noted above, North Korea has 162 170mm Koksans in this battle, all of which are HARTS-based, and 81 HARTS-based 240mm MRLs. Given that both operate in batteries of six, this means there are (rounding up) 41 HARTS in need of targeting.[53] We assume that the CFC has good, though not perfect, intelligence on which of the HARTS house North Korean long-range artillery in the battle. This means that 10% of the HARTS that *don't* contain long-range artillery (meaning 16 HARTS) are misidentified and attacked.[54]

As indicated in Figures D3-D5, underground-type HARTS typically have six discrete shelters that need destroying. Shed-type HARTS, as shown in Figures D1 and D2, have fewer discrete targets, since the artillery shed is typically a single building. But there is bound to be some uncertainty as to which of the nearby buildings is associated with the artillery battery, so we assume that the CFC fires at six targets for shed-type HARTS as well. With 41 HARTS that are occupied by long-range artillery, 10 percent over-targeting (16 HARTS), and six targets per location, there are approximately 350 discrete HARTS-based targets for the CFC.[55] Precision targeting of these buildings and tunnels is the key role for the CFC's GMLRS.

The primary role for the unguided MLRS (the M270s) is to target North Korean long-range artillery conducting mobile, shoot-and-scoot operations with dual-purpose improvised conventional

[53] (162 + 81)/6 = 40.5 → 41.
[54] 200 HARTS total – 41 already slated for attack = 159 HARTS remaining * 10% = ~16.
[55] (41 + 16) * 6 = 342 → 350.

munitions (DPICM, or "cluster" munitions). As noted above, 81 of North Korea's 162 240mm MRLs are assumed to be conducting mobile operations. Given that they operate in batteries of six, there will be 13 or 14 batteries in need of targeting.[56] We assume that the locations of these forces aren't known until they reveal themselves to CFC counter-artillery radar by firing on Seoul. We assume CFC fire-finding radar are able to locate North Korean mobile artillery 50% of the time. This then sets off a "race," where the North Korean mobile artillery forces rapidly pack up and try to relocate before the CFC has a chance to return counterbattery fire.

The primary role for the 155mm howitzers (the K-9s) is to support the GMLRS targeting of HARTS. We haven't seen evidence that the K-9s deploy with laser- or GPS-guided artillery shells, such as the M982 Excalibur. Their relatively small shells are also less effective than rocket artillery at targeting North Korea's mobile launchers with DPICM.[57] The K-9s are therefore used to deploy artillery-delivered anti-personnel and anti-vehicle mines around targeted HARTS, to suppress their operations until GMLRS can destroy them.

In sum, the CFC's GMLRS will target HARTS, its unguided MLRS will target mobile North Korean batteries with DPICM, and its 155mm howitzers will deliver mines to the HARTS.

*The Effectiveness of CFC Fire*

We model the effectiveness of CFC fire separately for each artillery category. For the GMLRS (the M270A1s and the K239s), we assume they fire two unitary guided rockets at each of the HARTS targets. As noted above, there are approximately 350 discrete HARTS-based targets (six per HARTS), meaning that the GMLRS will fire approximately 700 individual guided rockets at the HARTS. Each of the M270A1 and the K239 launchers carries 12 GPS-guided rockets, which can hit

[56] $81/6 = 13.5$.

[57] A standard U.S. 155mm DPICM artillery shell (M864) will carry 72 submunitions and cover an area up to 1,200 $m^2$, whereas a single DPICM rocket (the M26) carries 644 submunitions, covering an area up to 230,000 $m^2$. See: *Field Artillery Manual Cannon Gunnery*, TC 3-09.81 (Washington: Department of the Army, April 2016), pp. 3-31-32; "M26 Multiple Launch Rocket System (MLRS)," Federation of American Scientists, Military Analysis Network, DOD-101 (1999), https://man.fas.org/dod-101/sys/land/m26.htm.

targets up to 60 or 70 km away, meaning that each GMLRS launcher can target one HARTS in a single salvo.[58]

Open source discussions of HARTS describe them as having 10-40 cm walls and ceilings of precast, steel reinforced concrete, buried under several feet of earth and stones.[59] Our own measurements of a number of exposed underground-type HARTS indicate that their entrances average 15 meters long, 8.5 meters wide, and they have an approximate area of 100 $m^2$.[60] The U.S. M31 rocket used by the M270A1 carries a 200 pound unitary warhead with 51.5 pounds of high explosive fill,[61] and reportedly has a "median miss distance" as low as 2.5 meters.[62] Both CFC GMLRS are also capable of firing delayed-fuse rockets, whose warheads can penetrate and destroy lightly fortified underground targets.[63] While there is little open-source discussion of the penetrating capabilities of delayed-fuse artillery, the results of an old, World War II era field study suggest that large, modern, penetrating artillery should be sufficient to render the underground-type HARTS

