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An Analysis of the North Korean Nodong Missile

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In this paper, we analyze the North Korean missile program based on publicly available information and a technical understanding of missile systems. In particular, we present models for the 1,000 kilometer-range Nodong missile and a 1,300 kilometer-range variant, both based on Scud technology. These models are single-stage missiles with four clustered Scud-engines and would have a circular error probable (CEP) of two to four kilometers or larger. We conclude that a 1,000 kilometer-range missile with a one tonne payload could be built using Scud technology. Moreover, it appears feasible to extend the range to roughly 1,300 kilometers (with the same payload) if the missile body can be constructed out of high-strength aluminum rather than steel, although it is unclear whether North Korea has such a capability. If both missiles are based on Scud technology, their existence would not imply a breakthrough in North Korean missile technology. These missiles would then represent essentially the longest-range missiles achievable without technically difficult steps such as multi-staging, suggesting that future range increases may occur more slowly than past increases, depending on the level of technical assistance North Korea can acquire. We look briefly at what ranges could be achieved using a two-stage model with Scud engines and the difficulties a missile such as the Nodong would present to endo-atmospheric missile defenses.

INTRODUCTION

Since the early 1990s there have been an increasing number of reports that North Korea is developing a 1,000 to 1,300 kilometer-range missile, called the Nodong in western press reports. North Korea's missile program has generated international concern because of the country's proximity to South Korea and Japan and its reported missile sales to Iran, Syria, and Libya. The significance of the Nodong missile program to several regions of the world becomes

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clear if one considers the countries that become potential targets as the missile range increases to 1,000 kilometers and beyond. In particular, a missile with a range of 1,300 kilometers would give North Korea the capability to reach all of Japan, and Iran and Libya the capability to reach all of Israel.

At the same time, the extraordinarily closed nature of North Korean society has meant that little information is available about its missile program. In particular, there is little information to inform the public debate over the potential threats and policy options.

In this paper, we present a technical analysis of the North Korean missile program and show that based on publicly available information and a technical knowledge of missile systems it is possible to sketch a reasonably clear picture of the program and to draw some general conclusions about possible future developments. In particular, we present a model of the Nodong missile and consider the difficulties of producing the Nodong and longer-range missiles.

Our work is intended to answer the following questions. While North Korea has built missiles modelled on the 300 kilometer-range Soviet R-17/SS-1c "Scud-B" missile,* are reports of the Nodong credible, i.e., given what is known about its missile program, is North Korea capable of building a 1,000 kilometer-range missile? Is it possible to do so using Scud technology or would the existence of such a missile indicate that North Korea has achieved the capability to produce considerably more sophisticated missiles, either on its own or with help from abroad? The former might indicate that the Nodong is approaching the upper limit of what can be achieved without requiring the development of more sophisticated technology, such as multi-staging, and that as a result future increases in missile range might occur relatively slowly. On the other hand, the latter might suggest that at least one such technological barrier has been surmounted and future increases in range might occur relatively more rapidly. How credible are reports that North Korea has extended or will soon extend the range of the Nodong to 1,300 kilometers? What might be the next steps in a program to develop missiles with even greater range? How effective might one expect tactical missile defenses to be against a missile such as the Nodong?

Our main conclusions follow largely from combining general physical principles with an understanding of Scud technology; while we have drawn on publicly reported information about the North Korean missile program, our conclusions are relatively insensitive to whether this information is correct in

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* We identify Soviet and Chinese missiles by both their domestic and Western designations.

[redacted]

detail. The results draw heavily on calculations of the performance of missiles having a range of characteristics and structures[1] and information about the development of Soviet and Chinese missiles (especially the Soviet Scud-B).

Our goal is to provide a better understanding of the North Korean missile program and to present a set of plausible, self-consistent estimates of parameters for the Nodong missile. Since the available information on the North Korean missile program is limited, the values of the parameters we present are necessarily approximate, but are sufficient to answer some important questions about the missile.

THE HISTORY OF THE NORTH KOREAN MISSILE PROGRAM

Before analyzing the Nodong missile, we briefly describe the evolution of the North Korean missile program. This description will provide the basis for understanding the technology and knowledge base underlying the Nodong program. (Table 1 summarizes our estimates of the parameters of North Korea's missiles.)

DF-61 Program

From 1976 to 1978 North Korea was involved in a Chinese program to design a missile having a range of 600 kilometers with a payload of one metric tonne (1,000 kilograms). This project was suspended after its main supporters were ousted from the Chinese government. The program built on the experience Chinese missile designers had acquired during the 1960s and 1970s when they designed missiles up through the DF-5/CSS-4. The proposed missile, called the DF-61, was intended to incorporate storable liquid fuel with high pressure turbo-pumps and inertial guidance.[2]

NKScud Mod-A

Following the suspension of the DF-61 program, North Korea's next step toward developing ballistic missiles was acquiring Soviet Scud-B missiles.[3] After reverse-engineering the Scud-B it reportedly began flight testing an indigenously produced version in 1984, which we refer to as the NKScud Mod-A.[†,4] Like the Soviet Scud-B, the Mod-A is reported to have a range of 280 to

† We use "NKScud" to refer to North Korean missiles and distinguish them from Soviet missiles. The terms "Mod-A, Mod-B, etc. will refer only to North Korean missiles.

Table 1: Approximate values of the parameters describing the missiles North Korea is believed to have built or currently has under development. The entries are estimates derived from publicly available data as described in the text.

Parameter	Mod-A	Mod-B	Mod-C	Nodong	Extended-range Nodong
First flight test	1984	1985 (?)	1990	1993 (?)	—
Length (*m*)	11.25	11.25	12.55	15.5	15.5
Diameter (*m*)	0.88	0.88	0.88	1.3	1.3
Range (*km*)/ payload (*kg*)	300/ 985	340/ 985	500/ 700	1,000/1,000	1,300/1,000
Dry booster mass (*kg*)	1,385	1,385	1,500	3,800-4,000	2,800-3,000
Propellant mass (*kg*)	4,000	4,000	5,000	16,000	16,000
Fuel fraction	0.74	0.74	0.77	0.80–0.81	0.84–0.85
Specific impulse (*s*)	230	240	240	240	240
Burn time (*s*)	70	70	87.5	70	70
Thrust (*N*)	129,000	134,000	134,000	540,000	540,000
No. of engines	1	1	1	4	4

300 kilometers with a one tonne payload. This missile was probably used to gain experience in producing missiles but was not deployed. The missile was almost certainly constructed using the same materials and design as the Soviet Scud-B. The lower curve in figure 1 shows the range versus payload for a missile with the characteristics of the Soviet Scud-B or the NKScud Mod-A (appendix A gives the details of the Scud-B model).

NKScud Mod-B

By 1985 North Korea reportedly began producing the Mod-B, an improved version of the Mod-A. Following its war with Iraq, Iran apparently agreed in the mid-1980s to finance the development of this missile in return for North Korea supplying Iran with large numbers of the missile. Full-scale production reportedly began in 1986 to 1987 with the first 100 missiles being transferred

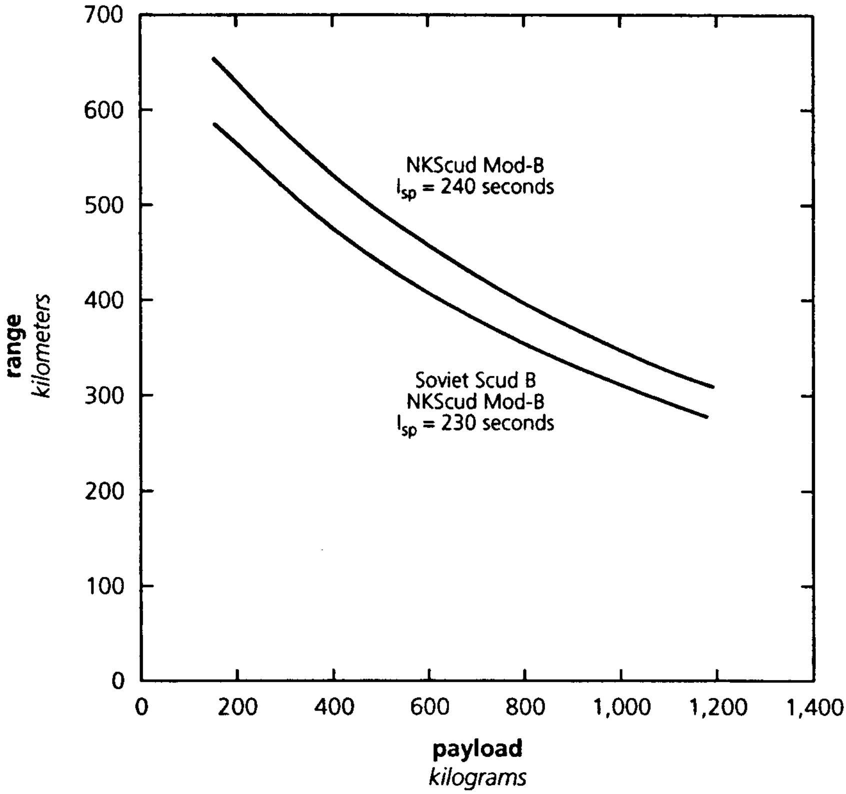


Figure 1: Range-payload curves for a missile assuming a dry booster mass of 1,385 kilograms, propellant mass of 4,000 kilograms, burn time of 70 seconds, and a specific impulse (I_{sp}) of 230 and 240 seconds. For a one tonne payload, these curves show ranges of roughly 300 and 340 kilometers, respectively, for these two values of specific impulse. We identify the model with I_{sp} = 230 seconds with the Soviet Scud-B and the NKScud Mod-A, and the model with I_{sp} = 240 seconds with the NKScud Mod-B.

to Iran in the fall of 1987.[5]

The Mod-B is reported to have a range of 320 to 340 kilometers with a one tonne payload—15 percent greater (about 40 kilometers) than the Mod-A—as a result of "minor modifications."[5] The most probable ways to achieve this increase would be to decrease the structural weight of the missile, to use a more energetic propellant, and/or to improve the engine to provide higher specific impulse by, for example, increasing the temperature and pressure of the combustion chamber. While it is possible that the North Koreans increased the size of the fuel tanks to carry more propellant, it seems more likely, given the modest range increase, that they would simply have used the same missile body produced for the Mod-A.

