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PROJECT ANTHRACITE

Raw Materials for Potential Chemical Warfare Agents

Technical Assessment 1

The Project Anthracite Team

Executive Summary

Understanding the raw materials and precursor chemicals required to support a chemical weapons (CW) programme is an important foundation stone in an assessment of whether North Korea's chemical industry possesses adequate infrastructure and capability to support such a programme.

This report outlines the chemical steps required to produce those key precursor chemicals. It considers the upstream and downstream processing steps from raw materials, such as coal, that could potentially give North Korea access to those precursor chemicals.

While the primary purpose of this report is to serve as a point of reference to identify relevant chemicals for the Project Anthracite team,[1] it will also serve as a useful reference for those engaged in similar work.

The analysis in this report is insufficient to determine whether North Korea is engaged in the production of chemical warfare agents (CWAs), but it does identify the chemical processes that would be required to sustain a CW programme. The availability of raw materials, coupled with the availability of basic technology, strongly supports the premise that North Korea can produce simple agents, such as sulfur mustard. There is, however, a greater degree of technical capability needed to produce nerve agents, and this capability may not be immediately obvious in North Korea's chemical industry.

This report is unique in that it considers the whole range of chemical processes and raw materials required to produce CWAs and does not assume the availability of chemical precursors. Instead, it traces the CWAs, which are relatively complex molecules, back to their roots in raw materials and minerals such as coal and apatite.

1. RUSI, 'Project Anthracite: Assessing the Chemical Weapons Capability of the DPRK', <https://rusi.org/explore-our-research/projects/project-anthracite-assessing-chemical-weapons-capability-dprk>, accessed 6 June 2025.

Background

North Korea has long presented a uniquely challenging environment for intelligence collection – as data is often obscured by limited access and high levels of operational security – and it is often referred to as a ‘hard target’ due to its extreme secrecy and control of information.[1]

Much of the international community’s intelligence focus has historically centred on North Korea’s nuclear weapons programme, owing to its strategic threat and geopolitical implications. However, there are also concerns around North Korea’s potential chemical weapons (CW) capabilities.

The rapid evolution and growing sophistication of open source intelligence (OSINT) have transformed the landscape of intelligence analysis. OSINT now allows analysts to synthesise data and to compile, corroborate and assess information from multiple unclassified sources, potentially offering valuable insights into otherwise opaque targets.[2]

This raises an important question: can OSINT provide meaningful insights into North Korea’s CW capability? While the regime’s access to small quantities of chemical agents is well-documented – most notably in the assassination of Kim Jong Nam in Kuala Lumpur using the nerve agent VX[3] – there are longstanding, although unverified, reports that North Korea may possess between 2,500 and 5,000 tonnes of historic chemical weapons (CW) stockpiles,[4] and the US Defense Intelligence Agency believed in 1997 that North Korea had a ‘sophisticated chemical weapons programme’.[5]

The aim of this paper is to establish a foundational understanding of the chemical infrastructure and materials North Korea would require to operationalise a large-scale CW programme. By identifying the key industrial processes and precursor chemicals necessary, the paper intends to provide a baseline for assessing feasibility and future indicators of potential proliferation activity.

1. Ken Dilanian, ‘North Korea is a Tough Target for U.S. Intelligence Agencies’, *Los Angeles Times*, 24 December 2011, <https://www.latimes.com/nation/la-xpm-2011-dec-24-la-fg-korea-intel-20111225-story.html> accessed 3 June 2025.
2. Ardi Janjeva, Alexander Harris and Joe Byrne, ‘The Future of Open Source Intelligence for UK National Security’, *RUSI Occasional Papers* (June 2022), <https://www.rusi.org/explore-our-research/publications/occasional-papers/future-open-source-intelligence-uk-national-security>, accessed 30 June 2025.
3. UN Security Council, ‘Report of the Panel of Experts Established Pursuant to Resolution 1874 (2009)’, S/2019/171*, 5 March 2019, <https://www.securitycouncilreport.org/atf/cf/%7B65BFCF9B-6D27-4E9C-8CD3-CF6E4FF96FF9%7D/s_2019_171.pdf>, accessed 3 June 2025.
4. International Crisis Group, ‘North Korea’s Chemical and Biological Weapons Programs’, Report No. 167, 18 June 2009, <https://www.crisisgroup.org/asia/north-east-asia/korean-peninsula/north-korea-s-chemical-and-biological-weapons-programs>, accessed 6 June 2025; Mark Fitzpatrick (ed.), *North Korean Security Challenges: A Net Assessment* (London: International Institute for Strategic Studies, 2011), p. 161.
5. US Government Publishing Office, ‘North Korean Missile Proliferation: Hearing Before the Subcommittee on International Security, Proliferation, and Federal Services of the Committee on Governmental Affairs United States Senate, One Hundred Fifth Congress, First Session’, Senate Hearing 105-241, 21 October 1997, <https://www.govinfo.gov/content/pkg/CHRG-105shrg44649/html/CHRG-105shrg44649.htm>, accessed 3 June 2025.