[58] This is 12 rockets per launcher, firing two rockets per target, at six targets per HARTS. See: "M270 American Multiple Launch Rocket System (MLRS)," and "K-239 Chunmoo South Korean 130mm/227mm/239mm Multiple Rocket Launcher (MRL)," both in OE Data Integration Network (ODIN), Worldwide Equipment Guide (WEG), Department of the Army (2021), https://odin.tradoc.army.mil/WEG. Note that while open-source information on the capabilities of the K239 is somewhat sparse, modern MLRS such as the U.S. M142 High Mobility Artillery Rocket System (HIMARS) have the ability to pre-program multiple targets and can adjust their aim in just 16 seconds, allowing multiple aimpoints to be targeted very quickly with a single volley. See: "M142 (HIMARS) American Artillery Rocket System," ODIN, WEG.

[59] James Dennis, "DPRK Briefing Book: HARTS in North Korea," *The Nautilus Institute* (1986), https://nautilus.org/publications/books/dprkbb/military/dprk-briefing-book-harts-in-north-korea/; *North Korean Tactics*, ATP 7-100.2 (Washington: Department of the Army, July 2020), p. 7-24.

[60] See "HARTS Data" section above for a description of the data.

[61] See: *JFIRE: Multi-Service Tactics, Techniques, and Procedures for the Joint Application of Firepower*, FM 3-09.32 (Fort Monroe: U.S. Army, December 2007), p. 32 (Table 8); *Program Executive Office Missiles and Space Weapon Systems Book* (Arsenal: Department of the Army, 2012), p. 112, Available at: https://www.msl.army.mil/documents/peoweaponsystems.pdf.

[62] On the XM30's accuracy, see: *Director, Operational Test and Evaluation, FY 2014 Annual Report* (Washington: Department of Defense, January 2015), p. 110, Available at: https://www.dote.osd.mil/annualreport/. Note that U.S. Army manuals list the M31's CEP as 5 meters. See: *Field Artillery Operations and Fire Support*, FM 3-09 (Washington: Department of the Army, April 2014), p. 2-24 (Table 2-3). Such specifications for the K-239's rockets do not seem to be available in the open-source literature.

[63] According to the U.S. Army Worldwide Equipment Guide, regarding the K-239, "it was a requirement of the ROK Army for the guided rocket to have a penetrator warhead to be used as a 'bunker buster' solution against the large number of bunkers along the DMZ." See: "K-239 Chunmoo," ODIN, WEG. On the M31's fuse settings, see: *PEO Missiles and Space Weapon Systems Book*, p. 111.

entrances impassable by North Korean artillery.[64] This will also hold for shed-type HARTS, as the sheds are larger and offer little real protection.[65]

As a result of the above, we assume that each GMLRS rocket has a 67 percent chance of destroying the HARTS, so the probability that at least one of the two rockets destroys the target is 89 percent.[66] (In our sensitivity analysis, we let the GMLRS's per missile "p(K)" against HARTS vary from 50%-84%.) As noted above, once all of the HARTS are destroyed, available GMLRS launchers are reassigned to be loaded with DPICM and to support the MLRS mission of targeting North Korea's mobile batteries.

For the unguided MLRS (the M270s) targeting mobile North Korean artillery, we model them as engaged in the following four-minute operational sequence:

- Fire-finding radar detect incoming long-range rockets and locate shooter (1 min.)[67]
- Radar operators transmit target data to MLRS launcher on alert (1 min.)
- MLRS launcher enters target coordinates and fires (1 min.)[68]
- Salvo flight time to target area (1 min.)[69]

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[64] The study found that 155mm shells with delayed fuses were able to create craters in heavily reinforced concrete to depths between 17 and 84 inches, in one case penetrating eight feet of earth to create a 27-inch crater. See: *Standard Artillery & Ammunition Against Reinforced Concrete Pillboxes*, Second Progress Report, War Department, Office of the Chief of Ordnance, Technical Division (15 February 1944, Washington, D.C.), pp. 33-57 (see pp. 36-37 for earth-penetrating case).

[65] For instance, the probable artillery sheds in Figures D1-D2 have the following dimensions (L x W) in meters: HARTS_22: 29 x 11.5; HARTS_32: 25.8 x 12.4; HARTS_141: 18.8 x 9.2; HARTS_167: 27.8 x 9.3.

[66] $1-(1-0.67)^2 = 0.89$.

