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Current and Near-Future Missile Defence Systems

Capabilities and Effectiveness

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Executive Summary

This report attempts to provide an illustration of the likely operational effectiveness of current and near-future missile defence systems. Accounting for various factors including the allocated roles of systems, likely operational environments, risk tolerances, and persisting operational barriers the study attempts to paint a broad picture as to how one might expect National, Theatre, and Cruise missile defences to perform when placed in their likely operating circumstances. The research has aimed to draw attention to the highly circumstantial and situation-specific nature of missile defence operations, to demonstrate the difficulties in evaluating "effectiveness" and "success", and to address the extent to which testing can be indicative of real-world performance. The analysis conducted by this study hopes to better inform discussions on the likely impact that the advent of hypersonic weapons will have on the effectiveness of missile defence operations and strategic stability; an issue that is briefly addressed in the final portion of the paper. The content of this report's pages produce the following key findings:

- The outcome of missile defence operations at all levels is dependent on a greater number of variables than can be accounted for in testing. Attempts to deduce the likely effectiveness of a system should look beyond the results of controlled tests and emphasise the influence of circumstantial factors that arise from a system's role and operating environment.

- Circumstantial factors will have a significant role in determining the meanings of "success" and "effectiveness"; definitions are likely to change between operations and are acutely sensitive to the assigned role of a system and the threats they are facing.

- In the majority of likely operating circumstances, national missile defences are unlikely to be permitted the necessary operational environment to be effective. Even in the most generous of scenarios, NMD systems will likely underperform and be unsuccessful in their assigned roles due to requiring a highly generous operating environment.

- In certain operational circumstances, theatre missile defences demonstrate a reasonable capacity to perform effectively. Though, their operational effectiveness appears highly sensitive to a number of situation-specific factors, particularly salvo size.

- The outcome of ACMD operations appears to be hugely dependent on early detection and reaction time. Systems conducting ACMD operations in optimal environments possess reasonable chances of success. However, environmental limitations and other factors can have a dramatic effect on outcomes.

- Based purely on the likely effectiveness demonstrated by missile defence systems, it is unclear as to why the advent of hypersonic weapons should be accompanied by an overall reduction in strategic stability. It is likely that the way states interpret and respond to hypersonic weapons will have a greater impact than the capabilities of the weapons themselves.

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Introduction

Research Overview and Focus

This research paper presents an investigation into the capabilities and effectiveness of current and near-future missile defence systems in intercepting non-hypersonic ballistic projectiles and cruise missiles. This paper is part of wider ongoing investigations by British Pugwash which are attempting to better understand the impact that the introduction of advanced and emerging systems - in particular hypersonic cruise missiles (HCM) and glide vehicles (HGVs) - may have on strategic stability. The logic behind the commissioning of this research is such that, if missile defences are effective against the existing generation of delivery systems, so as to provide a meaningful strategic utility to the possessor state, the introduction of hypersonic delivery systems and their perceived advantages over existing missile defences could be inherently destabilising. The alternative hypothesis of course being that if missile defences currently provide little or no strategic utility, then the introduction of hypersonics as a means of delivering ordinance should have little material impact on military affairs in this area.

This study utilises data within the public domain, drawing on a range of academic, civil, and industry sources in an attempt to deliver an estimation of the capacity for current active missile defence systems to fulfil their intended roles within their expected operating environments. In light of this, a critical focus of the paper will be to highlight the complexities involved in verifying and calculating what it means to be an 'effective' missile defence system. As will be seen, the paper evaluates this issue and considers a series of factors and variables that are then carried forward in its subsequent analysis (see Appendix A). Further, the research will stress the importance of circumstance and the inherently circumstantial nature of missile defence, illustrating that the outcome of missile defence operations is tied to a greater range of variables - outside of testing performance - than is perhaps commonly realised.

In light of the above, this paper will not, therefore, attempt to provide a definitive 'yes' or 'no' answer as to whether missile defence, in and of itself, is 'effective' - nor do the research findings indicate that this approach is sensible. Instead, the paper's analysis will divide ballistic missile defences into two respective subject areas: looking at what is commonly referred to as *Regional* or *Theatre* missile defences (TMD), against Short to Intermediate-range ballistic missiles. And then what is often termed 'strategic' or National missile defences, against ICBM threats (NMD).[1] The final portion of the paper will also be devoted to separately evaluating the capabilities and effectiveness of Anti-Cruise Missile Defences (ACMD), and later briefly introducing and evaluating the likely impact of hypersonic delivery systems. The analysis will review the body of evidence concerning the capabilities and effectiveness of a range of systems that fall within each cohort; paying special attention to the possible roles assigned to MD systems, their likely operating environments, obstacles facing effective deployment, understanding their testing and performance records, discussing relevant variables, and observing the evidence provided by in-depth sources. The paper will attempt to draw nuanced and evidence-led estimations over effectiveness, with specific attention being paid to circumstances and limiting factors that would likely play a role in any real-world use. It is important to recognise that the operational ecosystems within which these systems may find themselves, will not, at all times, match those described in the paper. Indeed, the report's depiction of operational circumstances is purely indicative. Theorised with the intention of indicating the *potential* and significant issues that missile defence systems may face when we call upon them to fulfil certain roles in the field. Where possible, the report will avoid making any potentially provocative claims on individual systems. The time that would be required for analysis on each and every system is beyond the scope of this paper but nonetheless remains a crucial area with which the literature should continue to engage.

Acknowledging Limitations

- When conducting source collection for this paper, it was evident that few countries are as transparent as the US with regards to their missile defence capabilities. For example, no other country publishes as comprehensive a record of both their successes *and* failures in testing as the US does. More often than not, we only ever hear of interception tests from other nations when they have been a success, forcing any estimation of those systems to be based even further on conjecture. This causes any impartial discussion on effectiveness to be heavily dependent on information from US systems. Consequently, this paper, as many others have, will be forced to make extensive use of US MD systems as a point of reference for evaluating effectiveness and capability.

- With nearly all current missile defence systems possessing little-to-no combat experience, this paper utilises the body of academic literature in order to deduce

[1] This format approach roughly follows that used by other papers: see George N. Lewis, "Technical Controversy: Can Missile Defence Work?" in *Regional Missile Defence from a Global Perspective,* ed. Peter Drombrowski & Catherine McArdle Kelleher (Stanford: Stanford University Press, 2015) pp.63-83.

meaningful, indicative, conclusions as to their capabilities and operational effectiveness. While the literature possesses much developed and in-depth work - especially on rigorous modelling and simulations that have proven essential in developing any conclusions - this paper will only be able to assess the *likely* effectiveness of missile defences relative to their performance track-record, predicted operational circumstances, and other important variables. Without any substantial empirical data on how most of these systems perform in the field, where possible, this paper will avoid making definitive and otherwise potentially provocative claims on individual systems.

- Given that this paper draws extensively from publicly accessible data, there are limits on the degree to which it can discuss and evaluate claims on certain subject areas. This is particularly the case concerning countermeasures, some specific testing details, and radar and discrimination capabilities. When addressing these areas, the paper will make efforts to deliver, but the constraints over the availability of information will inherently restrict the claims that can be made. By consequence, this paper's analysis on these issues relies heavily on data that has been at the heart of public discourse, and may, in certain instances, prove contestable.

Technical Aspects of Intercepting Ballistic and Cruise-Missiles

The first recorded interception of a ballistic missile carrying a warhead was conducted by the Soviets in March, 1961. The interception, employing a V-1000 missile, successfully defeated an incoming IRBM in its terminal-phase of flight at the Saryshagan test site in the remote Kazakhstani desert.[2] The subsequent tests that followed confirmed the technical feasibility of identifying, tracking, and intercepting ballistic missiles, and can be regarded as the bedrock on which later developments in kinetic ABM technology proceeded. Alongside developments of this kind, the U.S. and the Soviets developed, and in the case of the latter deployed, nuclear-tipped interceptors for the purpose of utilizing the destructive capacity of nuclear warheads for national missile defence (NMD).

Intercepting projectiles on sub-orbital (and in theory predictable) trajectories is deceivingly more complex in practice than at concept level; a commonly used metaphor comparing the task to "hitting a bullet with a bullet".[3] Principally, the anatomy of an interception for Theatre Missile Defences (TMD) is broadly different than that which would

[2] Mike Gruntman, "Intercept 1961: From Air Defence SA-1 to Missile Defence System." *IEEE*, 104:4 (April 2016): 883–86. https://doi.org/10.1109/JPROC.2016.2537023.
[3] Arms Control Association, "Missile Defense Systems at a Glance" https://www.armscontrol.org/factsheets/missiledefenseataglance

be seen with National - 'Homeland' - Missile Defences (NMD) or Anti-Cruise Missile Defences (ACMD).[4]

Speaking generally, NMD systems operate as long-rage, counter-ICBM systems; attempting exo-atmospheric interception in the midcourse-phase of an ICBMs flight with use of a Exo-atmospheric Kill Vehicle (EKV). This vehicle, once deployed, manoeuvres into the path of an oncoming warhead in the vacuum of space.[5] NMD platforms are designed to provide protection against projectiles over huge geographical areas, potentially spanning thousands of kilometres;[6] the notable example of this kind of system being the US' *Ground-Based Midcourse Defence* (GBMD) which became operational in 2004.[7] An outlier to this description is the SM-3 interceptor from the Aegis BMD system which, while technically falling under the category of a TMD system, does possess a midcourse, exo-atmospheric, Hit-to-kill (H2K) capability with an EKV. Indeed, the SM-3 recently intercepted an ICBM target in 2020 demonstrating a counter-ICBM capability, but it is generally deployed with the central role of defeating short to intermediate range threats with potential for integration into the wider NMD framework.[8]

Comparatively, TMD systems are designed to intercept ballistic missiles - and in some cases cruise missiles - over a much more limited "regional" geographical area; typically spanning from tens to hundreds of kilometres. Theatre defences can engage ballistic missiles with short to intermediate-ranges, either in their terminal phases in atmosphere - like the SM-2/6 [9] or S-400, or in their midcourse phases outside the atmosphere - like the SM-3.[10] The *Terminal High-Altitude Air Defence* (THAAD) platform also exists as a special case here, possessing the capacity to intercept warheads very early in their terminal phase outside the atmosphere with a total flight ceiling of ≈ 150km[11], or within the atmosphere as they descend closer toward their targets.[12] TMD interceptors employ either a H2K strategy

[4] Lewis, *Technical Controversy,* p.63-83 ; also see David Denoon, *Ballistic Missile Defence in the Post-Cold War Era*, (Oxford: Westview Press, 1995)
[5] See Laura Grego, George N. Lewis, & David Wright, *"Shielded from Oversight: The Disastrous US Approach to Strategic Missile Defence"*, (Union of Concerned Scientists:2016) https://www.ucsusa.org/sites/default/files/attach/2016/07/Shielded-from-Oversight-full-report.pdf (Accessed 8.8.21)
[6] George Lewis, *Technical Controversy,* p.63
[7] See "Ground-Based Midcourse Defence: Anatomy of a Missile Intercept", Boeing, ,https://www.boeing.com/defense/missile-defense/ground-based-midcourse/index.page
[8]"Sea-Based Weapons Systems", Missile Defence Agency:US. Department of Defence. MDA - Aegis Ballistic Missile Defense
[9] Congressional Research Service, *Navy Aegis Ballistic Missile Defense (BMD) Program: Background and Issues for Congress*, (Updated August 2021). Available at: https://fas.org/sgp/crs/weapons/RL33745.pdf p.5
[10] *Ibid,* p.4
[11] Bruce Klingner, "The Importance of THAAD Missile Defence" *The Journal of East Asian Affairs,* 29:2, (Winter 2015) pp.21-43 Available at: http://www.riia.re.kr/upload/bbs/BBSA05/202010/F6962.pdf#page=27 p.28
[12] Matt Korda & Hans M. Kristensen "US ballistic missile defenses, 2019" *Bulletin of the Atomic Scientists*, 75:6,(2019) pp.295-306. https://www.tandfonline.com/doi/pdf/10.1080/00963402.2019.1680055?needAccess=true

of directly impacting the incoming projectile, or, use Blast-Fragmentation (BlastFrag) charges;[13] closing distance with the target and projecting what is effectively shrapnel through a directed explosion at an optimally-close distance.[14] Some notably short-range interception systems like Israel's *Iron Dome,* or the US' *Patriot,* which intercepts short-medium range ballistic missiles within an area 35-40kms in radius and 25km in height,[15] are often placed under the category of "point defence systems", "Counter Rocket, Artillery, and Mortar" (C-RAM) systems, or simply "Short-Range Air-Defence Systems" (SHORADS). Terminology aside, they operate in effectively the same ways as their longer-range counterparts, and so, are kept within the same analytical parameters.