Future papers in this series will build on this framework to further analyse production pathways, dual-use facilities and potential international procurement networks supporting North Korea's CW ambitions by corroborating publicly available information with sophisticated imagery analysis.

Methodology

The research for this paper employed a multidisciplinary OSINT methodology to assess North Korea's potential for CW production by reviewing information from a wide range of sources, including North Korean patent applications, state television broadcasts, scientific literature, technical reporting and academic texts. Analysis focused on finding industrial processes and raw materials – such as coal, phosphate rock and arsenic-bearing minerals – relevant to the synthesis of key CWA precursors such as thiodiglycol, phosphorus trichloride and methylphosphonic difluoride. Patents and scientific publications were examined for reported industrial routes and chemical feasibility, while state media provided insights into industrial priorities, capabilities and self-reliance narratives aligned with Juche ideology.[6] Mainstream scientific and grey literature supported validation and cross-referencing of industrial routes and processes.

A structured framework was used to map upstream and downstream chemical processes against North Korea's resource base and industrial outputs. Limitations included restricted access to verifiable in-country data and the potential for bias in North Korean state sources, mitigated where possible by multisource corroboration.

Introduction

Most organic chemicals begin their life cycle as fossil fuel feedstocks, which undergo a series of refining and processing steps in chemical plants to produce basic building block chemicals, often referred to as 'upstream' processing. These fundamental chemicals subsequently undergo a series of processing and synthesis steps ('downstream' processing) to produce intermediate and speciality chemicals, which find use in industries ranging from pharmaceutical to agrochemical. Such transformation of raw materials forms the backbone of any chemical industry, and understanding these production pathways is essential to assessing a country's capacity to access the chemicals that could support a CW programme.

Basic Raw Materials

Coal is abundant in North Korea and plays a significant role in its domestic energy and industrial base.[7] Unlike petroleum-rich nations, North Korea relies heavily on

6. Grace Lee, 'The Political Philosophy of Juche', *Stanford Journal of East Asian Affairs* (Vol. 3, No. 1, Spring 2003), pp. 105–12.
7. Peter Makowsky, Jenny Town and Samantha J Pitz, 'A Snapshot of North Korea's Supply Chain Coal Activity', 38 North, 8 March 2019, <https://www.38north.org/2019/03/supplychaincoal030819/>, accessed 2 July 2025.

coal as a feedstock for a variety of industrial processes. This makes coal not only a source of energy but also a vital input for chemical manufacturing. The upstream and downstream processing of coal involves several stages that yield a wide range of chemical products.[8] In the context of North Korea, where access to global chemical markets is severely restricted, the ability to extract and refine chemical precursors from coal and minerals represents a potentially important contribution to the North Korean principle of self-sufficiency, Juche.

Upstream Processing

In the first stages of the chemical production chain in North Korea, coal is converted into fundamental feedstocks. One of the most important conversions is gasification, a process in which coal reacts with oxygen and steam at high temperatures to produce synthesis gas, or 'syngas', composed mainly of hydrogen, carbon monoxide and carbon dioxide.[9]

Syngas serves as a key intermediate in the production of various chemicals, such as methanol, ammonia and urea.[10] Methanol, for instance, can be further processed into methylamines – a group of chemicals which include dual-use chemicals with potential application in the synthesis of nerve agents.[11] Ammonia, another major product of syngas, is used not only in fertiliser production but also as a precursor for nitrating agents and explosives.[12] Thus, even the initial phase of coal chemical processing produces compounds that could serve as important building blocks for a CW programme, depending on the infrastructure and intent of the state.