[redacted]

Figure 1 shows that with no other changes in the missile, a 40 kilometer range increase would require a decrease in payload of more than 150 kilograms. Alternatively, the payload could be maintained at one tonne if the structural weight of the missile were decreased by this amount. Modernizing and miniaturizing the guidance system and using light-weight components in the engine and fuel pump might lead to some weight savings, but probably less than 150 kilograms. Another possibility, that they used high-strength aluminum for the missile body instead of steel, is unlikely since it would probably reduce the weight by 350 to 400 kilograms, which would lead to a considerably longer range.[6]

The most likely explanation for the range increase of the Mod-B over the Mod-A is improvements to the rocket engine that increase the specific impulse (possibly in addition to reductions in the mass of the missile). Figure 1 shows that increasing the specific impulse from 230 to 240 seconds would give roughly a 40 kilometer increase in range with no change in the missile mass. We will see that a value of 240 seconds appears to be consistent with the models of the other North Korean missiles given below. Such a four percent increase in specific impulse appears achievable, especially since North Korea is believed to have received assistance on engine design and production from China after Chinese missile engineers had considerable experience in producing missiles.[7] For example, North Korea could have upgraded the engines by using high-pressure turbo pumps similar to those the Chinese had developed for their DF-series missiles. Increasing the pressure and the temperature in the combustion chamber by a small amount would lead to an increase in specific impulse of the required magnitude.[8]

The circular error probable (CEP) of the Soviet Scud-B and NKScud Mod-B is reported to be 450 to 1,000 meters at a range of 300 kilometers.[9]

NKScud Mod-C

An obvious way to increase the range of the Mod-B is to lengthen the missile to carry more fuel, which is almost certainly what North Korea did to produce a longer-range version, called the Mod-C. This method was used by Iraq to produce the al-Hussein missile that it used against Iran during the War of the Cities and against Israel and Saudi Arabia during the Persian Gulf War.[10] North Korean engineers were probably familiar with the details of this missile since Iran is reported to have given North Korea access to al-Hussein wreckage from its war with Iraq.[5] North Korean production of the Mod-C probably began during 1989 with the first known test launch in June 1990. North Korea reportedly began selling Mod-Cs to Iran and Syria in 1991.[11]

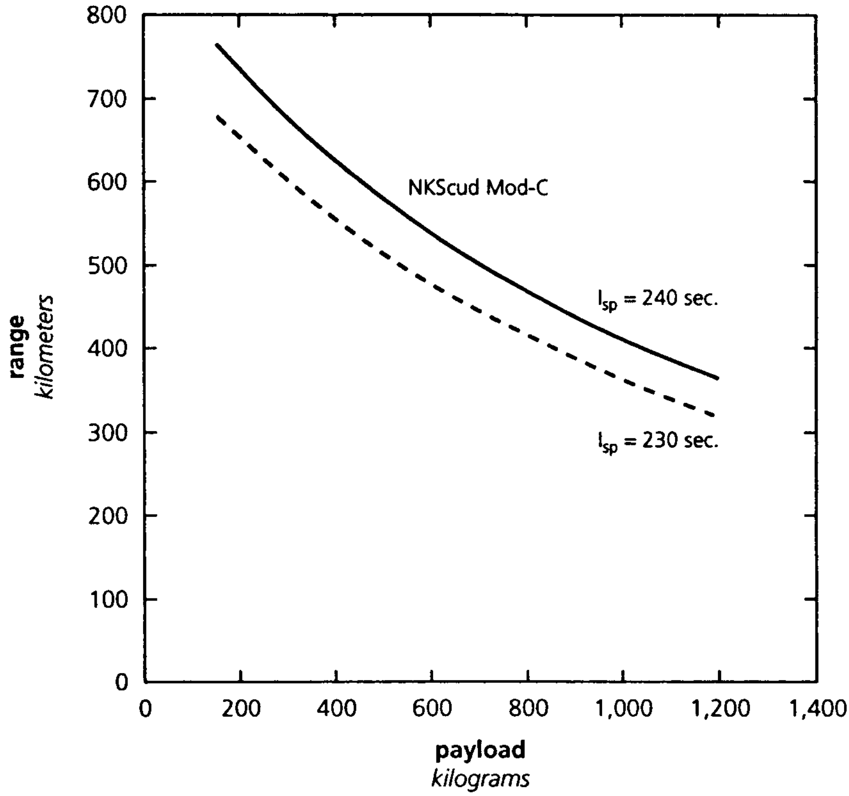


Figure 2: Range-payload curves for a missile with a dry booster mass of 1,500 kilograms, propellant mass of 5,000 kilograms, burn time of 87.5 seconds, and a specific impulse (I_{sp}) of 230 and 240 seconds. For I_{sp} = 240 seconds this model gives a range of 500 kilometers for a 700 kilogram payload and we identify it with the NKScud Mod-C.

Figure 2 shows the range-payload curves for a model of the Mod-C missile that carries 25 percent more fuel than the Mod-B. (This model assumes the same technology as the model used for figure 1; details are given in appendix A.) The range of the Mod-C is given as 500 to 600 kilometers with a 600 to 700 kilogram payload.[12] The figure shows that this range-payload capability corresponds well to a model of the Mod-C that uses a specific impulse of 240 seconds, which is the value also suggested by our model of the Mod-B.

The estimated accuracy of the Mod-C depends on what assumptions are made about its reentry. If the missile remains intact during reentry its accuracy will be considerably better than if the body separates from the warhead, as was seen to happen frequently with al-Hussein missiles during the Gulf War. Assuming it has an adequate static margin, an intact missile will lead to

[redacted]

increased accuracy since it will help keep the warhead aligned with the airflow rather than tumbling and will increase the weight and thus the speed of the warhead so that deflecting forces have less time to act. Assuming a CEP of 750 meters for the Mod-B we estimate a CEP of roughly 1,000 meters for an intact Mod-C and 1,300 to 2,600 meters for a separated warhead (see appendix B for details). The latter estimate assumes that the warhead is fairly stable during reentry; if instead it tumbles or spirals significantly the CEP could be considerably larger.[13]

Building a missile with range significantly greater than that of the Mod-C requires substantial redesigning. Even increasing the amount of fuel to 50 percent more than that of the Mod-B (while continuing to use a single Scud engine)[14] would give a range of about 550 kilometers for a 700 kilogram payload—a range increase of only 10 percent over the Mod-C. Reducing the structural weight of the missile by using aluminum rather than steel for the body would not produce a missile capable of flying 1,000 kilometers with a one tonne payload without a new, higher thrust engine.[15]

We argue below that if North Korea has built a substantially more capable missile it is most likely based on Scud technology and materials but uses a cluster of four Scud engines to increase the thrust. Such a configuration would be relatively straightforward to achieve given North Korea's existing missile program, but it would represent essentially the upper limit of what could be achieved without developing a more powerful engine or new technical capabilities, such as multi-staging.

THE NODONG MISSILE

The Nodong missile[‡] has been widely reported in the press as a new missile being developed by North Korea with an estimated range of at least 1,000 kilometers and capable of carrying chemical or nuclear warheads. It gained prominence in June 1993 after reports that North Korea had test flown the new missile in late May.

Development of the Nodong is believed to have started in 1988 to 1989 and was conducted in parallel with that of the Mod-C.[16] A number of countries have apparently shown interest in the missile. There are reports that Libya is

‡ The Western designation of the missile is "Nodong" or "No Dong" after the name of the city where it was first observed. The transliteration of the North Korean name is not unique and also appears as "Rodong." A number of sources refer to it as the "Nodong-1." Because of its characterization as a modified Scud, it is referred to as the Mod-D in some sources.

funding the development and will purchase the completed missiles and that North Korea will help it set up a production facility.[17] There are also reports that Iran is helping to fund the development of the missile[18] and has negotiated to receive 150 Nodongs,[19] possibly in return for oil shipments.[20] One report states that Syria may be the first country to receive the Nodong once it is operational.[21] Pakistani officials are also reported to have visited North Korea in 1992 to discuss the missile.[22] As mentioned above, North Korea is reported to have sold Mod-C missiles to both Iran and Syria.

A defector from the North Korean military claims that in the late 1980s, North Korea began constructing four underground bases (two of which are complete) for launching long-range missiles against U.S. military bases in Japan and Guam.[23]

The May 1993 Flight Test

There are conflicting reports about attempted flight tests of the Nodong prior to the May 1993 test.[24] In the May test, North Korea launched four missiles on 29 and 30 May, of which only one or possibly two were Nodongs, with the remainder being Mod-Cs. All reports agree that the Nodongs flew only 500 kilometers or less.[25] The identification of some of the missiles as Nodongs rather than Mod-Cs is almost certainly based on the size of the missile derived from monitoring by U.S. intelligence. North Korea has admitted that it tested a new missile but has not said whether the test was successful.[26] The launch site was given as Taepo-tong in Hwadae-kun, North Hamkyong Province, on the east coast of North Korea,[27] and the missile was reportedly fired from a mobile launcher.[28]

The tests were monitored by the U.S. and Japanese military, and were unusual for several reasons. First, the missiles were launched eastward across the Sea of Japan toward Japan (see figure 3) unlike previous tests of the Mod-C, which were launched to the south.[5] Second, the missiles did not send back telemetry and North Korea did not announce, as is typically done, that it was launching a missile into air space and sea lanes used by commercial planes and ships. Some analysts have speculated that the tests were a demonstration for potential buyers rather than a serious technical evaluation.[29]

There are several indications that the 500 kilometer range of the flight test was intentional and does not represent a failure of the missile. First, the missiles flew east toward Japan's Noto Peninsula. The Sea of Japan is only 750 kilometers wide at that point and is therefore too narrow for a full-range test. Moreover, Japanese planes identified two North Korean ships moored for two days near the impact site of the tests, roughly 300 kilometers from the