Describing and defining ACMD systems requires more nuance, principally because many ACMD-capable systems operate not solely for this purpose but also alongside anti-aircraft or BMD purposes. Further, there is also much contention over how one ought to define a 'cruise missile'. With there being so many variations in the designs and propulsion methods used for these weapons, using loose terminology is often problematic.[16] Regardless, cruise-missiles are frequently compared to manned or unmanned aircraft with regards to their flight profiles. They often utilise some form of jet-propulsion (or similar) as their predominant means of maintaining flight, traveling along flattened, more horizontal, trajectories at both extremely low altitudes or higher in the atmosphere.[17] Unlike ballistic projectiles, cruise missiles can adopt fluid and often adaptable flight paths, being able to utilise their control surfaces to place themselves in optimal attack positions. Cruise missiles can be delivered from a range of platforms such as aircraft where they are released at optimal speeds, or from submarines, ships, and land-vehicles, where the cruise missile will initially be accelerated by a rocket booster that eventually breaks off and the missile's air-breathing engine takes over.[18] The cruising speed for these weapons is not set, with some, like the *Tomahawk* being subsonic, and others like the P-700 *Granit* or 3M22 *Zircon* being supersonic or hypersonic. Perhaps the most important definition to make with

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[13]Some systems do posses both capabilities - The Aster-30 by *MBDA* possesses both a H2K "Dart" and a directional blast warhead: See https://www.army-technology.com/projects/aster-30/

[14] Committee for Naval Forces' Capability for Theatre Missile Defense, *Naval Forces' Capability For Theatre Missile Defense*, (National Academy Press: Washington DC. 2001) Available online at: https://ebookcentral.proquest.com/lib/bham/reader.action?docID=3375931

[15]Michael Elleman and Michael J. Zagurek, Jr. *THAAD: What it Can and Can't Do, 38North*. (2016) Available at: https://38north.org/wp-content/uploads/2016/03/THAAD-031016-Michael-Elleman-and-Michael-Zagurek.pdf

[16] For a detailed analysis of the issue, see Fabian Hoffman, *"Cruise Missile Proliferation: Trends, Strategic Implications, and Counterproliferation"* (European Leadership Network; March 2021) https://www.europeanleadershipnetwork.org/report/cruise-missile-proliferation-trends-strategic-implications-and-counterproliferation/

[17] See Committee for Naval Forces' Capability for Theatre Missile Defense, *Naval Forces' Capability For Theatre Missile Defense*

[18]*Ibid,* p.26

a cruise missile is with regards to its role. A Land-Attack Cruise Missile (LACM) will be a missile designed and fielded with the purposes of delivering ordinance to terrestrial targets. Because of this role, there are numerous technical differences made to these weapons, an important one being the use of Terrain Contour Mapping (TERCOM), GPS, or other technologies for in-flight and terminal navigation.[19] Alternatively, Anti-Ship Cruise Missiles (ASCM) are weapons that are deployed specifically against surface vessels and will more frequently use active or passive radar seeking methods as ships are typically more easily distinguished from their surroundings than land-based targets.[20]

Generally speaking, cruise missiles are more delicate than ballistic missiles and may require less kinetic disruption to ensure their mission fails. For example, they may only need to suffer minor damage to their control surfaces, sensors, or basic structure. Unless a cruise missile is feeding control and targeting data back to a human operator, it may operate autonomously which can leave it even more vulnerable to jamming efforts, deceptions, and decoys.[21] Although, "...the newest missiles that are entering into the operational inventories of potential adversaries appear to have extremely robust ECCM capabilities against current ECM techniques".[22] Cruise missiles are also often designed with stealthy exteriors, reducing their Radar Cross-section (RCS) and can sometimes be capable of conducting a range of terminal-phase manoeuvres. If a cruise missile is traveling at higher altitudes, it can be seen by search-radar more easily, unimpeded by terrain or the horizon, allowing an MD system greater time in diagnosing and engaging the threat; frequently, both LACMs and ASCMs will keep as low to the ground as possible. Collectively, the speed of a cruise missile, its flight path, visibility, and its final stage attack manoeuvres can greatly reduce the likelihood of a successful interception.

Exploring Effectiveness

The following section will form the central body of analysis, delivering an insight into the likely operational effectiveness of missile defences at National and Theatre level, and also against cruise missiles, within realistic operating environments. Remaining consistent with the objectives and parameters of the paper, the primary purpose of this section will not be to rigorously evaluate individual systems or attempt to address every conceivable

[19] See Thomas G. Mahnken, "The Cruise Missile Challenge", *Center for Strategic and Budgetary Assessments*, (March, 2005) Available at: https://csbaonline.org/uploads/documents/2005.03.10-Cruise-Missile.pdf
[20] *Ibid*, p.9-11
[21] *Ibid*, p.27
[22] *Ibid,* p.28. : The issues of electronic warfare techniques warrant much attention, but will only be seldom addressed in the course of this paper.

scenario in which these systems may see themselves - this, while important, simply exceeds the reasonable scope of the research.

Instead, the analysis will apply an understanding of the roles and objectives of missile defences in each given area, draw distinctions and address caveats where necessary, and use this to paint a reasonable picture as to what operational demands are likely to be placed on these systems. The paper will then deduce the realistic barriers presented in each domain, addressing the central question of "under what circumstances can the role and objectives of MD in this area be fulfilled?" The answer to said question will provide the space for conclusions on likely operational effectiveness.

Much meaningful work has been done in the way of drawing up thorough and realistic situations in an attempt to present a very detailed example of how certain systems may perform under specific circumstances; this section will not attempt that methodology.[23] Alternatively, this report chooses to focus on how constraints for a missile defence operation can change depending on the situation at hand. As previously outlined, how well a missile defence system will perform is inherently tied to the ecosystem it finds itself in and the problems that arise from that; this needs to be addressed and factored into any respectable estimations on operational effectiveness and is the primary issue under analysis. With this in mind, the section will devote the greatest attention to the problems that are likely to always be present for an MD system in that cohort, irrespective of a change in operational environment. More situation-specific dilemmas will of course be considered, but they are less useful for providing a more general overview of effectiveness.

National Missile Defence

The effectiveness of the current generation of NMD systems is arguably the most contentious area within missile defence discourse. The number of systems that operate solely for the purposes of long-range NMD, and exhibit the relevant characteristics, is effectively limited to the GBMD network operated by the US. As such, GBMD will remain the primary system under analysis. As touched upon earlier, the Aegis' SM-3 interceptor has demonstrated an ability to intercept ICBM threats in their midcourse and will therefore have some utility in the broader NMD architecture in the not-so-distant future. While steps to integrate other interceptor systems into the NMD architecture are being undertaken, as

[23] For an illustration of this approach, see Jaganath Sankaran, "Missile wars in the Asia Pacific: the threat of Chinese regional missiles and U.S.-allied missile defense response", *Asian Security,* 17:1 (June, 2021) pp.25-45
https://doi.org/10.1080/14799855.2020.1769069.

it stands, GBMD lacks the capability to communicate and coordinate with other deployed MD systems and will likely stand alone in its role until wide-scale interoperability is achieved. [24]

Role

National missile defence systems, like GBMD, are deployed for the purposes of protecting large swathes of territory from ICBMS which will, in pretty much all feasible circumstances, be armed with nuclear warheads of varying yields. The 2019 Missile Defence Review asserts that homeland missile defences in particular are deployed specifically to "provide significant protection against potential North Korean or Iranian ballistic missile strikes against the U.S. homeland... U.S. missile defense capabilities will be sized to provide continuing effective protection of the U.S. homeland against rogue states' offensive missile threats."[25]

GBMD appears to therefore possess a very specific role. One based largely on managing the threat posed by a highly limited attack - involving a single-digit to low-tens of warheads - fired intentionally or accidentally, against the homeland. Indeed, official statements and documents concerning the purpose and objectives of the US' NMD system explicitly state that it has little-to-no role in any large-scale nuclear exchange; the 2019 MDR proceeds to insist that nuclear deterrence, not NMD, will continue to provide a defence against the strategic threat posed by countries like China or Russia.[26] With this in mind, this report considers from the offset that GBMD would have effectively no utility in defending or even blunting the effects of a large-scale nuclear attack involving potentially hundreds of warheads against the United States. There is little indication that the NMD system is designed with this role in mind and is therefore not considered in the following analysis. This is notwithstanding the immense numerical and technical barriers an NMD system would encounter if it were asked to fulfil that role - in short, GBMD would simply be inconsequential in such an event.

Despite the assertions by the DoD, many have contested the stated role of the GBMD system. One associated concern is that the program itself has been designed as a safety net for enabling the US to conduct conventional or nuclear disarming-strikes against

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[24] Government Accountability Office, "*Missile Defence: Fiscal Year 2020 Delivery and Testing Progressed, but Annual Goals Unmet*", US GAO Report to Congress on Missile Defence. (GAO; April, 2020). Available at:http://web.a.ebscohost.com.ezproxyd.bham.ac.uk/ehost/pdfviewer/pdfviewer?vid=1&sid=4563d2d7-f1b8-44c2-a44a-4ec8506b1fcf%40sdc-v-sessmgr02 GAO-21-314

[25] Department of Defence, *2019 Missile Defence Review* (Office of the Secretary of Defence:2019). https://www.defense.gov/Portals/1/Interactive/2018/11-2019-Missile-Defense-Review/The%202019%20MDR_Executive%20Summary.pdf p.5

[26] *Ibid,* p.VII

developing or even established nuclear adversaries, and would be used to absorb any attempt at retaliation, should the initial attack not succeed.[27] Indeed, the 2019 MDR expresses that NMD is also designed to be a last line of defence… "If deterrence fails and conflict with a rogue state or within a region ensues, U.S. attack operations supporting missile defense will degrade, disrupt, or destroy an adversary's missiles before they are launched. Such operations are part of a comprehensive missile defense strategy and increase the effectiveness of active missile defenses by reducing the number of adversary missiles to be intercepted."[28]

Whatever the genuine rationale, [29] it is worth addressing that assigning a homeland defence role, like that illustrated above, shapes two important factors. 1) The risk-tolerance employed by the possessor state, and 2) The nature and character of success and effectiveness.

1. By implication, the task of defending cities against the destructive capabilities of nuclear weapons comes with the tolerance for mission failure being effectively zero. In short, this is because the failure to intercept even a single warhead - irrespective of how great a number the system has achieved in that event - comes with the total annihilation of the city being defended and the loss of thousands, potentially millions, of lives. The cost associated with mission failure thus implies that if an NMD system is to be developed and deployed, it will need it to perform with a one hundred percent degree of effectiveness, in whatever circumstances it may find itself. Interestingly, the explicit relationship between the incoming threat and what NMDs are trying to defend places missile defences in this domain under a greater degree of pressure to perform reliably. This is particularly true when compared with certain TMD systems that are expected to engage low-tech, inaccurate, and far less devastating conventional ballistic projectiles.[30]

2. Because of such a low tolerance for failure, what constitutes a "successful" mission, or "effective" system, is quite different for NMD than for a TMD or ACMD. A successful NMD mission will be intrinsically tied to that system's ability to *completely* deny the delivery of nuclear ordinance to the defended areas. Even if an NMD system intercepts 19/20 warheads fired at it - incredibly *effective* as far as missile defence goes - it would not produce what any reasonable person could

[27] From discussions had in an interview with Matt Korda, (August 19th 2021)
[28] U.S. Department of Defence, *2019 Missile Defence Review,* p.XIV
[29] Exploring this issue further would be beyond the scope of this paper; the research is forced to take GBMD's role at face-value, and avoid weighing-in on either side of the argument.
[30] Though, TMD systems can find themselves faced with nuclear threats too; this would of course then make risk tolerance more comparable to NMD operations.

consider a militarily successful outcome. Comparatively, a TMD system defending an airbase may only intercept 12/20 SRBMs, but because the projectiles proved inaccurate, conventionally armed, and did not end up inflicting significant damage to anything of value in the airbase, the mission has not necessarily been a failure in the same way that the high-effectiveness, heavy-loss NMD mission has.[31] Interestingly, there is less space for circumstance to make a difference to what success looks like at NMD level than elsewhere; in essence, success in NMD operations is heavily dependent on the system fulfilling its role perfectly.

There are therefore reasonable grounds for the proceeding analysis to conclude that measurements on NMD effectiveness ought to base "effectiveness" on an ability to intercept all incoming warheads, and "success" on an outcome where zero warheads are delivered on target.

Likely Operational Environment and Barriers to Operational Effectiveness

Due to the manner in which the current NMD system is deployed, its allocated role, and its specific operational character, GBMD operations are unlikely to see much variation in their actual operational environment. Unlike TMD and ACMD operations, where there is a huge variation between the possible situations in which those systems may need to be used, the likely operational environment for GBMD is comparatively rigid. Factoring in GBMD's highly specific role and its total lack of real-world experience, it appears that when envisaging a likely operational environment, the most important and persisting issues to address are...

1) **GBMD's performance under testing conditions and an ambiguous capability.**

2) **Warhead numbers and the issues associated with numerics and interception probability.**

3) **The availability and capabilities of supporting infrastructure.**

4) **Countermeasures.**

[31] It would be worth stating that while not a failure, it is contestable as to whether the TMD example here could be considered a success as well. Again, circumstances would dictate how this would end up being diagnosed.

Discussing GBMD's Testing

The NMD system's performance in testing, the way it has been tested, and the internal issues associated with those two areas has been a subject of tremendous controversy. While much appropriate space has been given to evaluating the nuanced issues of the GBMD project,[32] this analysis will avoid extensive elaboration and will proceed with a brief overview of GBMD's testing and performance. This will be followed by touching upon the major shortfalls and issues with GBMD's testing and what is not revealed about the system's operational capabilities.