[67] South Korea is believed to operate approximately thirty-two AN/TPQ-37 and ARTHUR-K counter-battery radars, as well as an unknown number of new, state-of-the-art TPQ-74K radars. The AN/TPQ-37 is capable of 10 simultaneous tracks at a range of 24-50 km, whereas the ARTHUR radar is capable of 100 simultaneous tracks at a range of 15 to 31 km. Little is publicly known about the TPQ-74K radar. See: Jeff Jeong, "South Korea Develops Artillery-Locating Radar," *Defense News* (24 April 2017), https://www.defensenews.com/industry/techwatch/2017/04/24/south-korea-develops-artillery-locating-radar/; "AN/TPQ-37 American Firefinder Radar," ODIN, WEG; "ARTHUR Norwegian Counter-Battery Radar," ODIN, WEG.

[68] Default rates of fire for U.S. MLRS are 5 seconds between rockets, so one minute for a full salvo (5*12 = 60). See: *Field Artillery Operations and Fire Support*, FM 3-09 (Washington: Department of the Army, April 2014), p. 2-24 (Table 2-3, "Note").

[69] The M270's standard M26 rocket is estimated to travel at approximately 415 meters/second. At a maximum distance of 32 km, flight time would be approximately 77 seconds (32,000 m/415 m = 77.1). We assume that many rockets would not be fired at maximum range. See: Dullum, *The Rocket Artillery Reference Book*, Appendix D, Table D3.7 (pp. 102-103).

What this means is that, if a CFC counterbattery radar detects and locates a launch (which we assume it does 50% of the time), and if an MLRS is available to respond, four minutes after a North Korean mobile battery fires CFC counterbattery fire will arrive.

For each North Korean mobile battery that fires, we model three CFC MLRS launchers firing their full salvos of 12 rockets. Each of the 12 rockets disperse DPICM in a roughly 1 $km^2$ square, meaning that three salvos cover an area of up to 3 $km^2$.[70] Recall that the North Korean 240mm MRL has a displacement time of approximately 2 minutes. This suggests that a North Korean MRL placed directly at the center[71] of a position targeted by CFC MLRS would need to travel 500-1,500 meters[72] in one minute or less to escape.[73] North Korea's 240mm MRL's maximum road speed is 60 km/h, but it takes some distance and time to get up to maximum speed. Therefore, we assume that these mobile MRLs will travel at an average speed of 30 km/h (or 8.3 meters per second) for the first

[70] Each M26 rocket contains 644 M77 submunitions and can cover an area of 0.23 $km^2$. A full salvo of M26 rockets is known to cover a full $km^2$. See: "M26 MLRS," FAS, DOD-101; "Notes" in "M270 American Multiple Launch Rocket System," ODIN, WEG; *Tactics, Techniques, and Procedures for the Multiple Launch Rocket System (MLRS) Operations*, FM 6-60 (Washington: Department of the Army, September 1993), p. 9-5.

[71] In reality, mobile North Korean MRL batteries in their firing positions are likely to form a roughly straight line with 15-50 meters between launchers, thereby occupying a position that is 95-270 meters across (This is the width of six North Korean 240mm MRLs (3 m * 6 = 18 m) plus the gaps between them (15 m/50 m * 5 = 75 m/250 m). On the size of North Korean MRLs, see: "M-1985 North Korean 240mm MRL" and "M-1991 North Korean 240mm MRLS," both in ODIN, WEG. Our spacing assumptions are based on old Soviet MRL tactical deployment norms. See: *The Soviet Army: Operations and Tactics*, FM 100-2-1 (Washington: Department of the Army, 1984), pp. 9-11, 9-21.) However, since we can't predict where any given launcher will be located within the target area, we conduct our calculations from the approximate center.

[72] Each MLRS launcher creates a roughly square-shaped zone of cluster munitions. If each launcher's square covers 1$km^2$, then its sides are approximately 1 km in length. A North Korean battery located in the middle of the square would be 500 meters to the closest edge. If the squares didn't overlap, and were aligned (for example) along a road on which the North Korean MRLs were operating (i.e., with one CFC MLRS battery aiming at the North Korean launch location, and one each to the left and right of that location), then a North Korean MRL would need to travel 1,500 meters to escape the DPICM barrage. If the CFC fire is aimed to overlap somewhat, then the NK MRLs would need to cross between 500 and 1,500 meters to get to safety.

[73] We assume the North Korean batteries have one minute to escape because of their operational cycle. Here's how the two sides' operational cycles line up:

| Minute | North Korean Mobile MRLs | CFC MLRS |
|---|---|---|
| 1 | MRL battery fires volley | Fire-finding radar detects and locates shooter |
| 2 | Battery displaces and prepares to move | Target data transmitted to CFC MLRS |
| 3 | | MLRS enter coordinates and fire |
| 4 | Battery in transit | MLRS salvo in flight to target |

minute. At this speed, it would take a full 60 seconds to travel 500 meters, and between 2 and 3 minutes to travel 1,500 meters.[74]