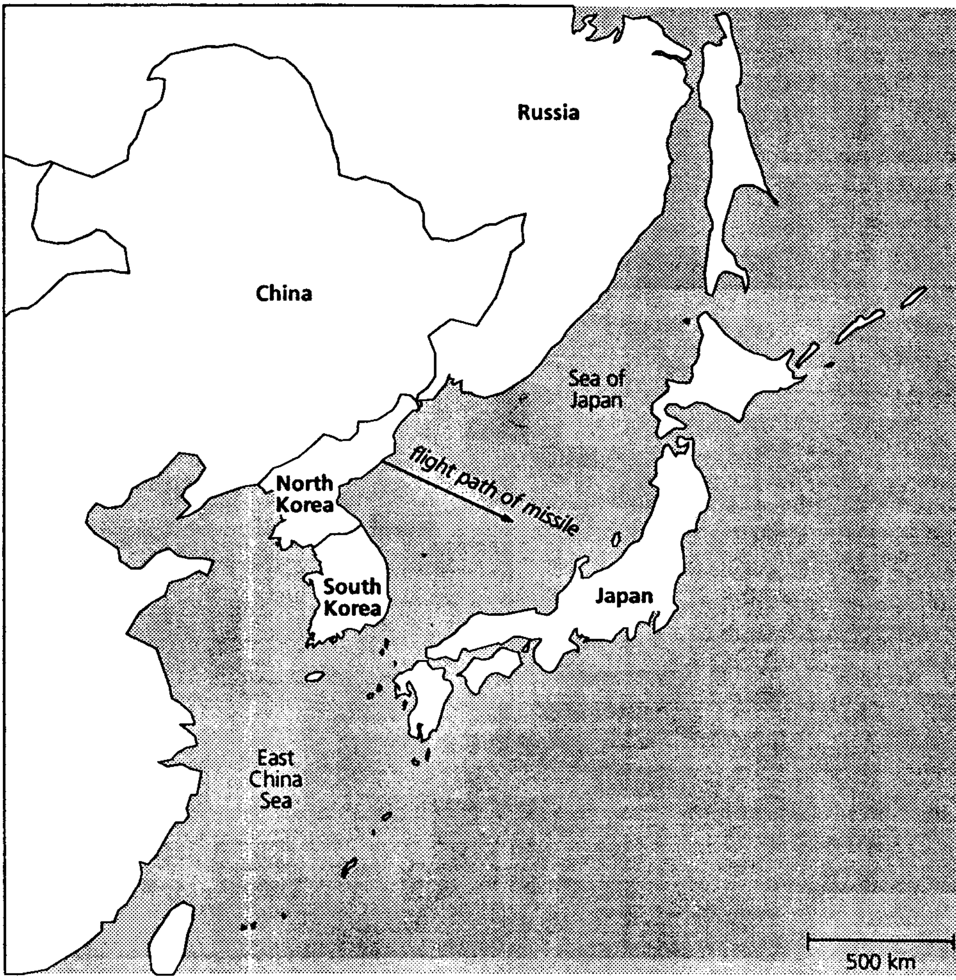


Figure 3: The flight path of the Nodong missile in late May 1993 is reported to have taken it eastward 500 kilometers across the Sea of Japan in the direction of Japan's Noto Peninsula.

Noto Peninsula. These ships are believed to have been positioned near the intended impact point to monitor the terminal portion of the flight.[30] The reason for a 500 kilometer test is not clear. The missile may not be ready for a full test. Alternately, reducing the Nodong range to 500 kilometers would have allowed North Korea to observe the impact of these missiles and the Mod-C missiles with the same set of ships. Doing so may also have been an attempt to conceal the Nodong test flight by launching it among Mod-C tests.

The Structure of the Nodong Missile

We present here the most likely structure for the Nodong missile. Our proposed structure results from combining technical information on the Soviet Scud-B, what little information has been reported about the Nodong missile, and what can be inferred from the history of the North Korean missile program and the histories of the Soviet and Chinese missile programs. Understanding the Chinese missile program is especially useful since North Korea was involved in the DF-61 missile development program with China in the mid-1970s.

Reports of the Nodong give a range of 900 to 1,000 kilometers with a payload of 800 to 1,000 kilograms.[31] Many reports also state that the range is expected to be increased to 1,300 kilometers with a one tonne payload.[32]

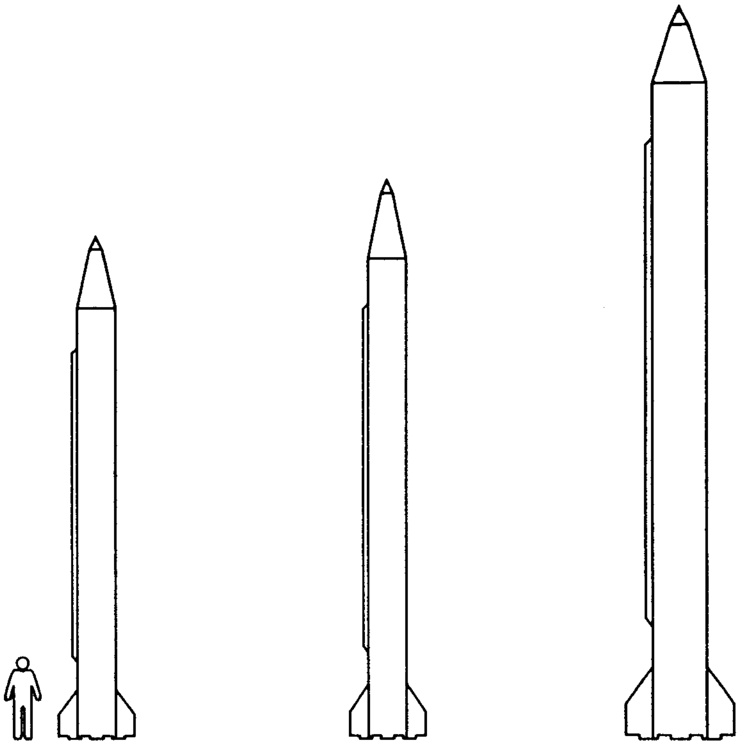
The most probable configuration for the Nodong missile is that it uses a cluster of four NKScud Mod-B engines to generate sufficient thrust. There are a number of factors that favor this configuration over one using a single, more powerful engine.[33]

First, clustering engines is a standard configuration—both the Soviet Union and China used clusters of four engines relatively early in their missile programs. The first such missiles were the Soviet R-12/SS-4 (first tested in 1955 and deployed in 1957) and the Chinese DF-3/CSS-2 (first successfully tested in 1966 and deployed in 1971).[34] Since North Korea has a working engine that it can produce and is well tested, it is likely to use a missile design based on that engine, especially since setting up production of a new engine could take considerable time and money.

Second, there are several technical reasons that favor clustering small engines. For example, testing large engines is considerably more difficult and expensive than testing smaller engines. In addition, experience shows that clustering engines greatly reduces the mechanical vibrations from the engines since the vibrations of the individual engines tend to destructively interfere with one another.[35] Thus the stresses and the structural demands on the booster are lower than if the missile used a single large engine.

Finally, building a single engine capable of the range-payload combination of the Nodong would be a large extrapolation from their previous experience, requiring an engine with thrust four times that of the Scud engine.

Several sources have given rough dimensions of the Nodong missile in the range of 15 to 16 meters in length and 1.2 to 1.3 meters in diameter.[36] These figures are almost certainly derived from remote imaging techniques and are therefore approximate. However, if the assumption of four clustered engines is correct we would expect the fuel tanks to hold four times as much fuel as the Scud-B, or roughly[37] 12.4 cubic meters. For a diameter of 1.3 meters, the



Soviet Scud-B
NKScud Mod A/B

NKScud Mod-C

Nodong

Figure 4: Relative sizes of the Mod-B, Mod-C, and Nodong missiles. The lengths are 11.25 meters, 12.55 meters, and roughly 15.5 meters, respectively. The diameters are 0.88 meters, 0.88 meters, and roughly 1.3 meters, respectively.

length of the propellant tanks would be 9.3 meters (plus some extra space between and at the ends of the tanks). Assuming the length of the section containing the engine below the propellant tanks is the same as in the Scud-B (two meters) and the section containing the guidance system and compressed air capsules between the warhead and the propellent tanks is increased from 1.3 meters in the Scud-B to about two meters to accommodate the additional air capsules required by the larger propellant tanks, one finds a booster length of roughly 13.5 meters (where we have included 0.2 meters between and at the ends of the propellant tanks). Further assuming that the warhead section is two meters long (see appendix C) gives a total length of 15.5 meters, which agrees well with the reported length (see figure 4).

We estimate the shape and the ballistic coefficient of the warhead by considering the heating of the warhead during reentry (see appendix C). We assume that, as with the Scud-B, the warhead does not have an ablative coating. A key assumption underlying our estimates of the heating and the accuracy is that the body of the Nodong will separate from the warhead before the warhead reaches deep into the atmosphere. Even if the warhead is not designed to separate, at 10 to 20 kilometers altitude the missile body would likely disintegrate under the action of the atmospheric forces as almost always occurred with al-Hussein missiles during the Iran-Iraq War and the 1991 Gulf War. Since the reentry speed of the full Nodong is much greater than that of the al-Hussein, the peak atmospheric forces on the Nodong will be roughly 70 percent larger, essentially assuring separation of the empty fuel tanks. As a result, North Korea may have designed the warhead to separate from the body before reentry since the process of breaking off the body can reduce the accuracy of the missile. Separating the warhead does not require sophisticated technology although if not done carefully it can cause the warhead to tumble, which will also degrade accuracy.

As discussed in appendix C, we estimate the ballistic coefficient of the warhead to be roughly 36,000 to 48,000 N m^{-2} (750 to 1,000 lb ft^{-2}), since larger values would lead to very high heating of the warhead as a result of the high reentry speed of the Nodong.

Assuming the missile holds four times as much propellant as the Scud-B gives a total propellant mass of 16 tonnes. We estimate a dry booster mass of roughly 3,800 to 4,000 kilograms, which gives a fuel fraction of 0.80 to 0.81 (see appendix D for details). Figure 5 shows range-payload curves for two models of the Nodong that use these masses, four clustered Scud engines, and the same propellant and construction as assumed for the Mod-B and Mod-C (see appendix A). These models give ranges of 915 to 965 kilometers for a one tonne payload. Given the approximate nature of the information available, this is in excellent agreement with reported values and suggests that a similar model is the source of the intelligence estimates of the missile's range.

Extending the Nodong Range to 1,300 Kilometers#

As noted above, a number of sources report that the range of the Nodong will be increased to 1,300 kilometers with a one tonne payload. We discuss here how such a range extension might be achieved. A Saudi Arabian newspaper has reported that North Korea plans to test this missile in southeastern

Some sources refer to this missile as the Nodong-2, although this name is usually reserved for a longer range missile that may be under development (see below). The 1,300 kilometer-range missile would more appropriately be called the Nodong Mod-B.