GBMD has been subject to multiple flight and interception tests, with some involving the CE-I and CE-II EKVs, intermittently since the mid-late 1990's.[33] In the most recent test in March 2019, GBMD successfully intercepted a "threat representative" ICBM target in what was described as a "salvo-mode" engagement involving two interceptors - the first test of its kind.[34] Since 2002, specific details on testing, particularly concerning the types of projectiles or decoys the EKVs engage, have been classified, leaving little room to explore any meaningful discrimination capabilities that the GMD system has exhibited in testing.[35] Nevertheless, the MDA routinely insists that GBMD is tested against realistic targets, situations, and ever-sophisticated countermeasures. The two most recent tests, FTG-15 in 2017 and FTG-11 in 2019, both involved what could be considered more realistic scenarios. In the former, the EKV is claimed to have been pitched against decoys,[36] and in the latter, the second EKV conducted a debris field analysis after the successful interception and proceeded to engage the next target it considered 'most lethal'.[37]

While the actual number of successful interceptions achieved by GBMD is contested, according to the MDA's interception record, of the 19 operational interception tests that have taken place since 1999, GBMD has intercepted 12, achieving a face value interception

[32] See the many works by T. Postel and G. Lewis in particular.
[33] See: Missile Defence Agency, *"Missile Defence Agency Fact Sheet: Ballistic Missile Defence Intercept Flight Record"* (US. Department of Defence; June 2021)
https://www.mda.mil/global/documents/pdf/testrecord.pdf
[34] Shervin Teheran, "*US Conducts 'Salvo Engagement' GMD Test"*, Arms Control Today (Arms Control Association, May; 2019)
https://www.armscontrol.org/act/2019-05/news/us-conducts-'salvo-engagement'-gmd-test (Accessed 19.9.21)
[35] K. Gildea, "*MDA Classifies Missile Defense Flight Test Target Countermeasure Data"*, (Defense Daily; May 15, 2002.) (Url Unknown. article Cited in George N. Lewis, *Ballistic Missile Defence Effectiveness*
[36] See Sydney Freedberg Jr. "*Missile Defence Test 'Realistic' Syring Insists"* May 31, 2017 (Breaking Defence; 2017) https://breakingdefense.com/2017/05/missile-defense-test-realistic-syring-insists/
[37] Shervin Teheran, *"US Conducts Salvo Engagement".*

capability of around 63%.[38] However, the more commonly accepted figure is actually closer to 11/19, which takes into account the fact that in one of the CE-I tests, a "glancing blow" on the target was considered a kill.[39] Whilst the last three tests have been successful, all three tests preceding them from 2010-2013 were failures, with EKVs suffering from a range of issues including guidance system failures, separation failures, and sensor performance issues.[40] To make capabilities even more ambiguous, a 2019 paper by the Bulletin of Atomic Scientists illustrated that "Nearly half (20 out of 44) of the currently deployed GMD interceptors are fitted with the Capability Enhancement (CE)-I kill vehicle, which has only succeeded in two of its four interceptor tests… Similarly, over a third of the interceptors (16 out of 44) are fitted with the CE-II kill vehicle, which also has a 50 percent testing record".[41]

On top of what appears to be only a modest interception capability, academic literature has extensively dissected the testing history of the GBMD program, revealing a plethora of evidence to suggest that the testing record, as it stands, is not indicative of any likely performance in a realistic operating environment. Further, the gaps and shortfalls that arise from the nature of GBMD's testing creates an incomplete and ambiguous picture as to its genuine capabilities. These claims rest effectively on two main grounds. The first is that the manner in which tests are conducted is not representative of a realistic operating environment and therefore suggests nothing about how the system will perform outside of testing. And second, that none of the information actually released on decoys and countermeasure testing suggest that the EKV's possess any genuine discrimination capability, an essential condition to any effective NMD system.

The primary issue with GBMD's testing appears to be that it creates an artificial picture as to how responsively and reliably it would perform in a crisis-scenario. During testing, all relevant teams are prepared and aware of the exercise and on which day it will occur, they know - within a specifically allocated time window - when the incoming target is going to be launched;[42] every single piece of supporting infrastructure is on and working beforehand - this includes everything from detection and tracking radars to space-based sensors and communications equipment; in many previous tests the targets were launched from optimal locations in Alaska "…that geography meant the distances were shorter and the

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[38] The actual number of recorded tests is listed as 20 but in FTG-03 (May, 2007) the target vehicle malfunctioned shortly after take-off and an interceptor was not launched. See MDA's Fight Test Record. ; also See Missile Defence Agency, *Missile Defence Intercept Flight Record*
[39] See Lewis, *Ballistic Missile Defence Effectiveness,* p.10
[40] Missile Defence Agency, *Missile Defence Intercept Flight Record*
[41] Matt Korda & Hans M. Kristensen, *US ballistic missile defenses, 2019,* p.299
[42] See Freedberg, *"Missile Defence Tests 'Realistic'"*

crossing angle was large, thus the closing speeds were relatively low."[43] In some instances, tests are even delayed due to concerns over the weather.[44] Exacerbating these issues further is the fact that there are some capabilities that ought to be tested but likely never will be due to inherent regulation and cost constraints. Statements by the MDA and other sources suggest that in a genuine salvo or "Shoot-Shoot" strategy, GBMD would potentially allocate four interceptors for every warhead.[45] As it stands, the capacity for the system to carry out this task has never been attempted in testing and likely never will. The May 2017 test used one interceptor and came with a bill weighing in at $244 million dollars.[46] A test attempting to use four interceptors simultaneously would likely cost far in-excess of that figure; all with the looming uncertainty as to whether it would even succeed. Further, in 2014, when responding to questions over scripted testing, the previous MDA Director Vice-Admiral Syring remarked "...we were constrained by range, we are constrained by safety; we are constrained by environmental regulations."[47] indicating further that GBMD's effectiveness in realistic circumstances, and therefore any potential lessons learned, may be impossible to attain within the permitted boundaries of testing. Fundamentally, there is no guarantee that GBMD's likely operating environment would permit the situational luxuries that we see in testing. Even within these generous conditions, as noted previously, the system only appears to be intercepting just over 50% of its test targets. While the system will undoubtedly improve over time, so long as it's testing remains "operationally unrealistic" its genuine effectiveness will remain questionable.[48]

Competently distinguishing threats from any likewise objects surrounding them is one of the essential pillars of any functional NMD system. In short, if a system cannot differentiate between objects, it will lack the ability to prioritise threats over non-threats and be more efficient with its limited interceptor stockpile. The only alternative is to have an overwhelming surplus of interceptors in order to essentially shoot down every object being tracked[49] - this would of course come with its own host of problems, chiefly cost. When looking at potential discrimination capabilities, GBMD's operational prospects appear to worsen further. At the heart of this issue is the fact that the operational EKVs do not appear to have illustrated a capacity to *independently* discriminate between objects without the unrealistic degrees of external assistance provided in tests.

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[43] Grego *et al*, *"Shielded from Oversight"* p.30.
[44] *Ibid*
[45] Lewis, *Technical Controversy*, p.69
[46] See Freedberg, *"Missile Defence Tests 'Realistic'"*
[47] Washington Headquarters Service "*Transcript of Verbal Remarks of V.ADM J.D.Syring During His Presentation at the BMDS Symposium"*, (Aug. 13th, 2014). Available at: https://www.esd.whs.mil/Portals/54/Documents/FOID/Reading%20Room/MDA/15-F-0060_Transcript_of_Verbal_Remarks_of_VADM_Syring.pdf?ver=2017-05-16-145850-590
[48] Grego *et al*, "Shielded from Oversight", p.30
[49] *Ibid*, p.32

GBMD's discrimination capabilities draw from two main data sets: that provided from ground-based supporting radars, and that from the EKV's own infrared sensors.[50] Despite limited public insight into the more recent tests, the known issues concerning these respective data sets are still various. In a 1996 test designed to illustrate an IR discrimination capability, a kill vehicle was claimed to have successfully "discriminated" between targets with differing IR signatures. In reality, it engaged the one which appeared to match a scripted understanding of what level of brightness was equal to a warhead.[51] Similarly, and in spite of assistance, in 1997 another kill vehicle mistook a decoy as a warhead and the test failed.[52] In tests of this nature, the EKV's are given tell-tale information as to what to look for when approaching the threat, indicating that "...the tests... are not demonstrating any real discrimination capability. Rather, they are only demonstrating the ability of the kill vehicle to distinguish between objects with different infrared brightnesses and to home in on the one with the relative brightness that matches the information preprogrammed into the kill vehicle".[53] The reality of GBMD's likely operating environment is simply that it would be impossible to know beforehand what the exact IR signature of your adversary's warheads would be, particularly if they are utilising countermeasures that make warheads and non-threat objects appear similar. Unlike in testing, the defender would have no pointers to program into the EKV to aid its decision making. Equally, even supporting radar assets appear to discriminate with limited success in generous conditions. As recently as 2010, a Sea-Based X-band radar appeared to suffer from confusion when a stray piece of solid rocket fuel broke away from the target's booster, contributing to total interception failure.[54] In 1999 a Minuteman 3 ICBM containing replica warheads and chaff was launched towards the Kwajalein atoll in a radar discrimination exercise. The Radar appeared to be able to distinguish between objects, but the test involved no attempt to disguise the replica warheads as anything else.[55] The important question of course being, how likely is it that an aggressor, with full knowledge that the US employs an NMD system, would attempt to deliver warheads and make no effort to disguise them from discrimination radars?

Just how well GBMD would be able to both discriminate and intercept targets outside of the generous, controlled, environments seen in testing is uncertain. There is no guarantee that

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[50] Lewis, "*Ballistic Missile Defence Effectiveness*", p.8

[51] Andrew M. Sessler et al, *Countermeasures: A technical evaluation of the operational effectiveness of the planned US National Missile Defense System*, (Union of Concerned Scientists; 2000) https://drum.lib.umd.edu/bitstream/handle/1903/4333/2000-UCS-CM.pdf?sequence=1&isAllowed=y , p.104

[52] *Ibid*, p.105.

[53] Lewis, "*Ballistic Missile Defence Effectiveness*", p.11

[54] Grego *et al*, "*Shielded from Oversight*", p.31-32.

[55] Sessler *et al*, "*Countermeasures*", p.105

GBMD's actual operating environment would involve, amongst other things, optimal weather conditions, high levels of around-the-clock readiness,[56] faultless supporting infrastructure, or any pre-programmed assistance for object discrimination. As will now be seen, there are further variables involved in operational effectiveness that compound this ambiguity issue, extending beyond that which can be accounted for in testing.

Warhead Numbers and Interception Probability

The number of projectiles a system encounters is deeply significant in the likely outcome of an operation. True across all domains is the fact that an attacker could, in theory, just saturate a defender by simultaneously launching more projectiles at the target than the defender has interceptors. As established, the current NMD system would likely provide little utility in a nuclear attack of this nature. Consequently, GBMD's effectiveness should be predicted relative to its ability to manage a threat posed by a high single-digit number of warheads to perhaps a few tens of warheads.[57]

The number of interceptors for GBMD currently stands at 44.[58] As a part of a continual effort to expand the system, this is expected to have increased to 64 by 2023.[59] Due to this relatively low number of interceptors, the number of warheads the NMD system encounters will have a huge impact on its likely success. Placing aside detection and tracking issues, interception likelihood effectively comes down to two main factors; the "kill probability" of the individual interceptor and the number of interceptors fired.[60] One strategy used to off-set any shortfalls in an interceptor's kill probability is to assign more interceptors to each target. This however comes with a number of shortfalls. If NMD operators were indeed to allocate 4 interceptors to every potential warhead, this limits GBMD to being able to address just 11 threats. If they allocated 3, that number increases to around 14. Further, using multiple interceptors will increase the statistical likelihood of interception but presents the issue of "overkill".[61] If a defender launches 4 interceptors in sequence at a target, but the second interceptor succeeds, the defender has effectively wasted 2 interceptors. This issue could be addressed by adopting a "Shoot-look-shoot" (SLS) approach to conserve interceptors, but this strategy places great faith in the

[56] Though, if there is an on-going crisis, teams are likely to be operating at a greater level of readiness than they would be for an out-of-the-blue attack; circumstance will play a role here.
[57] See *"Countermeasures"* for another example of this metric in use.
[58] Missile Defence Agency, "Ground-Based Midcourse Defence", *US. Department of Defence.* https://www.mda.mil/system/gmd.html
[59] Boeing, *"Ground-Based Midcourse Defence, Anatomy of a Missile Intercept"*
[60] Debasis Dutta "Probabilistic Analysis of Anti-Ship Missile Defence Effectiveness" *Defence Science Journal* 64:2 (March; 2014) pp.123-129 https://core.ac.uk/download/pdf/333720715.pdf (Accessed 4.8.21) p.124
[61] *Ibid*

kill-probability of each individual interceptor and also depends on the time available to the defender; each interception attempt would need to be followed by an assessment period, and then potentially another launch, all-the-while the warhead is nearing its target.

Though it cannot be said with any certainty as to what each individual interceptor's kill probability is - even when using multiple interceptors - it appears that NMD systems will face significant strain when encountering anything more than a few warheads. Estimates by George Lewis revealed that, even if we were to assume a generous kill- probability of 80% for each interceptor, three interceptors would be required to attain a near-definite kill likelihood of 99.2%.[62] With these numbers in place, GBMD's ability to intercept warheads with near-absolute certainty would cap-out at effectively 14 warheads. Anything more would come with a compounding decline in interception likelihood as interceptors would need to be spread more thinly. It is important to remember that the above calculations are simply indicative. Factoring in what is suggested by testing performance, a GBI's kill probability is almost certainly less than 80%. Meaning, in a likely operational environment, the number of interceptors required to achieve a guaranteed kill per-warhead is likely to be higher. By implication, the total interception potential of the current GBMD stockpile would operationally cap-out at a lower number than we see above. Equally, these estimations are made without due consideration as to the negative impact that countermeasures or disrupted supporting infrastructure would have on kill-probability. With ICBMs also being capable of carrying multiple warheads, the possibility that GBMD would encounter threats numbering greater than its operating capacity is not far-fetched. Considering these issues, one could therefore suggest that NMD systems like GBMD, when faced with even low tens of warheads, would experience significant difficulty in being able to reliably destroy the majority of incoming threats. Even then, if faced with a single-digit number of warheads, the issue remains as to whether GBMD would ever experience circumstances generous enough to permit the kill probabilities needed to fulfil its role.

Supporting Infrastructure

The operational effectiveness of missile defence systems, at all levels, rests heavily on the reliability and availability of essential supporting infrastructure. As illustrated (right), NMD in particular relies on an extensive and potentially delicate network of

Image Credit: CSIS Missile Defence Project. https://missilethreat.csis.org/system/gmd/ CSIS MISSILE DEFENSE PROJECT

[62] Lewis, "*Technical Controversy*" p.63

supporting systems and assets in order to carry-out a successful interception. As was briefly observed when discussing testing, a persisting issue for NMD is that there is no guarantee that the operational benefits provided by supporting infrastructure would not be restricted, or even denied, in real-world use.

Given the importance of these supporting assets to the NMD architecture - illustrated through how even minor mistakes by a single X-Band radar can cause total interception failure[63] - attention ought to be paid to the possibility that attackers could directly disrupt these assets to aid warhead penetration.[64] Of the many ways in which this could be undertaken,[65] one apt example could be through the use of cyber warfare techniques against radar or communications assets.[66] Currently, GBMD utilises SATCOM or fibre-optic cabling to communicate with its guidance infrastructure,[67] posing severe limitations to operational effectiveness should the former operate poorly or be completely restricted. Fibre-optic cabling can only connect GBMD to certain assets, yet, there is very little publicly known about how GBMD would perform, if at all, with even a partial-loss of its communications infrastructure.