However, since: there will likely be targeting errors; some North Korean MRLs will fortuitously find themselves at the edge of a targeted area, and escape in the right direction; up to 10 percent of the DPICM may fail to detonate;[75] and even detonating DPICM may only be 75 percent effective against North Korean MRLs for a variety of reasons, we assume that only 2/3 (67%)[76] of North Korean mobile batteries will be destroyed by CFC counterbattery fire each time a volley of three salvos is fired at them. (In our sensitivity analysis, we let the effectiveness of a 3-launcher barrage vary from 50%-84%.) In line with the slowest rates listed in U.S. Army doctrinal manuals, we assume it takes a full 35 minutes for CFC GMLRS and MLRS to relocate, reload, and be ready to fire again.[77]

Finally, we model the 155mm howitzers (the K-9s) as delivering remote anti-armor mines (RAAMs, or anti-vehicle mines) and area denial artillery mines (ADAMs, or anti-personnel mines) to HARTS in support of the GMLRS. Based on data we collected, the average area of a HARTS complex is 8,467 $m^2$.[78] U.S. military doctrine considers a minefield dense enough to be capable of blocking enemy operations when there are approximately 0.004 RAAMs and 0.002 ADAMs per square meter.[79] Achieving this kind of density would require approximately four 155mm shells delivering the RAAMs and a single 155mm shell delivering the ADAMs per HARTS.[80] Because of

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[74] 500/8.3 = 60.2; speed could increase after the first minute, allowing them to cross 1,500 meters in 2-3 minutes.
[75] Mark Hiznay, "Operational and Technical Aspects of Cluster Munitions," in Jane Linekar and Valérie Compagnion, eds., *Disarmament Forum: Cluster Munitions*, Vol. 4 (Geneva: United Nations Institute for Disarmament Research, 2006), p. 19.
[76] This is 75% * 90% = 67.5%
[77] *Tactics, Techniques, and Procedures for Multiple Launch Rocket System (MLRS) Operations*, FM 6-60/MCRP 3-1.6.24 (Washington: Department of the Army/U.S. Marine Corps, April 1996), p. 4-20 (Figure 4.4).
[78] The average for underground-type HARTS is 10,275 $m^2$ and the average for shed-type HARTS is 7,661 $m^2$. See: "HARTS Data."
[79] *Mine/Countermine Operations*, FM 20-32 (Washington: Department of the Army, February 2004), p. 3-14 (Table 3-6).
[80] Each HARTS requires an average of 34 RAAMs (8,467*0.004 = 33.9) and about 17 ADAMs (8,467*0.002 = 16.9) delivered to it. Standard 155mm RAAM shells (M741) include 9 mines per projectile, meaning at least four projectiles

the varied sizes and configurations of many HARTS complexes, and the uncertainty of the extent of their areas of operation, we assume that the CFC mines an area of 40,000 $m^2$ per HARTS. This requires 21 155mm shells—18 delivering the RAAMs and three delivering the ADAMs.[81] Once loaded and emplaced, a CFC battery of six K-9 Thunders can deliver this many rounds to a HARTS in a little over two minutes.[82] Once these rounds are delivered, we assume that 25% of the HARTS covered with this density of mines are out of action until they can be cleared (which is beyond the timescale of the analysis).

In sum, the CFC's GMLRS destroy their HARTS targets with a probability of 89%, the MLRS targeting mobile North Korean batteries destroy the batteries with a probability of 67% (conditional on the fire-finding radars identifying them, which occurs 50% of the time) and the 155mm howitzers are able to put 25% of the HARTS out of action by delivering anti-vehicle and anti-personnel mines.

would be needed (34/9 = 3.8). Standard 155mm ADAM shells (M692) include 36 mines per projectile, meaning just one projectile would be needed. See: *Mine/Countermine Operations*, FM 20-32, pp. 3-2, 3-4 (Tables 3-1 and 3-2).

[81] 160 RAAMs are required for the desired density per HARTS (40,000*0.004 = 160), necessitating about 18 155mm shells to deliver them (160/9 = 17.8). 80 ADAMs are required for the desired density per HARTS (40,000*0.002 = 80), necessitating about three 155 mm shells to deliver them (80/36 = 2.2).

[82] A battery of six would each need to deliver 3-4 rounds (21/6 = 3.5). The K-9 Thunder's sustained rate of fire is 3 rounds per minute, meaning it would take 80 seconds to fire four rounds (4/3 * 60 = 80). The K-9 Thunder's muzzle velocity is unknown, but the U.S.'s 155mm M109A6 ("Paladin") has a muzzle velocity of 890 meters/second. At a maximum distance of 40 km, this means that travel time for the K-9's rounds would be less than one minute (40,000/890 = 44.9). See: "K9 Thunder Self-Propelled Howitzer," Hanwha Defense (2019), https://www.hanwha-defense.co.kr/eng/products/firearms-system-k9.do; "M109A6 Paladin American 155mm Self-Propelled Howitzer (SPH)," ODIN, WEG.