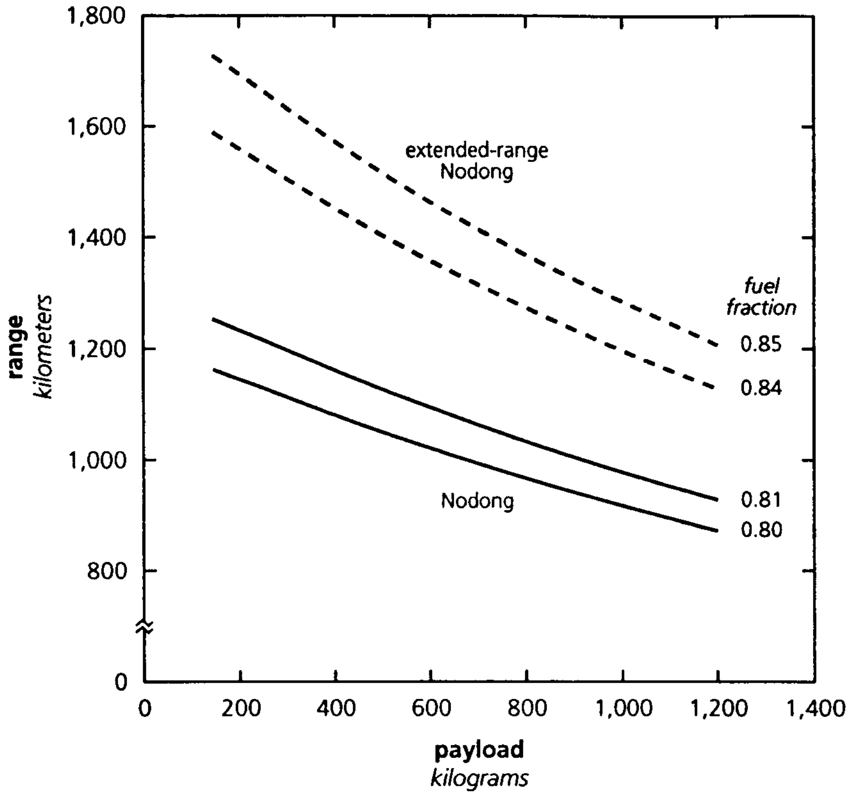


Figure 5: Range-payload curves for models of the Nodong missile. The curves assume four Scud engines, a propellant mass of 16,000 kilograms, a burn time of 70 seconds, a specific impulse of 240 seconds, and a fuel fraction (propellant mass divided by the full booster mass (including propellant)) as given on the plot.

Iran.[38] While North Korea denies such reports, the local geography restricts where North Korea could test such a missile (see figure 3) and may increase its interest in using a foreign test site.

Figure 5 shows that part but not all of the 300 kilometer range increase could result from reducing the payload below one tonne. However, we assume here that in extending the range North Korea would attempt to keep the payload near one tonne to accommodate a potential future nuclear warhead.[39]

The main options for increasing the range are:

- building a new engine or modifying the existing engine to give greater thrust,

- lengthening the missile to increase the amount of fuel, as was done to produce the Mod-C, and/or
- reducing the structural weight of the missile.

We will argue that the third option is the most likely.

Achieving a 300 kilometer increase in range would require increasing the thrust of the Scud engine by 10 to 15 percent, which is probably too great an increase to achieve by modifying the existing engine. On the other hand, if North Korea decided to design and build a new engine, it seems unlikely it would focus on such a moderate increase in performance. Moreover, a substantial redesign of the engine would likely require a substantial enough redesign of the missile that it would not be considered a modification of the Nodong.

Our calculations show that lengthening the missile and increasing the amount of propellant by 25 percent would only increase the range of the missile by 100 to 150 kilometers, depending on the amount of structural weight added to the booster. Even a 50 percent increase in propellant would only increase the range by about 200 kilometers.

On the other hand, it appears to be possible to extend the range by 300 kilometers while retaining a one tonne payload by reducing the structural mass of the booster. We have assumed above that the Mod-B, Mod-C, and Nodong missile bodies were made of steel. It is known, however, that aluminum-magnesium alloy was used for the missile bodies of the Chinese DF-3/CSS-2 and DF-4/CSS-3 missiles, which were developed in the 1960s.[40] If North Korea had the capability to construct missiles out of a similar material, it is possible they could reduce the structural mass of the booster by roughly one tonne (see appendix D). Range-payload curves calculated assuming fuel fractions of 0.84 and 0.85 show that this reduction would increase the range by roughly 300 kilometers while retaining a one tonne payload (see figure 5).

It is unclear whether there are indications that North Korea is actually building a 1,300 kilometer-range missile or whether it is a worst-case analysis considered by U.S. intelligence. Moreover, it not clear whether North Korea could build such a missile, although the technical barriers do not seem particularly large. While North Korea does not have a domestic airline industry that would give it experience in fabricating large bodies using aluminum alloys, the techniques are standard and well-known. It could presumably receive materials and technical assistance from a number of countries, including Iran.

Estimates of Nodong Accuracy

It is likely that the Nodong's inertial guidance system uses gyros and body-mounted accelerometers. The control system almost certainly uses graphite vanes in the exhaust to divert the thrust, which is the method used in the Scud-B as well as early Chinese missiles including the DF-3/CSS-2, which had four clustered engines.[41]

In estimating the accuracy of the Nodong we assume it uses Scud guidance technology and we scale up the errors of the Mod-B, as described in appendix B. As mentioned above, we assume that the warhead will separate from the missile body before it reaches low altitudes. We conservatively estimate that the CEP of the Nodong at 1,300 kilometers range will be 2,000 to 4,000 meters (see appendix B). If the warhead tumbles or spirals significantly during reentry the CEP may be considerably larger. One source reports a figure of 2,000 meters for the Nodong CEP;[42] we believe this figure is probably too small. The total error for a missile has two main contributions: errors in placing the missile on the proper ballistic trajectory at the end of boost phase and errors from atmospheric buffeting during reentry. If, as is likely, the reentry errors are the dominant contribution to the inaccuracy, then improving the guidance system of the missile would do little to improve the CEP since the guidance and control system only acts during the missile's boost phase and can only reduce the first contribution above. Improving the accuracy would instead require reducing the reentry errors, which is difficult.

Missile Reliability

The reliability of North Korea's missiles may be questionable since the expense of conducting flight tests may limit its testing program and thus its ability to achieve confidence in the missile's performance. Moreover, some analysts question the quality of workmanship on the missiles. Reports that North Korean missiles provided to Iran in the past were defective suggest that reliability has been a problem.[43] On the other hand, some key components, such as the engine, could be tested on the ground without requiring flight tests.

The reliability of the Nodong would be expected to be lower, perhaps significantly, than that of the Mod-B or Mod-C for a couple reasons. First, the Nodong is larger and faster than previous missiles and is therefore subjected to substantially higher stresses, which could lead to increased structural failures. Second, the presence of four engines instead of one will multiply the probability of a propulsion failure. For example, if individual Scud engines are 95 percent reliable, a cluster of four would be only $(0.95)^4 = 81$ percent reliable; if instead the individual engines are 90 percent reliable, the reliability of a cluster of four drops to 66 percent.

THE NEXT STEP?

There are reports that North Korea is planning a Nodong-2 missile with a 1,500 to 2,000 kilometer range.[44] Such a range would require developing either a considerably more powerful engine than the Scud-B engine, or multi-staging. Both methods have precedents. The Chinese DF-3/CSS-2 missile, which was first flown in late 1966, is a single-stage missile with four clustered engines that produce enough thrust to achieve a reported range of 2,800 kilometers with a two tonne payload. The first Chinese two-stage missile, the DF-4/CSS-3 (first tested in 1970), used the DF-3 as the first stage and a single DF-3 engine to power the second stage.[45] Both methods of extending the range are technically demanding, and the time required for North Korea to accomplish them depends largely on what foreign assistance it is able to get.

To understand the extent to which multi-staging could increase the range of a missile that still used Scud engines, we consider a simple model of a two-stage missile that uses the Nodong as the first stage and a variant of the Mod-B as the second stage. Optimizing the size of the second stage for a Nodong first stage gives a second stage mass roughly equal to the mass of the Mod-B. Thus, we take the second stage to be essentially a Mod-B with the fins removed. This configuration leads to a range of 1,750 to 1,800 kilometers for a 1,000 kilogram payload.[46] We emphasize that this estimate is crude and should be considered only as suggestive.

CONCLUSIONS AND IMPLICATIONS

Several important conclusions follow from our analysis:

First, it is possible to build a missile capable of flying 1,000 kilometers with a one tonne warhead using Scud technology that North Korea is known to produce. As a result, reports of the Nodong's development appear to be technically credible. On the other hand, the current state of North Korean industrial capabilities has led to some skepticism that it could produce such missiles.[47]

Second, it appears feasible in principle to further increase the Nodong range to around 1,300 kilometers with a one tonne warhead by constructing the missile body from high-strength aluminum. We have no evidence, however, to suggest whether this is actually being done or whether reports of such a development represent a worst-case analysis by U.S. intelligence analysts.

If both the 1,000 and 1,300 kilometer-range missiles are based on Scud technology, their existence would not imply a breakthrough in North Korean missile technology.

Third, the Nodong missile is essentially the longest range missile that North Korea could build with its existing level of missile technology. Further range increases would require steps such as building a considerably more powerful engine or using multiple stages—both of which are technically more demanding than using existing components to build the Nodong. Thus, future range increases may occur relatively more slowly than in the past five years. However, the technical issues involved in both approaches are widely understood and the time required for North Korea to master them if it is interested in doing so depends largely on what foreign assistance it can get.

Fourth, the accuracy of the Nodong is expected to be several kilometers and reducing this figure significantly would be very demanding. For example, if the errors are dominated by reentry errors rather than guidance and control errors, as appears likely, improving the guidance system of the missile would have little effect on the accuracy. With such poor accuracy the Nodong would not be a militarily significant weapon if equipped with a conventional or chemical warhead but could be an effective terror weapon. Its ability to carry a one tonne payload could make it a more significant threat in the future if North Korea or Iran develop a deliverable nuclear weapon. However, even if armed with a nuclear warhead its accuracy is so low that it still could not be used against military point targets.

Finally, while some key missile components could be tested without requiring flight tests, the overall reliability of the missiles may be low since it would be expensive for North Korea to carry out an extensive flight testing program. An emerging nuclear state may be reluctant to trust such a missile to deliver one of its few nuclear weapons.