Crucially, a 2018 GAO report revealed that many of the supporting systems essential to NMD are deployed with very little being known about their ability to withstand cyber disruption efforts during operational deployment.[68] It was even noted that some pieces of equipment were still running Windows XP as their operating systems and were expected to carry-on doing so beyond the end of their life cycles.[69] Despite vulnerabilities being expected to be low, the report further admits that if known or unknown deficiencies were to be exploited… "mission capabilities like BMD planning, radar control, track reporting, and situational awareness may be significantly degraded".[70] Even with the expected

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[63] Grego *et al*, "*Shielded from Oversight",* p.31-32.
[64] Much of the same logic is illustrated in James Acton "Escalation Through Entanglement: How the Vulnerability of Command-and-Control Systems Raises the Risks of an Inadvertent Nuclear War" *International Security*, 43:1 (Summer; 2018) p.56-124
https://direct.mit.edu/isec/article/43/1/56/12199/Escalation-through-Entanglement-How-the
[65] In conjunction, an attacker could in theory use radar-jamming, ASAT techniques, or even direct attacks on ground assets but this depends on the technical sophistication of the adversary; regardless, it is worth exploring the issue.
[66] Lauren Borja, "Missing From the 2019 Missile Defence Review: Cybersecurity" Bulletin of the Atomic Scientists, (February 22nd, 2019)
https://thebulletin.org/2019/02/missing-from-the-2019-missile-defense-review-cybersecurity/
[67] Missile Defence Agency, *"Ground-Based Midcourse Defence"*,
[68] Government Accountability Office, "The Warfighter and Decision Makers Would Benefit from Better Communication about the System's Capabilities and Limitations" US GAO Report to Congress on Missile Defence. (GAO, May; 2018), GAO-18-324 Available at:
https://www.gao.gov/assets/gao-18-324.pdf
[69] *Ibid,* p.65
[70] *Ibid*

introduction of new supporting assets,[71] the picture doesn not appear to be improving. According to a recent GAO report,[72] the MDA has failed to meet its annual operational cybersecurity assessments every year since 2017.[73] In 2020, of the 13 *Cooperative Vulnerability and Penetration Assessments* (designed to evaluate the operational resilience of supporting systems to cyber attacks) and the 4 *Adversarial Assessments*, (designed to indicate the impact of cyber attacks on operational capabilities) the MDA cancelled every single one of them. This has meant that in spite of testing starting in 2017, "some MDS elements have not received any cyber operational testing to date, while others have only received partial testing of cyber defensive postures.".[74]

While defences to these kinds of attacks will have certainly been considered in the development processes for these assets, without comprehensive testing, the extent to which essential infrastructure can withstand cyber disruption efforts - notwithstanding other potential types of attacks - appears largely unknown. It remains unclear as to why a potential attacker would hedge their bets on solely their warheads penetrating defences without making attempts to disrupt other essential systems. Thus, while there is no guarantee that cyber efforts would succeed, as this would depend on the technical capabilities of the aggressor at the time, it is worthwhile noting that, so far as is publicly known, the current and in-coming generation of NMD systems will have had few lessons learned - begging further questions as to how reliably NMD systems would perform with even a minor attack against supporting assets.

The Question of Countermeasures

The barriers presented by midcourse countermeasures are widely considered the most significant factor affecting the outcome of NMD operations; some even go as far as to regard countermeasures as the "Achilles Heel" of any current or future system.[75] From a policy-perspective, any NMD system *must* have the ability to manage the problems presented by both rudimentary and sophisticated countermeasures, as there is no guarantee that a system like GBMD would never come across them in the field. With regards to GBMD's likely operating environment specifically, there are a multitude of reasons to believe that the system would certainly have to deal with countermeasures. Firstly, any

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[71] See CSIS Missile Defence Project, "Long-Range Discrimination Radar (LRDR)", *CSIS.* (July, 2021) https://missilethreat.csis.org/defsys/lrdr/
[72] Government Accountability Office, *"Delivery and Testing Progressed"*
[73] *Ibid*, n.p
[74] *Ibid,* p.20
[75] Joseph Cirincione, "Assessing the Assessment: The 1999 National Intelligence Estimate of the Ballistic Missile Threat", *The Nonproliferation Review,* 7:1, Spring, 2000, 125-137 https://www.nonproliferation.org/wp-content/uploads/npr/circ71.pdf p.129

country with the capacity to develop an ICBM capability would also have the ability to develop or acquire countermeasures.[76] This is principally because 1) The level of technical sophistication required to develop rudimentary but effective countermeasures is far lower than that which is required to defend against them.[77] Especially if utilising readily-available technology, making countermeasures is a highly-cost effective option for even technologically-underdeveloped actors.[78] 2) Even if a state lacks the expertise or materials to indigenously develop more sophisticated countermeasures, there is no reason to believe that they could not acquire them in relatively short amounts of time from foreign sources.[79] Secondly, even in the rarest instances of an accidental launch of a single ICBM - arguably the easiest scenario an NMD system may be faced with - there is simply no reason to believe that the ICBM would not have any countermeasures pre-installed.[80] It would be therefore safe to proceed with the mentality that even if an NMD system like GBMD were to encounter an operational environment mirroring exactly that of its design, against a limited lunch from Iran or North Korea, there is little reason to believe that it would not / should not require the capacity to overcome countermeasures.

As is the case across missile defence in general, the technical barriers presented by midcourse countermeasures are accompanied by what one may describe as an inherent Offender's Bias; by and large, the odds favour the attacking party when it comes to overcoming defences.[81] This bias is essentially underpinned by the fact that an NMD system must be designed to overcome *every* conceivable countermeasure.[82] This includes ones that the operator nation has developed, ones that any other state has developed, and with greater difficulty, ones the defender does not even know to exist. This dilemma is compounded further by the fact that, in theory, a potential aggressor need only develop countermeasures with the specific NMD system in-mind. In effect, a state could "build-around" a system like GBMD simply by paying attention to its known or estimated limitations or shortfalls, and proceed to develop countermeasures that exploit them.[83] Interestingly, this was largely the attitude held by US officials in the late Cold War. In remarks made by Laurance Woodruff regarding the issue presented by the Soviet's A-135 ABM system around Moscow, he noted … "For much less expense we believe we can still penetrate these defenses with a small number of Minuteman missiles equipped with highly effective chaff and decoys. And if the Soviets should deploy more advanced or proliferated

[76] *Ibid*, p.129
[77] Sessler *et al*, *Countermeasures*, p.xxii
[78] Cirincione, *Assessing the Assessment*, p.129
[79] *Ibid*, p.129
[80] Sessler *et al*, *Countermeasures*, p.xxii
[81] Dean Wilkenen, "Nuclear Zero and Ballistic Missile Defence" *Survival*, 52:6, pp.107-126 (Taylor and Francis:2010) https://doi.org/10.1080/00396338.2010.540785
[82] Lewis, *Technical Controversy*, p.74
[83] *Ibid*, p.74

defenses, we have new penetration aids as counters under development".[84] Similarly, British scientists who were tasked with designing countermeasures for the Blue Streak missile in the late 1950's developed a package so elaborate - containing multiple jammers and decoys that would deploy in a cloud 30km wide - that according to one of the leading scientists "As regards invulnerability, it is so advanced that neither the U.S. nor ourselves can conceive of a counter to it."[85] By implication, in any case of real-world use NMD systems will be deployed with comparatively lower situational-confidence than that which may be had by the attacker. A reality of NMD in this essence is that the operator simply will not know what type of countermeasures they are going to encounter during an operation. In certain scenarios, the operator will also only know if they have succeeded in overcoming them at such a time where it will be too late to make a difference anyway.

Other key issues to consider are the realities of NMD's relatively uninspiring performance in testing and, again, the limitations as to how indicative testing could ever be. Across the board, GBMD is tested at a rate fewer than once a year. It is extremely implausible, without an immediate and costly upsurge in testing frequency, that the system in its current form has been, or ever will be, pitched against a broad enough range of countermeasures for its operational effectiveness to be genuinely guaranteed.[86] Further, hitherto now, there is little to indicate, at least in the public domain, that GBMD has been at all tested against, for example, credible and challenging decoys,[87] tumbling warheads,[88] *Mylar Balloons* which seek to render warheads in the threat cloud indistinguishable,[89] or *Cooled Shrouds* - which seek to reduce the IR signature of a warhead to such a degree that by the time it can be analysed by an EKV, it is too close to conduct an interception manoeuvre.[90] The number of potential countermeasures that an NMD system could encounter is, in theory, ever-expanding; their character and design, ambiguous. With countermeasures appearing to be almost certain within an NMD's operating environment, an enormous amount of testing would be required for that aforementioned kill-probability and confidence level to be increased; at least to a point where genuine operational effectiveness could be indicated off-field.

[84] Laurance Woodruff, remarks to the House Armed Services Committee, (1987) *Cited in* Democratic Caucus of the U.S. House of Representatives, *Strategic Defence, Strategic Choices: Staff Report of the Strategic Defence Initiative*, (May; 1988) Available at: http://www.bits.de/NRANEU/BMD/documents/strategic%20choices.PDF
[85] Richarch Moore, *Nuclear Illusion, Nuclear Reality: Britain, the United States, and Nuclear Weapons 1958-64*, (Houndsmills; Palgrave, 2010) p.111-112 *Cited In* Lewis, "*Technical Controversy*", p.74
[86] Grego *et al*, *Shielded from Oversight*, p.3
[87] See *Ibid*, p.2
[88] See *Ibid*, p.2
[89] See Sessler *et al*, *Countermeasures*, p.44
[90] See *Ibid*, p.81

In fair defence of NMD, countermeasure capabilities are a highly classified topic within defence and government circles. Concerning the multiple criticisms that those in the public domain frequently declare, particularly regarding physical properties and capabilities, it is reasonable to acknowledge that those who could otherwise deliver insightful ripostes are bound by secrecy to not do-so. In a sense, the situation is as one committee noted, "“physical first principles” arguments are not hampered by security issues. With insight into some of the ongoing restricted or classified work in this area, the committee would caution against the over-simplistic arguments often heard in the public rhetoric."[91] Irrespective of the on-going debate, it remains that the limited information on midcourse countermeasures appears to present a hugely complex - and seemingly unsurmounted - barrier to the likely effectiveness of an NMD system in the field.

Conclusions

NMD, as illustrated through the sole example of GBMD, has been conceived and deployed with a very specific role - and therefore set of operational circumstances - in mind. By consequence, it appears that an outcome in which it would achieve operational effectiveness - as measured by its ability to *completely* deny the delivery of nuclear payloads by warheads - would be dependent on the existence of an equally specific set of factors being unrealistically in its favour. As the analysis revealed, it is highly questionable as to whether the vast majority of these necessary conditions would ever be mutually present when an NMD system is called to use in real-world circumstances.

Even in the most generous of situations, such as those against a single-digit number of warheads, it is highly improbable that current NMD systems would *simultaneously* benefit from having: constantly favourable weather conditions, around the clock readiness, faultless and undisrupted supporting infrastructure - particularly communications assets and discrimination radar, the ability to competently distinguish between warheads and other objects without unrealistic external assistance, been designed and tested to the extent that it could reliably defeat every conceivable type of countermeasure - including the ones catered to exploiting that specific system, so few targets that its limited interceptor stockpile could meaningfully compensate for a weak kill-probability, or the ability to reliably co-ordinate multiple salvo and SLS tactics against different targets with different trajectories and respective challenges at the same time. Even if one was to depict a scenario in which only a few of the above guarantees were not in place, NMD appears to demand such a sensitive and largely inalienable environment in order to succeed in its role,

[91] Committee for Naval Forces' Capability for Theatre Missile Defense, *Naval Forces' Capability For Theatre Missile Defense*, p.37

a seemingly minor number of things need only be out of place for a mission to fail in its entirety. As discussed, NMD systems cannot afford to 'miss' a single warhead; the stakes, and therefore the demands placed on systems in this cohort are comparatively higher than elsewhere. By this metric and the findings of the above analysis, this study concludes that it is unlikely that any current or near-future NMD system would be successful in defending, with the necessary degrees of effectiveness, against even a limited nuclear attack against cities.

Theatre/Regional Missile Defence

When discussing the likely effectiveness of TMD, this paper is forced to adopt an approach much different to that which was seen in the section prior. The reasons for this are various but specifically come down to the following. 1) 'TMD' is a broad term which considers a far greater number of systems than was seen for NMD.[92] Unlike the previous section which was able to conduct its analysis using only one example, it would be beyond the reasonable limits of the paper to exhaustively discuss the nuanced issues of every-single system's testing performance, likely operational environment, and possible obstacles. 2) There is a dramatic variation in the possible environments, and therefore constraints, that TMD systems could find themselves facing. They can be based on ships - either in the open sea or in proximity to land, deep in-land or on the coast, in disruptive terrain such as cities or in open fields, they could operate in the epicentre of a conflict or be situated on the periphery; each of those environments would present their own set of factors that could positively or negatively impact the outcome of an operation. Compounding this is also the fact that not every TMD platform is designed for the same role or conducts its operations in the same way. Further complication is also added when recognising that, unlike NMD which we can reasonably expect to handle only nuclear threats, TMD operations could involve either conventional or nuclear-armed projectiles (or both). This makes the task of narrowing down a specific "likely operational environment" immensely difficult as there is simply no one scenario that would be truly representative of TMD as a whole. Indeed, by implication, TMD will arguably be influenced the most by circumstance than any other domain. 3) Because of the above, what constitutes an effective system or successful operation is hugely dependent on a range of factors that could not realistically be accounted for in full within the parameters of this paper. When compared to NMD, where success is inherently tied to operational effectiveness and GBMDs ability to produce an outcome that sees zero warheads hitting their target, TMD operations - particularly against light conventional threats - will not necessarily need to be measured by the same metric. The nature of

[92] Indeed, many TMD platforms possess ACMD functions. This study has however placed ACMD operations in a separate analytical cohort.

effectiveness and success in TMD can perhaps therefore only be defined through a mix of competing factors, such as the nature of the threat being handled, the total interception rate, and the nature or extent of damage inflicted on the defended area.

Consequently, this section's analysis is forced to be far more general when delivering an indication as to the likely operational effectiveness of TMD systems across the board. In doing so, the following analysis will make use of testing performance and real-life experience where appropriate and when using a specific system as an example. Further, the section will also draw attention to how slight changes in the operational environment may alter the extent to which specific barriers may be exacerbated or even invalidated.

Role

TMD is what one might call a "Multi-Role Domain"; a wide net that considers multiple different systems that conduct regional or immediate-range missile defence operations as a means to various ends. Importantly, because of such role-diversity, nuance ought to be applied when discussing the implications of any assigned functions of TMD systems. In one regard, the 2019 MDR considers a primary function of TMD to be that of "Enabling Regional and Transregional Military Operations… It helps preserve U.S. freedom of action by limiting adversary capabilities to inhibit or disrupt U.S. regional military operations abroad through missile attacks on U.S. forward deployed forces, allies, or critical in-theatre infrastructure."[93] In this sense, the roles of TMD systems can include defending airbases, major military settlements, fleets and individual vessels, and also deployed forces in the field. Alternatively, some systems have much more specific roles - such is the case with *Iron Dome*, *Arrow,* and various other Israeli interceptor systems whose assigned task is to shield population centres as opposed to enabling terrestrial warfighting.[94] As mentioned, some TMD systems can also be expected to serve as a defence against nuclear-armed threats alongside the above duties - inherently changing what one may then be asking from that system in terms of interception rate. *THAAD*, as an illustration, sees much service in the Western Pacific and on the Korean Peninsula, and is an example of a system that is widely expected to be called upon should nuclear weapons be launched in the region.[95]

Unlike GBMD which appears likely to conduct its operations alone - at least for the current term, an increasing trend for current and near-future TMD systems is interoperability. Adopting a "mass and mix" approach, TMD systems could be deployed complementary to

[93] Department of Defence, *Missile Defence Review,* p.VII
[94] See Uzi Rubin, "Israel's Air and Missile Defense During the 2014 Gaza War" *Mid-East Security and Policy Studies*, No.111 (BESA; 2015) Available at: https://besacenter.org/israels-air-missile-defense-2014-gaza-war/
[95] Klinger, "*The Importance of THAAD Missile Defence*"

one another in an attempt to fulfil their roles; the logic being that the limits and shortfalls of one system can be compensated for by the capabilities of another, leading to an overall increase in defensive capabilities.[96] This does however require a degree of technical integration that is still largely being explored with mixed-success.[97] Nevertheless, it would be reasonable to suggest that near-future systems in this cohort can be expected to operate alongside another frequently and with a resulting increase in effectiveness.

Likely Operational Environment and Barriers to Effectiveness

Given the highly circumstantial nature of TMD operations, identifying both the likely operational environment and resulting barriers should be approached by addressing the factors which are most likely to be relevant in the majority of conceivable environments. As the analysis proceeds, attention will however be paid to how changes in circumstance may influence these specific barriers. Naturally, some of these issues will be more applicable to certain operations or to certain systems but the approach allows for a more general conclusion on effectiveness. Nevertheless, the issues pertinent for TMD operations more broadly appear to be the following…

1) **Salvo Size and Operating Capacity**

2) **The Limits and Vulnerabilities of Supporting Assets**

3) **Evasion Techniques and Countermeasures**

Salvo Size and Operating Capacity

As is the case across MD, the nature and size of an attacker's salvo hugely influences the likely effectiveness of a missile defence operation. This is a particularly acute problem for TMD as there is significant disparity between the costs of attacking in comparison to defending. Irrespective of the role, TMD systems and their interceptors appear to always be significantly more expensive to develop and field than the weapons they are designed to defend against. A 2010 paper illustrated that if the US Navy were to allocate two SM-3 interceptors for every Chinese DF-21 ASBM, the US would be worse-off financially to the

[96] *Ibid*, p.28

[97] For an example, see Arms Control Today, "*Two of Three Missile Defence Tests Fail*", (Arms Control Association; June, 2021) https://www.armscontrol.org/act/2021-06/news-briefs/two-three-missile-defense-tests-fail

sum of around $10 million USD *per exchange*.[98] In larger-scale scenarios involving different systems, one paper suggested it is four times more expensive to be the defending party.[99] Interestingly, this dilemma appears to dramatically increase when faced with a less sophisticated adversary. A single *Iron Dome* battery is estimated to cost around $50 million USD,[100] yet, some reports have suggested that the missiles fired into Israel are so inexpensive that they have at times been made in homes and small workshops.[101] By implication it appears that in whatever environment TMD systems may operate, there is a persisting likelihood that even the least financially endowed attacker will attempt to utilise simple numerical superiority to overwhelm a system.

That said, interestingly, the more sophisticated the adversary, the likelihood that they will need to use as many missiles in their attacks may actually decrease. If attacking soft-targets, like parked aircraft, an attacker may employ missiles with advanced cluster/submunitions as the lethal-area coverage of these types of warheads is significantly greater than those with unitary warheads.[102] By implication, more technologically-advanced actors may consider the number of missiles needed to carry-out an attack to be far less than we could see elsewhere. In short, then, the number of projectiles a TMD system may face is largely a product of circumstance, and would depend chiefly on what the system is attempting to defend and the technological capabilities of the attacker.

The prospect of being numerically overwhelmed by an attacker for comparatively less cost does however produce a subsequent issue; even if the defender's TMD system has indicated a significant interception capability in testing, the extent of its effectiveness will be inherently limited by basic operational constraints. To illustrate, the US' THAAD system has demonstrated a respectable interception capability within testing since major re-designs were made in the early 2000's. As it stands, THAAD has a 100% interception record, seeing success in 16/16 of its tests conducted between 2006 and August 2019.[103] In

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[98] Thomas J. Culora, "*The Strategic Implications of Obscurants: History and Future*", *Naval War College Review*, 63:3 Summer 2010, pp.73-84 (Naval War College; 2010) p.75 https://www.jstor.org/stable/26397125?seq=2#metadata_info_tab_contents

[99] See Sankaran, *Missile wars in the Asia Pacific*, p.35

[100] Michael Armstrong, "Modelling Short-Range Ballistic Missile Defence and Israel's Iron Dome System" *Operations Research*, 62:5, September 2014, pp.1028-1039 (INFORMS; September 2014) https://www-jstor-org.ezproxye.bham.ac.uk/stable/pdf/24540643.pdf?refreqid=excelsior%3Ac594372b4a82db7e9244cd16c403f80d

[101] Rubin, *Israel's Air and Missile Defense During the 2014 Gaza War*, p.11

[102] See John Stillon and David Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks*: *Technology, Scenarios, and U.S. Air Force Responses*, (Santa Monica, RAND; 1999) Available at: https://www.rand.org/content/dam/rand/pubs/monograph_reports/1999/MR1028.pdf p.xiii

[103] Missile Defence Agency, *Missile Defence Intercept Flight Test Record,* p.3

conjunction with a clean sheet of interceptions, THAAD has illustrated an ability to intercept multiple different projectiles simultaneously - its 2011 and Nov. 2015 tests each included two targets, both of which were intercepted.[104] Operationally, THAAD typically deploys anywhere between 48-96 interceptors per-battery;[105] this could be supplemented by more batteries and by stockpiling interceptors but at a greater cost.[106] When assigning two interceptors to each projectile in an attempt to guarantee a kill, we could estimate that THAAD could manage a threat posed by 20-50 individual missiles[107] - this is of course assuming that it could perform on-par with its testing record in a wartime setting. In numerically smaller salvos - at face value - TMD systems like THAAD could perhaps operate effectively. However, this would only be the case until such a time where the attacker's salvo overwhelmed the battery's operating capacity or saturated the radar. Even with supplementary interceptors, THAAD canisters need upwards of an hour to be restocked.[108] This is arguably more than enough time for an attacker to swamp its targets with comparatively cheaper missiles, unimpeded, and with severe consequences if they were to be nuclear-armed. Numerical suppression thus appears to be a comparably cheap yet effective means of overcoming even the best TMD systems.

In certain settings however, just as important to any numerical superiority is *how* the attacker carries out their attack. In the most high-intensity operations, Israeli systems achieve impressive interception rates in the mid-80%, despite being faced with huge numbers of projectiles over the course of an operation[109]. However, modelling by Michael Armstrong on *Iron Dome* indicated that much of this highly-acclaimed operational success is due to a lack of coordination by the various attacking groups. Analysing *Operation Pillar of Defence* in 2012, Armstrong's modelling indicates that the operation would have seen around five-times the number of casualties had the aggressors co-ordinated an attack to use multiple salvos of around fifty missiles at a time; as opposed to trickling-in projectiles in over the course of eight days. [110] With this in mind, it could be suggested that a large contributor to operational effectiveness is the existence of certain luxuries. Further, it remains apparent that TMD performance is "highly sensitive to salvo size" and that even

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104 *Ibid.*
105 Elleman and Zagurek, *THAAD: What it Can and Can't Do*, p.7
106 *Ibid*
107 *Ibid*
108 *Ibid*
109 See Rubin, *Israel's Air and Missile Defense During the 2014 Gaza War* : These interception rates are routinely contested but a widely accepted rate is somewhere between 80-90%: it is beyond the scope of this paper to dissect this issue further.
110 Armstrong, *Modelling Short-Range Ballistic Missile Defence and Israel's Iron Dome System*, p.1029

the best-performing systems could experience dramatic collapses in their effectiveness if circumstances change and their operational capacity is simply exceeded.[111]

The Limits and Vulnerabilities of Supporting Assets

Similarly to NMD, the supporting infrastructure and assets that enable TMD operations appear to be increasingly vulnerable to 1) Both inherent and environmental limitations to C&C infrastructure and 2) Disruptive efforts by attacking forces. This issue is perhaps even more so relevant to TMD because of the possibility that some systems will be placed in close-proximity to the combat-area. In these instances, systems will be expected to perform their roles within high-intensity conflicts involving a multitude of aircraft and other projectiles; all the while being potentially within the crosshairs of the enemy. The impact that a combat ecosystem would have on TMD collectively is difficult to narrow-down and appears to be a largely system-dependent issue. Further, countries tend to not disclose the operational limitations of things like tracking radar for fear of aggressors exploiting systems.[112]

One persisting issue for TMD systems would be the nature of the operating air-space and the limitations of tracking and guidance radar. Principally, every radar system has what may be referred to as a "saturation point" or "limit". That being, an often undisclosed cap on the number of objects that a radar can competently track and guide interceptors to before it begins to experience difficulties. While these numbers are difficult to attain, even the most powerful radar will have its limits. For example, THAAD uses the AN/TPY-2 Phased-Array Radar for target acquisition and interception. So long as the radar cross-section of the projectile is more than 1m², THAAD radar has a target tracking range of about 1000 km.[113] Despite these impressive capabilities, Elleman and Zagurek suggested that the individual radars would likely reach their saturation limit if they were to be faced with 60 objects at once.[114] This is also notwithstanding the impact of friendly missiles, aircraft from both sides, rocket stages, or chaff and decoys. Tracking limits could be improved with multiple radars, but given many systems have not been exposed to high-tens of objects in testing, it is unclear how well certain systems would operate if tasked with blunting the impact of large-scale salvos.

A second issue arising from likewise environments would be that of discrimination. With air-space potentially being filled with multiple friendly and non-friendly objects and

[111] *Ibid*, p.1028
[112] Armstrong, *Modelling Short-Range Ballistic Missile Defence and Israel's Iron Dome System*, p.1029
[113] Elleman and Zagurek, *THAAD: What it Can and Can't Do*, p.2
[114] *Ibid*, p.7

aircraft, it is plausible that some systems could become as much of a threat to friendly personnel as they are to enemy projectiles. This could be due to shortfalls in the situational-awareness capabilities of C&C infrastructure when placed in unfamiliar environments. The Patriot air defence system exemplifies this issue, possessing a track record of multiple friendly-fire incidents when operating in a combat-ecosystem. In one instance, a patriot system and crew mistakenly downed a friendly RAF *Tornado*, killing both crew members;[115] in another, it erroneously began tracking and targeting a US *F-16* which resulted in the pilot in-turn attacking the patriot battery.[116] A subsequent 2005 report summary revealed that Patriot consistently demonstrated situational-awareness limitations in exercises, thus its failures in the field were "not exactly a surprise".[117] In congested air-space, the potential for systems being unable to distinguish between targets could make them a hindrance to integrated operations, limiting their effectiveness and utility to operators. Even if a system has not indicated any C&C or situational awareness limitations in testing, there is still little reason to believe that this would be the case when placed in the field where unfamiliar environments and challenges may reveal previously unknown issues. Indeed. Patriot's performance in the Gulf War illustrates how a system that wins acclaim in testing can drastically underperform when placed in combat. [118]

With the significant value to be had in deploying operationally effective air and missile-defence assets, the reality of direct attack operations as a means of disrupting them has been regarded as an increasingly likely characteristic of modern warfighting.[119] The plethora of options available to a potential attacker could include direct kinetic attacks, cyber warfare operations - particularly relevant given the uncertainty over resilience, or electronic warfare techniques like jamming - a common tactic used in SEAD operations. Of the many one could draw upon, one increasingly relevant vulnerability is that to unmanned aircraft and drones. Notably, the likelihood of this potentially low-tech, low-cost, type of attack is not far-fetched. In Summer 2017, US forces stationed in South Korea discovered a

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[115] See Borja, "Missing From the 2019 Missile Defence Review: Cybersecurity"
[116] See David Axe, "That Time an Air Force F-16 and an Army Missile Battery Fought Eachother, *War is Boring*, July 5th, 2014 (2014) Available at: https://medium.com/war-is-boring/that-time-an-air-force-f-16-and-an-army-missile-battery-fought-each-other-bb89d7d03b7d
[117] Defence Science Board, *Report of the Defense Science Board Task Force on Patriot System Performance - Report Summary*. 20301-3140 (Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics; January 2005) Available at: https://apps.dtic.mil/dtic/tr/fulltext/u2/a435837.pdf p.2
[118] See Theodore Postol, "Lessons of the Gulf War Experience With Patriot" *International Security,* 16:3 pp.119-171 (MIT Press; 1991) . Available at: https://www.jstor.org/stable/2539090
[119] See Thomas Karako, "The Missile Defence Review: Insufficient for Complex and Integrated Attack", *Strategic Studies Quarterly,* 13:2, Summer 2019, pp.3-15 (Air University Press:2019) Available at https://www-jstor-org.ezproxyd.bham.ac.uk/stable/26639670?sid=primo&seq=5#metadata_info_tab_contents

crashed North Korean UAV that had been taking pictures of a nearby THAAD battery.[120] One 2019 paper suggested that "If that UAV had instead carried an explosive device and flown into the face of the single radar on which the THAAD battery depends, the THAAD capability on the entire peninsula could have been effectively eliminated."[121]

The degree to which the above issues will impact operational effectiveness appears to be heavily influenced by circumstance. If systems are exposed to less demanding environments, such as those with fewer potential threats and less congested airspace, and perhaps further from enemy disruption, there would likely be an increase in operational effectiveness. But how possible it would be to reap the utility of TMD systems whilst also keeping them at a safe 'arm's length' is unclear. In particular, TMD assets are likely to always be under threat in some form when taking part in large-scale modern warfighting operations, irrespective of their proximity to the epicentre of the conflict; with crises being unpredictable, there is also little to suggest that systems would not encounter unforeseen problems. Further, in theatres like the Korean Peninsula where TMD batteries maintain a persistent presence, it is unlikely that an operator would have much sway over how a system performs as the nature of the combat environment could largely be decided by the attacker. In these circumstances, TMD systems would likely need to play the hand they are dealt with potentially severe repercussions if projectiles are nuclear-armed.