Implications for Tactical Missile Defense

The possibility that a missile such as the Nodong could be operational in the near future is already having important ramifications in number of countries, especially Japan and Israel. In particular, it has played a role in the debate over theater missile defense in both countries.[48]

The prospects for effective missile defense against such a missile using endo-atmospheric missile defenses appear poor for several reasons, which we discuss below. High altitude interceptors, such as THAAD, would face other problems, in particular decoys and debris clouds. THAAD is currently in early stages of development; while "operational prototypes" may exist in the late 1990s, current schedules do not call for a fully operational system until 2001.

The intrinsic inaccuracy of the Nodong makes it a perfect candidate for some of the countermeasures that worked successfully (albeit unintentionally) against the Patriot anti-missile system during the Gulf War.[49] The Nodong's inaccuracy results largely from unpredictable motions of its warhead caused by atmospheric forces during reentry. These motions place high demands on an interceptor since it must be able to generate extremely high lateral accelerations in order to change directions quickly enough to reorient toward the new position of the warhead and intercept it. The same principle was used by the United States in developing its "evading MaRV," which was designed in the 1970s to evade Soviet missile defenses.[50] The low accuracy of the Nodong is evidence that it experiences strong atmospheric forces and severe buffeting. These forces could even be increased by intentionally adding a small asymmetry to the warhead (similar to the bent nose of the U.S. MaRV). The accuracy of the Nodong is low enough that the additional inaccuracy caused by such a measure would be unimportant.

Moreover, increasing the speed of the incoming warhead would increase its lateral accelerations and further increase the demands on a defensive system. Thus a second obvious countermeasure would be to increase the ballistic coefficient of the warhead to increase its reentry speed.[51] Such an increase can be achieved simply by changing the shape of the warhead. The resulting increased heating of the warhead would probably require an ablative heat shield to be added (see appendix B). Adding an ablative layer is not technically difficult if one is willing to accept some degradation in accuracy that would result from asymmetric ablation. If the goal is to evade defenses, asymmetric ablation may be a benefit since it would make the reentry forces even more variable with time and thus make the warhead's path even less predictable.

Achieving even moderate intercept rates against such a missile would be extremely demanding and the costs of developing such a system must be weighed against the potential role they could play in reducing casualties and damage. Missiles with conventional and even chemical warheads are unlikely to cause high casualty rates against adequately prepared populations, unless they are used in very large numbers.[52] As seen in the Gulf War, measures such as adequate warning of attack and reinforced concrete construction can play a major role in protecting the population.[53] On the other hand, any leakage rate of the defensive system low enough to be acceptable against nuclear weapons is probably unattainable. Even if the attacker had only a few nuclear warheads it could launch a barrage of conventional and nuclear armed missiles to overwhelm the defense.

Thus missile defenses do not offer a solution in the near term to the problem of the development and potential use of missiles by North Korea or Iran. Other solutions should be explored and must be evaluated in terms of their feasibility, likely effectiveness, and cost. While diplomatic approaches to reducing these problems are extremely difficult and will likely have mixed success, countries must be careful not to let a focus on missile defenses distract them from addressing the underlying issues motivating these states.

APPENDIX A: TECHNICAL DETAILS OF THE NKSCUD MOD-A, B, AND C MISSILES

The Soviet R-17/SS-1c "Scud-B" missile is 11.25 meters long, 0.88 meters in diameter, and has a launch weight of 6.37 tonnes when equipped with a 985 kilogram payload.[54] It is fueled by four tonnes of unsymmetrical dimethylhydrazine (UDMH) with inhibited red fuming nitric acid (IRFNA) as an oxidizer[55] and uses fuel pumps to move the fuel to the engines. The optimum mass ratio of oxidizer to fuel for this combination is roughly three and the volume ratio is 1.5;[56] however, the actual ratios used by the missile appear to be closer to 3.6 and 1.8.[57] The latter values give a propellant volume of 3.1 cubic meters.

Below the warhead section is a compartment containing the guidance system and a second compartment containing several canisters of compressed gas that is used to displace the fuel and oxidizer from their tanks. The Scud is believed to use simple inertial guidance with three gyroscopes and body-mounted accelerometers, and has four graphite diverter vanes in the exhaust to control the flight path during boost phase.

With four tonnes of propellant the fuel fraction (the propellant mass divided by the total mass of the booster without the payload) is 0.74. Assuming a burn time of 70 seconds and a specific impulse of 230 seconds gives a thrust of 129,000 newtons.[58] We calculate that this configuration (with a 985 kilogram payload) will have a maximum range of 290 to 300 kilometers, which is roughly the quoted range of the Scud-B and the NKScud Mod-A. Figure 1 shows the variation of range with payload for this missile assuming a specific impulse of 230 and 240 seconds.

We estimate the masses of various components of the missile as follows. We assume that the walls are made of two to three millimeter thick steel, which has a density of 7,800 kg m^{-3} and thus an area density of about 20 kg m^{-2}. The outer surface area of the booster is roughly 25 m^2, giving a mass of 500 kilograms. The ends of the fuel tanks and guidance compartment plus the fuel feed pipe would add roughly 125 kilograms. The fins consist of two sheets of steel enclosing a lattice of supports plus the vanes for steering and the mechanism for controlling them. Each fin has a surface area of about one square meter and we estimate their mass at 40 kilograms each. We assume roughly 100 kilograms for the guidance system, 50 kilograms for the air canisters, and 200 kilograms for the engine, fuel pump, and related plumbing. Given the reported dry mass of the booster of 1,385 kilograms, this leaves roughly 250 kilograms for structural supports, etc.

We assume here that the NKScud Mod-C is essentially the same configuration as the Iraqi al-Hussein missile. The al-Hussein is said to have been produced from the Soviet Scud-B by lengthening the fuel tanks by 1.3 meters[59] to achieve a 25 percent increase in fuel. Assuming, as above, that the missile body is made of two to three millimeters thick steel and that some supports would be added, this extension would increase the booster mass by roughly 100 kilograms. Since the propellant mass would increase to 5,000 kilograms, the booster mass (without payload) would be 6,500 kilograms, with a fuel fraction of 0.77. Range-payload curves for this model are shown in figure 2 assuming a specific impulse of 230 and 240 seconds.

APPENDIX B: ESTIMATING MISSILE ACCURACY

We estimate the accuracy of the Mod-C and Nodong missiles by scaling the errors reported for the Mod-B to the longer ranges and higher reentry speeds. For this calculation, we consider a Nodong with a 1,300 kilometer range.

The reported values for the circular error probable (CEP) of the Mod-B (and the Soviet Scud-B) ranges from 450 to 1,000 meter at 300 kilometer range. For our calculation we assume a value of 750 meter, which is in the middle of this range. The CEP is related to the dispersion in impact location by:

$$CEP = 0.59\,(D_R + D_{XR}) \qquad \text{(B-1)}$$

where D_R and D_{XR} are the average dispersions in the range and crossrange directions. Assuming $D_R = D_{XR} \equiv D_B$, we find $D_B = 640$ m for the Mod-B.

The total dispersion of a missile results from two principle contributions: (1) guidance and control (G&C) errors, which lead to small errors in the missile velocity and orientation at booster burnout and (2) reentry errors. Since we do not know the relative size of these two contributions for the Mod-B, we consider three cases: one in which the two contributions are equal, one in which dispersions resulting from reentry errors dominate, and one in which dispersions resulting from G&C errors dominate. In the second two cases, we assume that the dominant error leads to dispersions three times as large as the contribution arising from the other error. We also assume that reentry errors and G&C errors are independent of one another so that the total dispersion is given by the square root of the sum of the squares of the component dispersions:

$$D = \sqrt{(D^{(R)})^2 + (D^{(GC)})^2} \qquad \text{(B-2)}$$

where $D^{(R)}$ and $D^{(GC)}$ are the reentry and G&C dispersions, respectively.

These assumptions allow us to calculate $D^{(R)}$ and $D^{(GC)}$ for the Mod-B for each of the three cases. We then scale each of these dispersions separately to values appropriate to the Mod-C or Nodong and combine the resulting values to produce an estimate of the new total dispersion.

Guidance and Control Dispersions

We assume here that the guidance technologies used in the Mod-C and Nodong are essentially the same as in the Mod-B. To scale the guidance and control errors, we calculate the sensitivity of the missile's range to small changes in the vertical and horizontal components of the burnout velocity. These sensitivities, $\partial R/\partial V_v$ and $\partial R/\partial V_h$, can be calculated from the trajectory equations.[60] We then use the values of these sensitivities appropriate to the Mod-B to determine the uncertainty in the components of the Mod-B's burnout velocity, δV_v and δV_h, that leads to the assumed G&C dispersions for the Mod-B:

$$D^{(GC)} = \delta V \sqrt{\left(\frac{dR}{dV_v}\right)^2 + \left(\frac{dR}{dV_h}\right)^2} \qquad \text{(B-3)}$$

where we have assumed $\delta V_v = \delta V_h \equiv \delta V$. Assuming that the guidance system will give uncertainties in the burnout velocity of roughly this same size for the Mod-C and Nodong, we can calculate the G&C dispersions for these missiles using equation (B-3) with values for the sensitivities appropriate to these missiles. Since the burnout speed of the Nodong is much greater than that of the Mod-B, δV for the Nodong may in reality be greater than that of the Mod-B. On the other hand, improvements in the guidance and control system will reduce δV. Nonetheless, the method outlined above will give a rough estimate of the G&C errors for the Mod-C and Nodong.[61] The values for the three cases are given in table B-1.

Reentry Dispersions

Reentry dispersions result from aerodynamic forces acting on the warhead and have a number of causes, including variations in atmospheric wind and density and a number of "lift effects" that produce lateral forces on the reentering missile. For simple missiles such as the Mod-B and Nodong the lift effects will dominate. The dispersions will result from net lateral forces that are not averaged out during reentry.

The lift force experienced by a body travelling at speed V in an atmospheric density ρ is given by:

$$F_{LIFT} = \frac{1}{2} C_L A \rho V^2 \qquad \text{(B-4)}$$

where C_L is the lift coefficient, and A is the cross-sectional area of the warhead transverse to its direction of motion. Thus lift forces will be greatest for missiles travelling at high speeds, especially those with large values of ballistic coefficient (β) since they will experience relatively low drag and will have large speeds low in the atmosphere where ρ is large. Lift forces can have a number of causes, including asymmetries in the reentry vehicle and a misalignment between the direction of motion and the axis of the reentry vehicle (a non-zero angle of attack). In general, the lift force will fluctuate in magnitude and direction during reentry; some of these fluctuations will tend to average out, especially if the warhead is spinning, but the net, non-averaged lift forces will lead to unpredictable lateral motions of the warhead.[62] We estimate the effect of these net forces in two ways, described below.