Evasion Techniques and Countermeasures

As missile stockpiles become more sophisticated, the probability that TMD operations will involve projectiles capable of conducting manoeuvres or carrying penetration aids is likely to increase. In particular, this will present issues for those systems that employ H2K tactics as a means of eliminating targets, as the degree of accuracy required for this is in some ways higher than when using blast fragmentation.[122] Further, it appears that even the most technologically challenged adversaries are capable of producing weapons that have these characteristics. As recently as October 2021, North Korea unveiled and tested what it claimed to be a manoeuvring Hypersonic Glide-Vehicle


HGV being showcased at a North Korean Military Exhibition. Circa-October 2021 //
Image shared on Twitter by Joeseph Dempsey
@JoesephHDempsey Oct. 12th 2021
https://twitter.com/JosephHDempsey/status/1447716305340178437

[120] *Ibid*
[121] *Ibid*, p.7
[122] See Sessler *et al*, *Countermeasures*, xxii

(Pictured Above) - presenting a new threat to the MD systems stationed on the Korean peninsula.

While manoeuvrable warheads themselves are not a new phenomenon, they do present issues for TMD systems that are potentially unaccounted for in testing. In the Gulf War, much of Patriot's poor performance can be attributed to the fact that many of the Iraqi Scuds conducted high-speed corkscrew manoeuvres when entering their terminal phase.[123] These manoeuvres made the task of predicting where the Scud would be at the time of interception difficult for the Patriot missile; even then, the incoming Scuds were descending at twice the speed of the fragments projected by the patriot's blast-frag munitions - "So unless Patriot was right on target, the Scud just sped past the defence".[124] As missile defences improve, so too will the need to develop and employ countermeasures as a means of overcoming them. Much like NMD, the problem of countermeasures for TMD operations is one that could come in many forms - though, even with the technologies being somewhat readily available, the nature and extent of their use will indeed be highly circumstantial; not every current or near-future MD system in this cohort can expect to encounter them. Nevertheless, countermeasures in this domain could include terminal-phase flares or IR/Radio Frequency Chaff- to disrupt guidance radars, decoys or tethered objects- to lure interceptors away from the actual threat, or escort radio-jammers - which would menace the radar-guidance systems of incoming interceptors.[125] How effective these countermeasures would be, or how capable TMDs are at overcoming them, is difficult to say. Indeed, much of the analysis on the issue of countermeasures appears to focus predominantly on NMD rather than theatre-level. However, there is little suggesting that TMDs are routinely tested against countermeasures of this nature. This could imply that many of the criticisms which we see placed at the feet of NMD on this issue are by-and-large applicable to TMD. By that measure, one could suggest that there exists huge ambiguities over how well these systems would perform in the field if they were to face countermeasures - historically, unaccounted for phenomena during interception has typically rewarded the attacker, not the defender.[126]

Conclusions

Just how effective the current or incoming generation of theatre missile defences will be in fulfilling their roles is likely to always come down to system-specific and situation-specific

[123] David Denoon, *Ballistic Missile Defence in the Post-Cold War Era*, p.75
[124] *Ibid.*
[125] See Committee for Naval Forces' Capability for Theatre Missile Defense, *Naval Forces' Capability For Theatre Missile Defense*, p.36
[126] See Patriots issues with poorly made Scuds in: David Denoon, *Ballistic Missile Defence in the Post-Cold War Era*

factors. At face value, TMD systems appear to routinely demonstrate higher interception rates and kill-probabilities in testing than NMD, with some being able to carry-over operational competency into the field. This, however, paints only a partial picture as to the likely operational effectiveness of theatre missile defences as a whole. Given that testing alone cannot be relied upon, the principal issue for TMD systems more broadly will be whether their allocated roles, operational environment, and other circumstantial factors will permit the conditions necessary for them to attain these otherwise promising interception capabilities in the field.

Unless facing nuclear threats, where again, interception rates would need to be effectively flawless in order to bring about anything resembling a success - conventional TMD operations need not attain a 100% kill-rate in order to be considered effective in their assigned roles. As evidenced through Israeli experiences, despite some projectiles still inflicting damage and casualties, attaining a mid-high 80% interception rate may be sufficient for certain missions and certain demands - the deciding factor here consequently being what it is you are asking the system to do. This approach, however, risks reducing the issue to a numbers game. The reality appears to be that making estimations on effectiveness for other TMD operations is much more complicated. Based on these factors and the findings of the above analysis, this study concludes the following.

In a low-intensity, conventional, combat environment perhaps characterised by manageable numbers of objects,[127] access to reliable situational awareness and discrimination through undisrupted supporting infrastructure, and perhaps being faced by an adversary who cannot/does not employ effective countermeasures, manoeuvring warheads, or highly sophisticated projectiles - TMD systems could well attain the necessary levels of effectiveness so as to be considered successful in their roles. The nuance, however, being that 'success' would be measured not purely by interception rates, but by outcome and the implications that arise from missiles that did happen to penetrate defences. If a system defending a fleet indeed achieved a high 80% interception rate against multiple ballistic projectiles but still permits the destruction of an aircraft carrier, by what measure could one reasonably consider that a successful operation?

However, in environments that present greater numerical or technical challenges - and where any number of the above luxuries are not in place - the prospects for operational effectiveness decrease dramatically. In cases such as these, TMD systems will likely underperform and fail to conduct successful operations. When faced with large, organised salvos, or, when operating in highly congested theatres, even the most effective systems

[127] What would constitute 'manageable' would of course be system-dependent.

could be handicapped by the basic operational limits of their radar or limited interceptor stockpile. With the financial bias being in the aggressor's favour, adopting a strategy of saturating your opponent will continue to present a cost-effective option for attackers wishing to overcome TMDs. While developments in system integration and layering assets could help remedy certain issues, the benefits of this would only be felt to a certain extent. Indeed, deploying more radars and complimentary systems would still not address the fundamental vulnerabilities of supporting infrastructure to direct attacks or the complications of manoeuvring projectiles and countermeasures. On matters such as these, TMDs appear to possess a very ambiguous capacity for handling countermeasures or evasion techniques, and an even more ambiguous tolerance for losing supporting assets. In the case of the latter, it is probable that TMD operations would fail in their entirety.

Anti-Cruise Missile Defence

Recent decades have witnessed a rapid increase in cruise missile ownership across the globe. Of the varying causes, this has been driven chiefly by the greater accessibility of technologies previously limited to those with the significant economic and technical capabilities to develop them.[128] For many, the spread of cruise missile technology signals an increasingly important need to develop effective ACMD capabilities as a means of overcoming the various threats presented by their deployment.

Analysis into the likely effectiveness of ACMD-capable systems is particularly difficult for a number of reasons. First, Unlike TMD or NMD, there is often very little tangible information indicating the kill-probabilities of individual systems or interceptors. This is due largely to lack of accessible testing on a comparable scale to TMD or NMD and, again, a lack of real experience. In other cohorts, the impact of likely operational barriers could be evaluated relative to any indicated interception rates; the case is not the same for ACMD. Second, as the following analysis hopes to illustrate, ACMD missions appear to be tremendously sensitive to a small number of factors very difficult to account for or estimate pre-emptively. In particular, the ability to actually detect and track a cruise missile with enough time to conduct a response is something that will make a huge difference for the vast majority of ACMD operations. Irrespective of the actual capabilities of a system, not having enough time to respond will effectively "make or break" an attempt to defend oneself. Lastly, the number of systems that could in theory conduct ACMD functions is vast. Systems that have previously fallen under the TMD cohort, like *Patriot* or *Aegis* will also have ACMD roles. Further, ACMD efforts can be undertaken by much shorter-range assets and Close-In Weapon Systems (CIWS) such as *Phalanx* or *Pantsir-M.* By implication, the

[128] See Mahnken, *The Cruise Missile Challenge*, p.20-21

success of ACMD operations will likely be just as situation-specific as observed elsewhere. These factors make any concrete - or perhaps more satisfying - answer as to whether ACMD operations can be successful significantly challenging.

Consequently, this study approaches the likely operational effectiveness of ACMD from a broader angle, providing a much more general conclusion. The section will avoid going into exhaustive detail on the capabilities of individual systems and will instead aim to present an illustration of what the most significant persisting barriers to ACMD operations are across the board. In a similar nature to that seen in TMD, "effectiveness" and "success" are likely to have very nuanced definitions. The former likely being influenced, amongst other things, by the task assigned to a system and its operational environment; the latter being largely dependent on the outcome of the operation and the extent of any damage.

Role

Unlike the broader cohorts of TMD or NMD, ACMD could perhaps be understood as a role in and of itself. Indeed, many systems conducting various TMD operations will likely be tasked with intercepting cruise missiles if they can - perhaps even alongside ballistic threats. An interesting aspect of ACMD operations is that the problems a system will encounter appear to also be tied to the type of cruise missile being intercepted. The characteristics and ways in which both LACMs and ASCMs are used present nuanced problems for each type of mission. When encountering LACMs, missions could include defending deployed forces or civil and military installations or bases - the geographical characteristics of course being various. Against ASCMs, systems could in theory be based on the coast, but ship-based at-sea systems are more likely to be playing a self-defence role here. With these factors in mind, the following analysis will observe LACMs and ASCMs respectively. With there being certain crossovers between these two roles, the analysis will focus on addressing the prominent issues particular to each mission with the aim of delivering a conclusion on the likely effectiveness of ACMD operations generally.

Barriers to ACMD Operations

Defending Against Land-Attack Cruise Missiles (LACM)

The task of detecting and tracking cruise missiles is broadly speaking the most significant problem involved in any attempt to intercept them. The issues at play are various and will be heavily influenced by things such as terrain and the nature of the immediate operating area. As the flight altitude of a cruise missile is increased, so too does its likely detection range. Consequently, LACMs will keep as low to the ground as possible during their approach, making maximum use of any differences in the terrain to mask themselves from the line-of-sight required by ground-based search radars.[129] LACM operators could integrate hills and valleys in their approach plan, shielding the missile from defensive radar until it reached an ideal distance to start an attack run.[130] In order to counter this, search and tracking radars are typically placed in optimal positions like on hills or away from imposing treelines, with some systems being able to extend their radar's height in order to better observe the surrounding area.[131] Even when doing so, terrain clutter can still play a significantly disruptive role - if a radar is in a position to observe an incoming cruise missile, attempting to distinguish it from the terrain behind or below can still be challenging and time-consuming.[132] For LACMs with low-observable characteristics like stealthy designs, this challenge appears even harder as the lower RCS of the projectile will reduce the distance at which radars will detect it.[133]

Compounding the detection and tracking challenge further is the fundamental issue of response time. Even if a search radar is able to detect an incoming missile, there are certain instances where systems assigned to ACMD operations will not be permitted the time necessary to launch an interceptor before the target is struck.[134] This could certainly be the case if the cruise missile had indeed covered a significant portion of its flight undetected until deep within the air-defence zone. A 2017 paper modelling the S-400's air defence capabilities estimated that the various tasks involved in identifying, tracking, and then engaging an incoming LACM would take approximately 54-151 seconds.[135] At even the most generous end of that estimate, a subsonic LACM travelling Mach 0.7 will have covered nearly 13km in that same 54 second time span and potentially 24km in 100 seconds.[136] A critical issue identified by the authors was also that this process relies on a continual visual of the incoming target…"Detection and tracking could be lost at any time during the sequence, at which time the TLAM [Tomahawk Land-Attack Missile] would have to be reacquired and the sequence started from scratch".[137] In an effort to improve detection range, and therefore reaction time, a defender could deploy Airborne Early Warning (AEW/AWACS) aircraft. Equipped with powerful long-range radars, AEW aircraft could alert

129 Committee for Naval Forces' Capability for Theatre Missile Defense, *Naval Forces' Capability For Theatre Missile Defense*, p.26-27
130 Thomas G. Mahnken, *The Cruise Missile Challenge*, p.33
131 *Ibid*
132 *Ibid*
133 Thomas G. Mahnken, *The Cruise Missile Challenge,* p.33
134 See Michael Pelosi & Amie K. Honeycutt, "Cruise Missile Integrated Air Defence System Penetration: Modeling the S-400 System", *Embry-International Journal of Aviation, Aeronautics, and Aerospace.* 4:3. Article 2. (Riddle Aeronautical University:2017) Available at: https://commons.erau.edu/cgi/viewcontent.cgi?article=1104&context=ijaaa
135 *Ibid,* p.12
136 Mach 0.7 = 0.2401km/s
137 Pelosi and Honeycutt, *Modeling the S-400 System,* p.12

ground crews and systems to the threat of an incoming missile allowing for better preparedness. However, AEW will only play a limited role as it is unclear as to whether AEW aircraft can supplement or perform missile guidance functions. Near-future systems could achieve further connectivity but as it currently stands, many systems will need to rely on their directly associated radars to conduct operations.[138]

In circumstances where detection and tracking are provided, further issues arise from the basic limitations of systems and their operating capacity. With the increasing accessibility of cruise missile technology, one report suggested that a developing nation could acquire 100 cruise missiles for around $50 million dollars.[139] In similar nature to the issues seen for TMD operations, if an aggressor deployed even a small portion of that stockpile simultaneously, defensive systems would likely experience significant difficulty in managing and engaging threats - particularly if an attacker adopts multiple attack angles. Against more sophisticated adversaries, cruise missiles may also use terminal phase chaff or Jamming techniques to disrupt defensive tracking radar. In such instances, it's plausible again that systems may completely fail to attempt interception.[140]

Defending Against Anti-Ship Cruise Missiles (ASCMs)

Defence against ASCMs involves many of the complexities seen when defending against LACMs. Particular areas of crossover include the issues presented by countermeasures, low-observable projectiles, and terrain features. Indeed, ASCMs may also utilise low-flying altitudes and potential terrain features to mask their approaches. ASCMs could position themselves between ships and nearby islands or coastlines to capitalise on radar background disruption.[141] An issue more unique to detecting and tracking ASCMs however, is that of sea-skimming projectiles and the radar horizon. Almost all ASCMs will descend to altitudes sometimes as low as 15m from the surface in order to decrease the range at which ship-based detection radar may be alerted, granting less time to respond.[142] With ships possessing various designs, the type of ship and how high its radar is positioned will have an influence in its detection range. For illustration, a radar situated 40m high will be able to detect a sea-skimming ASCM flying 30m in altitude at around 48km distance.[143] If that

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[138] See David Gormley, *Addressing the Cruise Missile Threat; Defence and Diplomatic Response*, Proliferation Papers (Ifri; Spring 2002) Available at: https://www.ifri.org/sites/default/files/atoms/files/Gormley.pdf p.15

[139] See Mahnken, *The Cruise Missile Challenge*, p.33

[140] *Ibid*, p.33-34

[141] *Ibid*, p.33

[142] See Committee for Naval Forces' Capability for Theatre Missile Defense, *Naval Forces' Capability For Theatre Missile Defense*, p.26

[143] Calculations made using an online radar-horizon calculator tool. Available at: https://www.translatorscafe.com/unit-converter/en-US/calculator/radar-horizon/

projectile is travelling at Mach 1.5, the surface vessel would have less than two minutes to defend itself.[144] The importance of detection and reaction time was illustrated in the case of HMS Sheffield which sank as a result of being hit by an *Exocet* ASCM during the Falklands War. A subsequent inquiry concluded that, amongst other factors, a lack of adequate reaction time, failure to man and load defensive systems, and poor simulator provision by *Sea Dart*'s defensive tracking radar were the main causes of failure.[145] Taking multiple issues into account, even if larger ASCMs with more visible RCS were to approach a vessel, they could adopt sea skimming techniques and higher velocities to compensate for their radar visibility - in certain circumstances forcing a vessel to rely solely on electronic countermeasures and decoys.[146]

When faced with more developed adversaries, systems may encounter ASCMs that possess an additional range of penetration-aiding capabilities and techniques. At close ranges, ships may attempt to use CIWS as a final defence against an incoming projectile. In an effort to overcome this, some ASCMs conduct last-minute 'pull-up' manoeuvres, whereby the missile will engage in a steep climb and then dive back down onto the vessel from a different angle of attack with little-to-no notice.[147] Alternatively, some missiles like the Russian *Klub* will approach its target on a low altitude subsonic flight profile where, at around 20km from its target, it detaches its cruise stage engine and rapidly accelerates to supersonic speeds in the final phase of flight.[148] These techniques increase the unpredictability of ASCM operations, making the role of engaging projectiles at various ranges significantly harder. Despite these capabilities, certain ACMD systems catered to defeating ASCMs have however demonstrated promising interception capabilities against in exercises. In 2012 and as recently as 2021, *FS Forbin* successfully used its *Principle Anti-Air Missile System (PAAMS),* operating the *Aster 15/30* interceptors, to engage supersonic sea-skimming targets.[149] While specific details are largely unknown, the 2012 test was described as a "complex operational scenario" involving tracking assistance from a friendly vessel against a target travelling at around Mach 2.5.

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[144] Mach 1.5 = ≈30km per minute
[145] See HMS Nelson Board of Inquiry, *Report by the HMS Nelson Board of Inquiry into the loss of HMS Sheffield*, May 28th, 1982. (HMS Nelson Board of Inquiry:1982) Available at: http://www.admiraltytrilogy.com/read/BOI_Rpt_HMS_Sheffield_May82.pdf
[146] See Committee for Naval Forces' Capability for Theatre Missile Defense, *Naval Forces' Capability For Theatre Missile Defense*, p.6
[147] *Ibid*, p.27
[148] Mahnken, *The Cruise Missile Challenge*, p.13
[149] See Ministere Des Armees, "Interception of a supersonic target moving along the water" April 5th, 2012 (DICOD; 2012) https://www.defense.gouv.fr/actualites/articles/interception-d-une-cible-supersonique-evoluant-au-ras-de-l-eau (Accessed 10.10.21) : Defence World, "French Aster 30 Missile Downs Sea-Skimming Supersonic Projectile in NATO Exercise" May 29th, 2021 (Defence World; 2021) https://www.defenseworld.net/news/29683/French_Aster_30_Missile_Downs_Sea_Skimming_Supersonic_Projectile_in_NATO_Exercise#.YWmUgxrMKUk (Accessed 10.10.21)

Conclusions

Cruise missiles are likely to carry on presenting a growing threat to both terrestrial and at-sea operations long into the future. With their relatively low-cost, and the accessibility of the technology required to produce them, the prospect of large-scale use will likely remain high - though, this depends highly on the nature of the opponent. As previously discussed, the large array of ACMD-capable systems, the lack of definitive answers as to their kill-probabilities, and the highly situation-specific character of operations makes any concrete answer on likely effectiveness challenging. Nevertheless, the above analysis makes for the following general conclusions.

Collectively, the effectiveness of operations against both LACMs and ASCMs will be highly sensitive to early warning, reaction time, and the reliable function of detection and guidance radar in the given environment. In defending against LACMs, systems will benefit hugely from advantageous terrain, positioning, and the availability of supporting assets like AEWs. If these factors are in place, systems will have a greater chance of detecting incoming cruise missiles early, in some cases allowing for multiple interception opportunities which will increase the likelihood of mission success. It is in these circumstances that systems will experience the highest levels of effectiveness. In environments where systems are denied these factors, however, there is likely to be a sharp decline in reaction time and therefore opportunities to engage a target - even for the most effective of air-defence systems. This problem is compounded further by an increase in the number of threats; in the worst-case scenarios, it is entirely plausible that some systems may simply be denied the opportunity to engage every incoming missile. This is particularly true if targets come from multiple directions, deploy effective countermeasures which significantly degrade radar capabilities, or have such a low RCS that radar has difficulty in distinguishing them until too close.

When countering ASCMs, the challenges are broadly transferable, but other variables will also be at-play. In particular, because a ship's independent detection range is limited to its radar horizon, unless working with other assets, the time a missile takes to be detected and close distance with its target will be critical. With many ASCMs being able to reach either subsonic or supersonic speeds, the time awarded to the defender will be largely threat dependent. Nevertheless, ships in optimal environments, where there are little-to-no additional constraints to detection, and where they are awarded reasonable response times against less sophisticated projectiles, serve the best chance at effective ACMD operations. This likelihood, however, decreases as more factors come into play; such as background disruption, unpreparedness, multiple projectiles, and in particular, terminal-phase manoeuvres. If these factors were to compile, in certain instances, ships may completely lack the opportunity to defend themselves and indeed may need to turn to passive countermeasures.

The Advent of Hypersonic Weapons

The subject of hypersonic weapons has occupied a tremendous amount of space in security discourse over the last decade, with particular interests centring around technicalities, capabilities, and likely implications. Much of the discussion, and such is indeed a focus of this study, has been around the potential for hypersonic delivery systems to undermine the effectiveness of current and near-future missile defence systems - the consequence being an overall reduction in strategic stability. It would therefore be within the interests of this paper to briefly discuss the introduction of these systems and the potential implications they may have for the missile defence 'equation'.

The following section will attempt to briefly explore the advent of hypersonic weapons as a potential barrier to missile defence effectiveness. The analysis will proceed initially with a general overview of the key characteristics and conceived roles of hypersonic weapons. With much of the genuine capabilities and utilities of these weapons often being lost amongst speculation and hype, this will be followed by an attempt to rationalise hypersonic weapons and draw attention to their limitations as military hardware and the realities of their utility. The section will conclude on the likely implications of hypersonic weapons by taking into account the respective observations that have been drawn on National, Theatre, and Anti-Cruise Missile Defence earlier in the study. Here, the paper will focus on the existing limitations of MD systems as a means of deducing the likely impact hypersonics may genuinely have on missile defence operations.

Technical Characteristics and Conceived Roles.

With much work having been done examining the in-depth technical characteristics of hypersonic delivery systems,[150] this section will avoid exhaustive detail and will instead provide a brief overview of both HGVs and HCMs, their utilities, and potential roles. Hypersonic Glide Vehicles are unpowered projectiles that utilise specially designed exteriors and control surfaces to 'glide' towards their targets; either just above or within the Earth's atmosphere and typically anywhere between 40-100+km in altitude.[151] At

[150] In particular, see Richard Speier *et al "Hypersonic Missile Nonproliferation: Hindering the Spread of a New Class of Weapons"* (Santa Monica, Rand Corporation;2017) Available online at: https://www.rand.org/pubs/research_reports/RR2137.html
[151] *Ibid*, p.8

certain altitudes, HGVs may simply be out of range for most TMDs, at least until descent.[152] Much like a contemporary warhead, HGV's conduct the boost-phase portion of their flight on a ballistic missile, later detaching and completing the glide-phase and terminal-phase of their flight independently. HGV speeds are various but they are believed to be capable of reaching up to Mach 20;[153] through use of control surfaces, they may also conduct various in-flight manoeuvres which, in theory, translates into an evasion capability against interceptors. Unlike current warheads, which will often possess a high-arching ballistic trajectory, HGVs will adopt a flattened flight path, skimming across the upper layers of the Earth's atmosphere along a variable pattern. Due to the radar horizon, in this sense, HGV's will be detected by Over-the-Horizon Radar much later in their flight than other warheads.[154] With the potential to carry either nuclear or conventional payloads, HGVs are theorised to possess a number of potential utilities; including swift "decapitation" strikes against nuclear C&C, sophisticated surgical strikes against high-value targets and infrastructure, or as part of broader Anti-Access / Area Denial (A2/AD) capabilities.[155]

Alternatively, HCMs inherit many of the same characteristics, flight patterns, and manoeuvrability features of contemporary cruise missiles - like those discussed earlier. One notable difference is the implications that utilising a *scramjet* for propulsion has on flight altitude and velocity. In order to achieve the pressures necessary to function, HCMs will need to be accelerated to high-supersonic speeds, typically by a rocket booster, before the scramjet can take over; requiring optimal altitudes to achieve this, HCMs will likely cruise somewhere between 30-40kms.[156] Making use of the unique and highly aerodynamic frames typical of these weapons, once engaged, a scramjet could propel a HCM to potentially Mach-10.[157] Like contemporary cruise missiles, HCMs are understood to combine high-speeds with manoeuvrability to overcome missile defences - one key aspect here being the importance of response-time which would be dramatically reduced by hypersonic flight. Again, with the capacity to carry both nuclear and conventional payloads, the possible utilities of HCMs are broadly similar to HGVs; including tactical and strategic pre-emptive strike operations, A2/AD, and in particular posing a significant threat to surface vessels.[158]

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[152] *Ibid*, p.15
[153] *Ibid,* p.xi
[154] *Ibid*, see p.11 for illustration of flight pattern
[155] See Sergey Batsanov and Kevin Miletic, *"What are the roles and Missions of Hypersonic Weapons?"* Pugwash Briefing Paper (British Pugwash Group;2020) p.4 Available at: https://britishpugwash.org/wp-content/uploads/2020/11/Pugwash-Briefing-Paper-No5.pdf
[156] Speier *et al*, *Hypersonic Missile Proliferation*, p.12
[157] Sergey Batsanov and Kevin Miletic, *"What is a Hypersonic Weapon?"*, Pugwash Briefing Paper (British Pugwash Group;2020) p.4, Available at: https://britishpugwash.org/wp-content/uploads/2020/11/Pugwash-Briefing-Paper-No1-.pdf
[158] Batsanov and Miletic, *Roles and Missions of Hypersonic Weapons*, p.6

Keeping Feet Grounded: Realities and Limitations

While the technical expertise involved in the development and creation of hypersonic weapons is substantial, much of the publicity surrounding them has led to exaggerated, or perhaps misplaced, claims about their capabilities and novelty.[159] Consequently, it will be worth sparing some space to address just some of the limitations and realities of hypersonic weapons.