The first method we use to estimate reentry dispersions assumes that the magnitude and the direction of the lift force are constant throughout reentry.[63] To chose the magnitude of C_L, we calculate the trajectory of the Mod-B in the presence of such a lift force and pick C_L to give the value $D^{(R)}$ assumed for the Mod-B. To estimate the lift effects on a different missile, we then calculate the trajectory of that missile in the presence of a net lift force using the same value of C_L.

The second method assumes that the lift force varies randomly in magnitude and

Table B-1: Estimated CEPs for the Mod-C and Nodong missiles.[a]

Missile	$D^{(GC)}$ *meters*	$D^{(R)}$ *meters*	CEP *meters*
Case 1: G&C errors dominate for the Mod-B ($D^{(GC)} = 3\ D^{(R)}$)			
Mod-B	600	200	750
Mod-C (with body)	820	260	1,000
Mod-C (warhead only)	820	720	1,300
Nodong (low β)	1,430	1,210	2,200
Nodong (high β)	1,430	1,000	2,100
Case 2: G&C errors equal reentry errors for the Mod-B ($D^{(GC)} = D^{(R)}$)			
Mod-B	450	450	750
Mod-C (with body)	620	580	1,000
Mod-C (warhead only)	620	1,590	2,000
Nodong (low β)	1,100	2,840	3,600
Nodong (high β)	1,100	2,350	3,100
Case 3: Reentry errors dominate for the Mod-B ($3\ D^{(GC)} = D^{(R)}$)			
Mod-B	200	600	750
Mod-C (with body)	270	780	1,000
Mod-C (warhead only)	270	2,180	2,600
Nodong (low β)	480	3,900	4,600
Nodong (high β)	480	3,280	3,900

a. These tables list estimates for the guidance and control (G&C) dispersions and reentry dispersions and the CEPs for the NKScud Mod-C and Nodong missiles, calculated as described in the text. The calculations assume a CEP of 750 meters for the NKScud Mod-B missile and the three cases correspond to different assumptions about how the total dispersions of the Mod-B are divided between G&C and reentry dispersions. (The Mod-B is assumed to have β = 192,000 N m^{-2} (4,000 lb ft^{-2})). Dispersions are calculated for four missile configurations: (1) a Mod-C in which the missile remains intact throughout reentry (β = 178,000 N m^{-2} (3,700 lb ft^{-2})), (2) a Mod-C in which the missile body is assumed to separate and only the warhead reenters (β = 55,000 N m^{-2} (1,150 lb ft^{-2})), (3) a 1,300 kilometer-range Nodong missile with β = 36,000 N m^{-2} (750 lb ft^{-2}), and (4) a 1,300 kilometer-range Nodong missile with β = 48,000 N m^{-2} (1,000 lb ft^{-2}). Values of dispersions are rounded to the nearest 10 meters and CEPs are rounded to the nearest 100 meters. If the actual CEP of the Mod-B is larger or smaller than 750 meters, the estimates of the CEPs for the other missiles will increase or decrease accordingly. These figures assume that the bodies remain roughly aerodynamically aligned during reentry; tumbling or pronounced spiraling of the warhead, or the presence of pieces of the missile body attached to the warhead, can lead to larger lift forces and significantly larger dispersions.

direction throughout reentry so that the resulting dispersion is an average of this fluctuating force over the trajectory of the missile. Specifically, we calculated the trajectory in the presence of a lift force acting in the plane of the trajectory, with the magnitude of the force multiplied by a number between –1 and 1 that changed randomly with each step of the numerical integration (every 0.1 seconds). An average dispersion was then calculated by averaging over 2,000 runs. We calculated the trajectory of the Mod-B in the presence of this fluctuating force and chose the magnitude of C_L to give the average dispersion equal to the value of $D^{(R)}$ assumed for the Mod-B. This same value of C_L, again weighted by a random number, was then used to calculate trajectories of the Mod-C and Nodong, with an average dispersion calculated by averaging over 2,000 such runs in each case.

These two methods give results that are within several percent of each other in most cases, although in some cases they differ by 10 to 15 percent. The values for reentry dispersions in table B-1 are the average of the results of the two methods.

Having calculated the reentry and G&C dispersions for the Mod-C and Nodong we can calculate a total dispersion using equation (B-2), and a CEP using equation (B-1) (assuming that the crossrange dispersion will roughly equal the range dispersion we have calculated). These CEPs are listed in table B-1.

For these calculations, we assume that the Mod-B has a β of 192,000 N m^{-2} (4,000 lb ft^{-2}) (which assumes a drag coefficient of 0.2). For the Mod-C, we calculate the CEP for two cases: (1) the missile remains intact and the missile body does not separate from the warhead, which gives β = 178,000 N m^{-2} (3,700 lb ft^{-2}), and (2) the body separates from the warhead, giving β = 55,000 N m^{-2} (1,150 lb ft^{-2}) for the warhead (both values assume a drag coefficient of 0.2). As explained in appendix C, we assume the Nodong warhead will separate from the missile body and calculate the CEP for the two cases β = 36,000 N m^{-2} (750 lb ft^{-2}) and 48,000 N m^{-2} (1,000 lb ft^{-2}).

One way to reduce the reentry errors somewhat would be to increase the ballistic coefficient of the warhead to increase its reentry speed.[64] Significantly increasing the reentry speed, however, would greatly increase the atmospheric heating of the reentry vehicle and would almost certainly require adding an ablative coating to the reentry vehicle in order to allow it to withstand the greater heating. We assume that the Nodong currently does not have such a coating. Adding a simple ablative coating may not be technically demanding. However, such a coating must ablate smoothly and uniformly or the ablation process will give rise to large lateral forces that will tend to offset the gains in accuracy from the increased speed, and developing an advanced ablative coating of this kind is very demanding.[65] Thus even using such measures would not decrease the CEP enough to make the Nodong a militarily significant weapon with a conventional warhead.

Finally, we note that the estimates of CEPs listed in table B-1 assume that the axis of the warhead remains roughly aligned with its velocity during reentry. In that sense these estimates are best-case estimates. If the warhead is not well aligned during reentry so that it undergoes pronounced spiraling, or tumbles, or if it experiences large lift forces from pieces of the missile body that remain attached after the body breaks off, the resulting dispersions can be much larger than those listed in the table.

APPENDIX C: ESTIMATING THE BALLISTIC COEFFICIENT AND LENGTH OF THE NODONG WARHEAD

The heating of a reentering warhead increases with the ballistic coefficient and the reentry speed of the warhead:

$$Q_L \propto \beta^{0.5} V_E^2 \quad Q_T \propto \beta^{0.8} V_E^{2.48} \qquad \text{(C-1)}$$

where Q_L and Q_T are the total heat absorbed during reentry assuming the boundary layer of air flowing past the warhead is laminar and turbulent, respectively; β is the ballistic coefficient of the warhead; and V_E is its reentry speed at high altitudes.[66] Below we use the expression for Q_T since the boundary layer is almost certainly turbulent in the regions of greatest heating (although for the values of interest both equations give similar results).

We use this equation to compare the heat absorbed by the Nodong to that absorbed by the al-Hussein missile, under the assumption that the al-Hussein was designed to withstand the reentry heating in the case in which the missile body remains attached to the warhead during reentry. Using β = 178,000 N m^{-2} (3,700 lb ft^{-2}) and V_E = 1,700 m sec^{-1} for the al-Hussein[67] and β = 36,000 to 48,000 N m^{-2} (750 to 1,000 lb ft^{-2}) and V_E = 3100 m sec^{-1} for the Nodong, we calculate that the heating of the Nodong is 20 to 50 percent greater than that of the al-Hussein. A value of β = 72,000 N m^{-2} (1,500 lb ft^{-2}) for the Nodong gives an absorbed heat of over twice that of the al-Hussein. We therefore take the ballistic coefficient of the Nodong to lie in the lower range of values.

As noted in the text, we assume that the Nodong warhead separates from the missile body before it reaches low altitudes where most of the atmospheric drag and heating occur, so that the mass of the reentering body is 1,000 kilograms. Values of β in the range 36,000 to 48,000 N m^{-2} (750 to 1,000 lb ft^{-2}) for a warhead with this mass and a base diameter of 1.3 meters correspond to values of the drag coefficient[68] of 0.15 to 0.2. The drag coefficient can be related to the shape of the warhead using simple equations;[69] these relations give a warhead length of roughly two meters.

APPENDIX D: ESTIMATING THE BOOSTER MASS FOR THE NODONG

We use our estimates of the mass breakdown of the Mod-B in appendix A to estimate the booster mass for the Nodong as follows. Since the weight of the propellant and the atmospheric forces on the booster will be greater than on the Mod-B, we assume that the body is made from a heavier gauge steel. We therefore assume three to four millimeters of steel sheet metal with a mass per area of 27 kg m^{-2}. Using a booster length of 13.5 meters and including the mass of the outside walls of the booster, the ends of the propellant tanks and guidance compartment, and the fuel feed pipe, we calculate a mass of roughly 1,800 kilograms. Since both the length and diameter of the missile are larger than the Mod-B missile by about 50 percent, we assume the fins are also scaled up by this factor, which gives a mass of roughly 100 kilograms for each. We assume 800 kilograms for the four engines plus associated pumps and plumbing, 100 kilograms for the guidance package, and 200 kilograms for the air canisters. Scaling up the mass of the structural supports, etc., from the Mod-B gives 500 to 700 kilograms, which leads to a total dry booster mass of roughly 3,800 to 4,000 kilograms. This mass estimate leads to a fuel fraction of 0.80 to 0.81.

To estimate how much the missile's mass could be reduced by making the body out of aluminum, which has a density of 2,700 kg m^{-3}, rather than steel, we assume the skin, fins, and some of the structural supports are made of aluminum. We assume that the skin is four to five millimeters thick aluminum sheet, having a density of roughly 12 kg m^{-2}, and that the number of structural supports may need to be increased. Using these assumptions the mass reduction might be 1,000 to 1,200 kilograms. For our calculations we assume a booster mass of 2,800 to 3,000 kilograms, which gives a fuel fraction of 0.84 to 0.85.

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NOTES AND REFERENCES

1. The computer calculations are performed by integrating the equations of motion of the missile on a round, non-rotating earth in the presence of an atmosphere (for the level of accuracy considered here, the effects of the earth's rotation on missile range can be ignored). The drag coefficient of the missile as a function of speed during boost phase is approximated by using measured values for the V-2 rocket. For additional details see appendix B of Lisbeth Gronlund and David Wright, "Depressed Trajectory SLBMs," *Science & Global Security* **3** (1–2) 1992, p. 101.