Perhaps fundamentally, the ability to accelerate projectiles to hypersonic speeds is not a new phenomena. Indeed, in the late 1950's, the US had developed and tested a manned hypersonic aircraft and certain contemporary ballistic missiles will routinely reach hypersonic speeds during their flights.[160] Equally, as is evidenced throughout the paper, the ability to manoeuvre at various stages of flight is also not unique to HGVs and HCMs. Particularly in the TMD and ACMD domains, manoeuvres will be characteristic of many missile defence operations with the current technology to hand. Perhaps more significantly, however, is the reality that the technical characteristics of HGVs and HCMs also come with a host of inherent trade-offs. Concerning HGVs, two important trade-offs derive from a lack of in-built propulsion. 1) By traveling effectively under its own momentum, yet still being subject to aerodynamic drag, HGVs will suffer a significant speed penalty over time. The longer the duration of flight, the slower the HGV will be when it reaches its target; even if a glider achieves high-hypersonic speeds early in its flight, depending on range, it will likely be travelling significantly slower by the time it reaches its target.[161] 2) Any attempt at manoeuvres by HGVs will increase drag; subsequently reducing the speed and range of the projectile throughout its flight - it would appear that even the slightest changes in direction will exert a significant speed penalty on the glider.[162] Crucially, if a HGV suffers from these penalties in operation, the lower speed that comes as a consequence could indeed leave them more vulnerable to potential terminal-phase interception. Even with the supposed speed benefits of HGVs, it is widely accepted that firing contemporary ballistic missiles on depressed trajectories would enable an attacker to achieve the lower flight times seen by hypersonic systems. To illustrate, when adopting this technique, a current generation ballistic missile could cover 6,700km in 17 minutes with an average speed of Mach 20.[163] This is all the while being achieved without investments into alternative technologies.

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[159] See Ivan Oelrich, "Cool Your Jets: Some perspective on the hyping of hypersonic weapons" *Bulletin of the Atomic Scientists*, 76;1 pp.37-45 (Routledge: 2020) available at: https://www.tandfonline.com/doi/10.1080/00963402.2019.1701283
[160] See Speier *et al*, *Hypersonic Missile Proliferation*, p.7 ; Oelrich, *Cool Your Jets*, p.38
[161] see Oelrich, *Cool Your Jets*, p.38
[162] For an in-depth explanation see *Ibid*
[163] See *Ibid*, p.38-39

HCMs too are not exempt from certain technical limitations. Chiefly, it appears that the scramjets used by HCMs are acutely sensitive to changes in engine pressure and altitude. Relying on rigid conditions in order to function, such as high air flow and temperature "the vehicle itself and its orientation to the airflow are actually part of this temperamental engine. Maintaining the proper temperatures and densities inside the engine could also constrain the operation of the engine to certain combinations of speed and altitude".[164] If this is indeed the case, and HCMs will be constrained to specific operating altitudes, it is plausible that HCMs will be subject to radar detection at greater ranges due to being unable to adopt low-altitude flight profiles - other constraints notwithstanding, this could potentially grant the defender a more reasonable amount of time to mount a defence.

An important aspect to also consider is the meaningful utility that hypersonic delivery systems could bring to attack operations. With their limitations and substantial costs, it is plausible that the existing array of ballistic and cruise missiles already provide the capabilities that hypersonic systems appear to promise. Further, and particularly where missile defence is concerned, the previous analysis has illustrated that there are a number of factors that can negatively influence the outcome of MD operations irrespective of whether their threats are hypersonic. Whether protecting ships, cities, bases, or deployed forces, there remains a range of factors that need to be in the defender's favour in order for many systems to be effective in fulfilling their roles. In this essence, as opposed to presenting novel dilemmas, hypersonic weapons may instead merely compound already existing issues for missile defence systems tasked with defeating them.

Implications for Missile Defence Effectiveness

When considering the findings by this study on the likely operational effectiveness of missile defences, the probable implications of hypersonic weapons appear mixed. Consistent throughout the course of this paper has been the reality that missile defence operations, at all levels, are highly circumstantial; sometimes being influenced heavily by factors completely separate to the nature of the projectiles they are trying to defeat. These can include things such as disruptive efforts against supporting assets, geography, or the basic limitations of the system being used.

With the limitations, trade-offs, and costs of hypersonic weapons - which restrict the numbers in which they can be deployed and their utilities - it appears that only in certain operations would an aggressor genuinely benefit from using hypersonic weapons over current-generation delivery systems. At the NMD and TMD level, as has been seen, MD

[164] Oelrich, *Cool Your Jets*, p.43

systems can be overcome relatively effectively by utilising larger numbers of projectiles, by attempting to disrupt essential systems, or by deploying otherwise rudimentary countermeasures - techniques that would arguably be employed for much less cost than would be needed to develop hypersonic alternatives. For cruise missile operations, the existing array of subsonic and supersonic platforms, complete with their manoeuvrability, ability to capitalise on geographical features, and the techniques they can employ to reduce reaction time in some cases appear perfectly suitable for carrying out operations in spite of existing defences.

By measure of the brief analysis conducted in this section, it appears that hypersonic weapons will provide a niche capability - albeit for a greater cost. For the countries that can afford to develop and deploy them, hypersonic weapons will likely capitalise on the existing barriers already placed in the way of missile defence operations. Particularly, the speeds presented by both HGVs and HCMs will, more so at shorter ranges, dramatically reduce the time awarded to a defender to respond. In this sense, hypersonic weapons will simply add to the arguably substantial list of dilemmas already presented to missile defence systems at all levels. With this in mind, hypersonic weapons may indeed possess an edge over MD systems; but that is not to suggest that MD systems would routinely attain such levels of effectiveness so as to make hypersonics a silver bullet. Amongst the other feasible scenarios and instances this paper could discuss, there remains the question as to what the advent of hypersonic weapons could mean for strategic stability as a whole.

Taking into account the above, it is unclear - from a missile defence angle at least - as to why hypersonic weapons should represent a major downturn in strategic stability. This is in short because, while their use may present problems for missile defence operations, MD experiences such situation-specific success that in certain scenarios, the projectile being hypersonic could make an inconsequential amount of difference. For instance, if a TMD system's radar, in a high-intensity operation, experiences saturation and begins to fail because of multiple projectiles, the problem of any projectiles being hypersonic would be eclipsed by the broader issue that the radars performance was exceeded by the demands of the environment.

What could be speculated, then, is that the faith placed in missile defence systems will play the most significant role in how states respond to the introduction of hypersonic weapons and thus how stability is affected. By this metric, hypersonic weapons will present a greater threat to countries who possess, and perhaps rely on MD systems, than they will for those who do not. Further, actors who *perceive* their missile defences to provide tactical and strategic utility are likely to respond the most aggressively to the advent of hypersonic weapons. In essence, the impact of hypersonic weapons may potentially come down to what actors make of their capabilities, their own defences, and their tolerance for any vulnerability.

Concluding Remarks

With a global trend of ballistic and cruise missile proliferation, conversations regarding the operational effectiveness of current and future generations of missile defence systems will become increasingly relevant. For states who feel particularly threatened by expanding arsenals, missile defence is likely to be perceived as an attractive means of off-setting vulnerabilities and enabling force projection capabilities. Indeed, as missile defence systems themselves become more sophisticated, and higher kill-probabilities are achieved, integration of missile defence into warfighting and homeland defence strategies could become a reality for a greater number of militaries than we see today. An important deciding factor in these decisions, however, will be whether states consider the gains made in possessing missile defences warrants the substantial price-tag that accompanies them. Particularly where financial and technical matters are concerned, the preceding analysis has shown that missile defence operations at all levels appear to in some way favour the aggressor; this is likely to remain true for the coming decades and will need to be factored into any procurement commitments.

It has been one of the central aims of this report to draw attention to one fundamental reality of missile defence; that the question of just how effective a system will be in combat comes with a complex and deeply circumstantial answer. Consistent throughout this study's analysis has been that the outcome of an operation will largely be a product of various competing factors; each holding a large sway over the likelihood of both effectiveness and success. By drawing attention to the highly situation-specific nature of missile defence, the research has also illustrated that in all domains, testing will rarely - if ever - be able to account for every variable at play. The approach employed by this report was to interpret any known capabilities within our understanding of the roles, objectives, and likely operational environments of these systems. In doing so, this paper has attempted to deliver a general indication as to how one might expect the current and near-future generation of missile defence systems to perform in the field.

The conclusions made by this study have informed a brief yet somewhat nuanced prediction as to the likely impact of hypersonic weapons on missile defence effectiveness and strategic stability as a whole. Taking into account the number of variables at play, hypersonic delivery systems appear simply to add to an otherwise lengthy list of barriers that each missile defence system could face. There is little denying that hypersonic delivery systems indeed present challenges to missile defence operations, but, it would be largely flawed to suggest that their introduction presents an entirely new array of unique dilemmas. Quite conversely, many of the characteristics and capabilities hypersonic weapons exhibit, like manoeuvrability and dual-use, have been seen in other platforms for decades - begging the question as to what circumstances would using hypersonic weapons genuinely be preferable to arguably more cost-effective alternatives. Amongst other tasks, it will be the work of further studies to illustrate how, and in what specific scenarios, defence against hypersonic projectiles could play out. The considerations of this paper imply that perhaps the most significant influence on strategic stability will not be their capabilities, but the interpretations and responses of concerned actors to their introduction.

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Appendices

APPENDIX A.

Evaluating 'Effectiveness' and 'Success'

How one should measure the effectiveness of a missile defence system, and what is required for a system to 'work', is a complex issue. In the public domain, we typically employ baseline statistics as our unit of measurement; casting judgement on whether a system should be deemed effective or credible on interception percentages from its testing alone. This approach, however, provides an incomplete picture of the 'effectiveness' of the system under analysis.[165] This is notwithstanding the fact many of the MD-capable platforms deployed by countries other than the U.S. have little-to-no publicly accessible record of both successes *and* failures in testing. This over-reliance on testing also reduces the complexity of the issue to simply a numbers game, bypassing the reality that there are a

[165] Matt Korda, from remarks made in an interview with the Author (August 19th, 2021)

great number of variables which would dictate the performance of a system in the field.[166] With this in mind, it is important to recognise that "effectiveness" or "success" is highly circumstantial, and, in conjunction with testing performance, this paper attempts to look further and will consider the following in its analysis...

- **The Strategic/Tactical Objective and Role:** Missile defence systems, like all-other military hardware, are a means of attaining a strategic or tactical end, with each system being conceived and fielded with a specific objective in mind. Subsequently, calculations over effectiveness and success will be inherently tied to the respective 'end-game' of the system under analysis.[167] Questions to keep in mind when considering this factor include...

    - What threat(s) is the system designed for or being asked to handle?
    - What capability is the system trying to provide?
    - What dilemma (if any) is the system attempting to remedy?

    Strategic and tactical objectives set the context and parameters within which we may interpret and apply testing or real-world performance data. Using the example of the US' GBMD system, if a system is designed to operate as a homeland counter-ICBM system, to intercept a limited number of warheads - most likely nuclear - in their midcourse phase, as a result of a rogue, already blunted, or even accidental launch, and for the purpose of entirely preventing the damage inflicted by those warheads unto critical infrastructure or population centres,[168] then any data on its performance and calculations on effectiveness should be understood under that context.

- **Operating Circumstances and Environment:** Current and near-future missile defence systems will be expected to perform and fulfil their objectives, reliably, within a conflict or crisis environment. Both theatre - particularly those close to major areas of conflict - and homeland systems will be required to track, target, discriminate, communicate, and intercept potentially hundreds of projectiles over a prolonged period, and possibly within crowded air-space. The situation a system finds itself in will present a number of variables that alter the nature of what success will look like: Are you intercepting nuclear or conventionally armed warheads? How many have been launched against you? What are you defending? An

[166] George Lewis, "Ballistic Missile Defence Effectiveness", *AIP Conference Proceedings* (15th November 2017); https://doi.org/10.1063/1.5009222, p.5
[167] Dr. Bleddyn Bowen, from remarks made in an interview with the author (August 10th, 2021)
[168] See Department of Defence, *2019 Missile Defence Review*

airbase? A city? An aircraft carrier? Combined with the assigned role of a system, conflict circumstances also dictate "leakage" tolerance and the margin of penetration that can be reasonably accepted by the operator; that margin decreases with the greater damage potential of the warhead.[169] With few active systems possessing experience in conflict environments, and it being largely uncontentious to say that controlled testing is not a reliable basis for judging any realistic performance on the field alone,[170] factoring in the likey operating circumstances of a system when judging its likely effectiveness is essential. We should look to address questions such as "how comparable has a system's testing environment been to its likely operating circumstances?"; if a system is only achieving 60% interception success in controlled testing - where all operators are briefed, are aware of an incoming threat, are familiar with their operating environment, with all supporting infrastructure operating without disruption - how well might we reasonably expect it to perform when those guarantees may not be in place?

- **The Separation of "Effectiveness" from "Success":** The scenario-specific character of missile defence forces a distinction to be made between a system's performance being 1) 'operationally effective' and 2) producing what could be considered a 'militarily successful outcome'. The majority cause of this, amongst other factors like strategic objectives, is linked to the type of threat a system is attempting to engage and to what it is attempting to defend. As stated, the destructive potential of an incoming warhead increases the risks associated with interception failure, making leakage an existing issue compounded further by the value placed on whatever could be lost. In the context of a nuclear attack on a population centre "...even if you dramatically outperform your testing record, even if you over-perform, and a single warhead gets through, that's a disaster".[171] Alternatively, if a system achieves an interception rate substantially *lower* than its testing record implied, but engaged conventionally armed projectiles and nothing of any significance was damaged, then one could suggest that the system was ineffective (relative to predicted performance) but circumstances dictated that the outcome was not a military failure.

- **Conceived Utility:** One of the realities of contemporary missile defence is simply that some systems are fielded with missile interception being a complement to another utility. This is particularly true with certain theatre/regional missile

[169] Elleman and Zagurek, Jr. "*THAAD: What it Can and Can't Do,*" ; Debasis Dutta "Probabilistic Analysis of Anti-Ship Missile Defence Effectiveness" p.124
[170] See Sessler *et al*, *Countermeasures.*
[171] Matt Korda, from remarks made in an interview with the author (August 19th, 2021)

defences and point-defence systems (PDS), where the initial development of these technologies may have had as much to do with carrying-out an anti-aircraft role as it did a missile defence one. This was the case with the original MIM-104 Patriot interceptor whose role was, in-conjunction to short-medium range missile defence, to supplement Surface-to-Air Missile (SAM) capabilities against aircraft, a role it still fills today.[172] Measuring effectiveness should be strictly carried out relative to the realistic utility a system is trying to provide. Judging a system by its ability to perform a function completely outside its initially conceived purpose is logically insufficient.

[172] David Denoon, *Ballistic Missile Defence in the Post-Cold War Era*, p.2