2. John W. Lewis and Hua Di, "China's Ballistic Missile Programs: Technologies, Strategies, Goals," *International Security* **17**, fall 1992, p. 32; Joseph Bermudez, Jr., "New Developments in the North Korean Missile Programme," *Jane's Soviet Intelligence Review*, August 1990, p. 343; Joseph Bermudez, Jr., "Ballistic Ambitions Ascendant," *Jane's Defence Weekly*, 10 April 1993, p. 20.

3. Several sources report that North Korea acquired the Scud-Bs from the Soviet Union. Steven Zaloga states they were acquired in the mid-1970s ("Ballistic Missiles in the Third World," *International Defense Review*, November 1988, p. 1423) (see also Y.A. Koptev, "How to Save the Russian Rocket Industry," *Rossiyskiye Vesti* [Moscow], 17 August 1993, p. 7 in FBIS-SOV-93-158, 18 August 1993, p. 9). Bermudez reports they were acquired from Egypt in the early 1980s ("Ballistic Ambitions").

4. Throughout this paper, we follow the naming convention for North Korean missiles from Bermudez, "Ballistic Ambitions," with the replacement of "NKScud" for "Scud" to distinguish them from variants of the Soviet Scud missiles.

5. Bermudez, "Ballistic Ambitions."

6. In addition, Bermudez ("New Developments") states that one of the design param-

[redacted]

eters for the DF-61 program in the mid-1970s was a heavy-gauge skin to protect the missile from damage during transport and handling, since the missile was to be mobile. This report suggests that the North Koreans would use steel for their other mobile missiles as well.

7. Bermudez, "New Developments."

8. See for example, George P. Sutton, *Rocket Propulsion Elements* (fifth edition) (New York: John Wiley and Sons, 1986) p. 40.

9. Duncan Lennox, "Inside the R-17 'Scud B' Missile," *Jane's Intelligence Review* (July 1991), p. 302; Warren Lenhart and Todd Masse, *Persian Gulf War: Iraqi Scud Ballistic Missile Systems*, Congressional Research Service Report 91-173 F, 14 February 1991, p. 6; "Race To Find Iraq's 'Scuds'" *Jane's Defence Weekly*, 26 January 1991, p. 91; Bermudez, "Ballistic Ambitions"; Thomas Cochran, et al., *Nuclear Weapons Databook Volume IV: Soviet Nuclear Weapons* (New York: Ballinger/Harper and Row, 1989), p. 221.

10. W. Seth Carus and Joseph S. Bermudez, Jr., "Iraq's al-Husayn Missile Programme," *Jane's Soviet Intelligence Review*, May 1990, p. 204; Duncan Lennox, "Iraq's 'Scud' Programme," *Jane's Defence Weekly*, 2 March 1991, p. 301.

11. Sam Jameson, "North Korea Test Missile Able To Reach Japan," *Washington Times*, 12 June 1993, p. A13; Bermudez, "Ballistic Ambitions."

12. Reported range/payload combinations are 500 kilometers/700 kilograms (Bermudez, "Ballistic Ambitions"); 550 kilometers/600 kilograms (*Milavnews*, March 1991, p. 23); 640 kilometers/680 kilograms (Steven Emerson, "The Postwar Scud Boom," *Wall Street Journal*, 10 July 1991).

13. Our estimate of the CEP for the separated warhead agrees well with estimates given for the Iraqi al-Hussein missile: the Congressional Research Service gives a value of one to 1.5 miles (1,600 to 2,415 meters) (Lenhart and Masse, *Persian Gulf War*, p. 6) and *Jane's Defence Weekly* reports 1,600 to 3,200 meters ("Race To Find Iraq's 'Scuds' "). This estimate also appears to be consistent with data presented in the unclassified pages of the U.S. Army report *Patriot Performance Assessment in Desert Storm Roadmap*, 15 July 1992, p. 10, which suggests that the predicted impact point of an incoming al-Hussein warhead varied by two to three kilometers during its reentry.

14. The durability of the engine may limit how much the amount of fuel may be increased beyond that carried by the Mod-C. Increasing the fuel increases the length of time the engine is burning and therefore subjects the engine to greater heating, which the cooling system on relatively simple engines like the Scud may not be able to withstand without modifications. The configuration of the al-Hussein may suggest that the burn time, and thus the fuel, cannot be increased by more than about 25 percent. Iraq also reportedly built a missile called the al-Abbas with 40 percent more fuel than the Scud-B and a range of 900 kilometers with a 350 kilogram payload (Lennox, "Iraq's 'Scud' Programme"). However, it was not used in the 1991 Gulf War and there are indications that it may have had operational difficulties.

15. According to figure 2, reducing the structural weight of the Mod-C by roughly 450 kilograms, which would result from replacing the steel body with aluminum, would give a range of less than 600 kilometers with a one tonne payload.

16. Nan Yong-Chin, "DPRK's Advanced Weapons Analyzed," *Nuclear Developments*, 31 May 1991, p. 7 (original: *Hanguk Ilbo* [Seoul], 8 February 1991, p. 8); Bermudez, "Ballistic Ambitions."

17. "DPRK Reportedly to Build New Scud Missile," *Nuclear Developments*, 24 June 1991, p. 7 (original: *Yonhap* [Seoul], 3 June 1991); Emerson, "The Post-war Scud Boom"; Gerald Seib, "Missile Race in Mideast, Along With Nuclear Issue, Raise Concern," *Wall Street Journal*, 8 June 1992, p. A6. Libya will reportedly pay $7 million each for the missile (Bill Gertz, "Libya May Buy North Korean Missiles," *Washington Times*, 4 June 1991, p. 4).

18. Reuters wire service, 18 April 1993.

19. *Yonhap* (Seoul), 14 July 1993 in FBIS-EAS-93-134, 15 July 1993, p. 18; Jon Wolfsthal, "U.S. Prods Israel to Halt Talks with North Korea on Missile Sales," *Arms Control Today*, September 1993, p. 24.

20. David Fulghum, "Mideast Nations Seek to Counter Air Power," *Aviation Week and Space Technology*, 7 June 1993, p. 77; David Sanger, "Missile is Tested by North Korea," *New York Times*, 13 June 1993, p. 7.

21. Jack Anderson and Michael Binstein, "North Korea: Loose Nuclear Cannon," *IAEA* (International Atomic Energy Agency) *Daily Press Review*, 31 March 1992, p. 12.

22. Bill Gertz, "Iran-Bound Mystery Freighter Carried Parts for Missiles," *Washington Times*, 16 July 1992, p. A3.

23. C.W. Lim, "North Korean Tells of Nuclear Accident," *Washington Times*, 25 August 1993, p. A1. In 1990, construction of two bases for intermediate-range missiles was reported near the Demilitarized Zone (Bill Gertz, "Libya May Buy North Korean Missiles," *Washington Times*, 4 June 1991, p. 4). Guam is 4,000 kilometers from North Korea.

24. Bermudez ("Ballistic Ambitions") notes reports of a test failure in 1991 and a successful test (although not to full range) somewhat later. Other reports of a successful test prior to May 1993 include Gertz, "Libya May Buy North Korean Missiles"; *Tong-a Ilbo* (Seoul), 25 August 1991 in FBIS-EA, 26 August 1991; "Defense Ministry Says May Nodong-1 Test Successful" *Yonhap* (Seoul), 24 June 1993 in FBIS-EAS-93-120, 24 June 1993, p. 19; "North Korea Seen Successful in Test of Nodong-1 Missile," *Aerospace Daily*, 29 June 1993, p. 538. For reports that no previous tests had occurred see Joanna Pitman, "Worried Tokyo May Buy Patriot Defense," *Times* (London), 12 June 1993; Sanger, "Missile Is Tested." Reports that a Nodong exploded on the launch pad in May 1990 (Bill Gertz, "General Spotlights North Korean Threat," *Washington Times*, 15 September 1993, p. A6) apparently refer to U.S. satellite evidence (Bill Gertz, "North Korean Missile Apparently Blows Up," *Washington Times*, 5 July 1990). These reports are believed to refer to a new missile that may have been a Nodong prototype.

25. Reuters wire service, 11 June 1993; Andrew Katell, "North Korea Suspends Move to Quit Nuclear Arms Pact," *Boston Globe*, 12 June 1993, p. 4; Jameson, "North Korea Test Missile"; Seoul KBS-I Radio, 1 June 1993 in JPRS-TND-93-018, 14 June 1993, p. 3; *Yonhap* (Seoul), 15 June 1993 in FBIS-EAS-93-113, 15 June 1993, p. 28; "North Korea Seen Successful in Test of Nodong-1 Missile," *Aerospace Daily*, 29 June 1993, p. 538; *Aviation Week and Space Technology*, 5 July 1993, p. 17; *Yonhap* (Seoul), 14 July 1993 in FBIS-EAS-93-134, 15 July 1993, p. 18; Gertz, "General Spotlights Threat."

26. "Japan Says North Korea to Finish Missile Soon," Reuters wire service, 11 November 1993.

27. "Defense Ministry Says May Nodong-1 Test Successful" *Yonhap* (Seoul), 24 June 1993 in FBIS-EAS-93-120, 24 June 1993, p. 19; Sanger, "Missile Is Tested."

28. "Official Confirms North's Mobile Test Launch," *Choson Ilbo* (Seoul) 3 December 1993, p. 1 in FBIS-EAS-93-231.

29. Gertz, "General Spotlights Threat."

30. *Kyodo* (Tokyo), 12 June 1993 in FBIS-EAS-93-112, 14 June 1993, p. 5; UPI wire service, 14 June 1993; *Yonhap* (Seoul), 15 June 1993 in FBIS-EAS-93-113, 15 June 1993, p. 28.

31. Range estimates appear to be based on the size and fuel capacity as derived from images of the missile. References include: A. Platkovskiy, "North Korea Nuclear Program Viewed," *Nuclear Developments*, 12 September 1991, p. 24 (original: *Komsomolskaya Pravda* [Moscow], 24 August 1991); *Kyodo* (Tokyo), 20 September 1991 in *Proliferation Issues*, 29 October 1991, p. 7; Paul Lewis and David Silverberg, "West Worries China Will Sell Missiles," *Defense News*, 16 March 1992, p. 1; Gerald Seib, "Missile Race in Middle East Countries Despite U.S. Efforts to Stall Buildup," *Wall Street Journal*, 8 June 1992, p. A6; Katell, "Nor˙ Korea Suspends Move"; *Aviation Week and Space Technology*, 5 July 1993, p. 17; Martin Sieff, "Israel to Woo North Korea to Keep Missiles From Iran," *Washington Times*, 15 June 1993, p. A8.

32. "DPRK Reportedly Boosts Range of Nodong, Sells to Iran," *Yonhap* (Seoul), 8 June 1993, in JPRS-TND-93-018, 14 June 1993, p. 27; Yi Chang-sun, "Japan's Sense of Terror for Nodong-1," *Sinmun* (Seoul), 13 June 1993, p. 7 in FBIS-EAS-93-112, 14 June 1993, p. 31; "North Korea Seen Successful," *Aerospace Daily.*

33. Since the combustion chamber and nozzle of the Scud-B engine are roughly 0.4 meter in diameter there is room to cluster four of them in the 1.2 to 1.3 meter body diameter of the Nodong (estimates of engine size were derived from photographs provided by Israeli journalist Reuven Pedatzur of an Israeli Defense Force display of al-Hussein wreckage in Tel Aviv).

34. The fuel and oxidizer in these missiles were each stored in a single large tank; the Soviet design used a single large turbo pump that fed fuel to all four engines, but the Chinese version used a separate small pump for each engine (Hua Di, private communication).

35. Hua Di, private communication.

36. Nan Yong-Chin, "DPRK's Advanced Weapons Analyzed" gives values of 15.1 meters in length and 1.3 meters in diameter. The article states a range of 600 kilometers, which does not appear to be consistent with the dimensions. The author may have assumed the missile was a Mod-C rather than a Nodong, the author may have intended a range of 600 miles rather than 600 kilometers. *Yonhap* (Seoul), 14 July 1993, in FBIS-EAS-93-134, 15 July 1993, p. 18 gives values of 15.8 meters in length and 1.2 meters in diameter.

37. We assume here that the same fuel and oxidizer are used as in the Mod-B and Mod-C and are used in the same proportions.

38. Ed Blanche, Associated Press wire service, 22 October 1993; Reuters wire service, 28 October 1993.

39. It is possible North Korea might test the missile with a very small payload to suggest a greater range capability than it actually had.

40. Lewis and Di, "China's Ballistic Missile Program."

41. Lewis and Di, "China's Ballistic Missile Program." China switched to stabilized

platform guidance in the late 1970s with the development of the DF-5/CSS4.

42. *Yonhap* (Seoul), 14 July 1993, in FBIS-EAS-93-134, 15 July 1993, p. 18.

43. *Chicago Sun Times* (20 April 1993, p. 46) reported that Iran stopped shipping oil to North Korea in 1992 after the Scuds it had received (presumably Mod-Bs or Cs) were found to be defective.

44. Bermudez, "Ballistic Ambitions"; Tony Emerson, "Nuclear Nightmare," *Newsweek*, 29 November 1993, p. 20.

45. Lewis and Di, "China's Ballistic Missile Programs."

46. This calculation assumes the first stage is made of steel to provide the structural strength to support the second stage, and has a fuel fraction of 0.8. The second stage fuel fraction is 0.77. If the fuel fraction of the second stage could be increased to 0.80 to 0.81 (for example, by using aluminum alloy for the body) the range would increase to 1,950 to 2,050 kilometers.

47. Some Japanese military officers are reportedly skeptical that North Korea's current technical and industrial capabilities are sufficient to produce such a missile ("North Korean Missile Eyed With Skepticism," *Aviation Week and Space Technology*, 18 October 1993, p. 101).

48. Following the reported test of the Nodong missile in May of this year, Israel held three meetings with North Korea to discuss economic aid in return for commitments not to sell the missile to countries in the Middle East. Israel suspended the meetings under pressure from the U.S. (David Hoffman, "Israel Agrees to Suspend Contacts with North Korea," *Washington Post*, 17 August 1993; Jon Wolfsthal, "U.S. Prods Israel to Halt Talks with North Korea on Missile Sales," *Arms Control Today*, September 1993, p. 24). In addition, Japan has begun to consider developing or buying tactical missile defenses (David Sanger, "New Missile Defense In Japan Under Discussion with U.S.," *New York Times*, 18 September 1993, p. 1; Barbara Opall and Naoaki Usui, "Japan, U.S. Pursue Ballistic Missile Defense," *Defense News*, 4 October 1993, p. 3).

49. Philip Finnegan, "Gulf War Exposes Effectiveness of Countermeasures," *Defense News* 12 August 1991, p. 1; Theodore Postol, "Lessons of the Gulf War Experience with Patriot," *International Security* **16** (3), winter 1991/92, p. 119; George Lewis and Theodore Postol, "Video Evidence on the Effectiveness of Patriot During the 1991 Gulf War," *Science & Global Security* **4** (1), 1993, p. 1.

50. A bent nosetip on the MaRV produced the same type of lateral accelerations that the Nodong warhead would experience (see for example Matthew Bunn, "The Next Nuclear Offensive," *Technology Review*, January 1988, p. 28.

51. A Nodong warhead with a ballistic coefficient of 72,000 N m^{-2} (1,500 lb ft^{-2}) would have a speed 30 to 60 percent faster than the al-Hussein missile at altitudes of 10 to 30 kilometers, resulting in lateral forces 70 to 250 percent greater.

52. Steve Fetter, "Ballistic Missiles and Weapons of Mass Destruction," *International Security* **16**, summer 1991, p.5.

53. Steve Fetter, George Lewis, and Lisbeth Gronlund, "Why Were Scud Casualties So Low?" *Nature* **361**, 28 January 1993, p. 293.

54. Duncan Lennox, "Inside the R-17 'Scud B' Missile," *Jane's Intelligence Review*, July 1991, p. 302. This article contains a number of detailed photographs of the missile, which were used to derive some of the dimensions of the missile used below.

55. The export version of the Scud-B, the R-17E, may use UDMH fuel with N_2O_4 rather than IRFNA as the oxidizer. The density of N_2O_4 is 1.44 g cm^{-3} and the optimum mass ratio (N_2O_4/UDMH) is about 2.6. Four tonnes of propellant would therefore have a volume of 3.4 m^3. Using N_2O_4 could increase the specific impulse by several per cent compared to using IRFNA. Assuming N_2O_4 is used instead of IRFNA would make only small changes in our model and would not affect our conclusions. In particular, the estimated length of the Nodong would increase by 0.5 meters, and the booster mass would increase by about 60 kilograms.

56. IRFNA III-A is 83.4 percent HNO_3 and 14 percent NO_2, and IRFNA IV HDA is 54.3 percent HNO_3 and 44 percent NO_2. The optimal mass ratios (IRFNA/UDMH) for these two oxidizers are 3.13 and 2.85, respectively. The density of UDMH is 0.789 g cm^{-3} and for IRFNA (III-A) is 1.57 g cm^{-3} (Dieter K. Huzel and David H. Huang, *Modern Engineering for Design of Liquid-Propellant Rocket Engines* [Washington DC: AIAA, 1992] p. 20).

57. This ratio agrees with Carus and Bermudez's claim that the al-Hussein tanks were increased by 0.45 and 0.85 meters over the Scud-B (Carus and Bermudez, "Iraq's al-Husayn Missile Programme"). The ratio may be increased above optimum to keep the combustion chamber from overheating.

58. These quantities are related by the expression $T = g_0 I_{sp} M_p / t_b$, where T is thrust in newtons, g_0 is 9.8 m sec^{-2}, I_{sp} is specific impulse in seconds, M_p is the propellant mass in kilograms, and t_b is the booster burn time in seconds.

59. Carus and Bermudez, "Iraq's al-Husayn Missile Programme."

60. See equations (D-3) and (D-4) in Gronlund and Wright, "Depressed Trajectory SLBMs" *Science & Global Security* **3** (1–2). It is equivalent, but simpler, to do this calculation using the two components of burnout velocity as we do here rather than using the magnitude and direction of the burnout velocity, which is more standard.

61. We ignore the other contributions to guidance and control errors, such as errors in the burnout height, which will give small contributions to the total.

62. Net lift forces can occur even if the reentry vehicle is spinning (see, for example, D.H. Platus, "Dispersion of Spinning Missile due to Lift Non-Averaging," *AIAA Journal* **15**, July 1977, p. 909).

63. Using a constant perturbation whose magnitude is chosen to give the observed dispersion is a standard technique used to estimate the effects of other atmospheric effects on reentry dispersions (see, for example, Doreen H. Daniels, *Ballistic Correlation Altitudes for Reentry Winds and Nonstandard Air Densities* (Dahlgren, Virginia: U.S. Naval Weapons Laboratory, April 1965) NTIS, AD-614-710, p. 9).

64. This is illustrated by the difference in CEPs of the two cases calculated for the Mod-C missile. While increasing the reentry speed increases the lift forces acting on the warhead, which are proportional to V^2, it also reduces the time these forces act on the warhead, which leads to smaller dispersions. The calculations for the two Mod-C cases assume that the magnitude of the lift coefficient is the same in both cases; as discussed below, however, increasing the ballistic coefficient may give rise to additional lift forces.

65. For a discussion of some of these issues, see D.W. Hall and D.T. Nowlan, "Aerodynamics of Ballistic Reentry Vehicles with Asymmetric Nosetips," *Journal of Spacecraft and Rockets* **15**, January/February 1978, p. 55; W.S. Kobayashi and J.L. Saperstein, "Low-Temperature Ablator Tests for Shape-Stable Nosetip Application on Maneuvering

Reentry Vehicles," in *Thermophysics of Atmospheric Entry*, editor T.E. Horton (New York: American Institute of Aeronautics and Astronautics, 1982) p. 148.

66. J.R. Sellars, "Reentry and Recovery," in H.S. Seifert and K. Brown, *Ballistic Missile and Space Systems* (New York: John Wiley & Sons, 1961) p. 452.

67. This value of β is large because the weight of the reentering warhead and attached missile body is large. It assumes a value of the drag coefficient of 0.2

68. The drag and ballistic coefficients are related by $\beta = g_0 m/(C_d A)$, where C_d is the drag coefficient, g_0 is the acceleration of gravity, m is the mass of the warhead, and A is the cross-sectional area of the warhead perpendicular to the direction of motion.

69. Frank J. Regan, *Re-entry Vehicle Dynamics* (New York: American Institute of Aeronautics and Astronautics, 1984) p. 230.