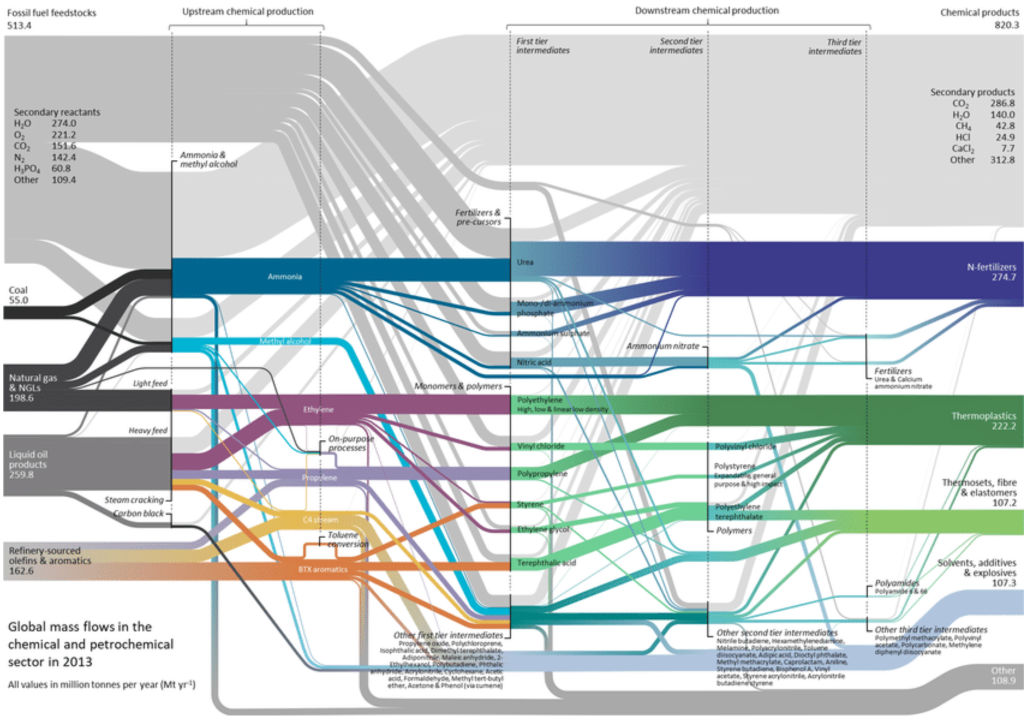
Downstream Processing

Downstream processing expands the range of chemical products significantly. Through processes such as Fischer-Tropsch synthesis,[13] coal-derived syngas can be converted into a variety of hydrocarbons, alcohols and other organic chemicals.[14]

The breadth of chemical building blocks that can be obtained from fossil fuel feedstocks in shown in the Sankey diagram in Figure 1.

8. James G Speight, *The Chemistry and Technology of Coal*, Third Edition (Boca Raton, FL: CRC Press, 2016); Eric Croddy and James J Wirtz, *Weapons of Mass Destruction: An Encyclopedia of Worldwide Policy, Technology, and History: Volume 1, Chemical and Biological Weapons* (New York, NY: ABC-CLIO, 2005).
9. Speight, *The Chemistry and Technology of Coal*.
10. *Ibid*.
11. US Congress, Office of Technology Assessment, 'Proliferation of Weapons of Mass Destruction: Assessing the Risks', August 1993, <https://ota.fas.org/reports/9341.pdf>, accessed 6 June 2025.
12. Athanassios Giannis, 'Nitrogen Oxides, Explosives, and Angina Pectoris', in Athanassios Giannis, *Natural Compounds Enabled Therapies* (Cham: Springer, 2025), pp. 71–84.
13. Chengtao Wang et al., 'Fischer–Tropsch Synthesis to Olefins Boosted by MFI Zeolite Nanosheets', *Nature Nanotechnology* (Vol. 17, No. 6, 2022), pp. 714–20.
14. Steven S C Chuang, 'Conversion of Syngas to Fuels', in Wei-Yin Chen et al. (eds), *Handbook of Climate Change Mitigation* (Cham: Springer, 2012), pp. 1605–21.

Figure 1: A Sankey Diagram Depicting Chemical Products Obtained by Downstream and Upstream Chemical Production from Fossil Fuel Feedstocks



Source: Peter G Levi and Jonathan M Cullen, ‘Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products’, *Environmental Science & Technology* (Vol. 52, No. 4, 2018), pp. 1725–34.

Some reactions in figures 2–6 are implied and omitted for brevity. Similarly, some reactants (which have had their production routes described elsewhere in the paper) are omitted for clarity.

Processing of Minerals and Brine

Although organic chemicals begin their lifecycle as fossil fuel feedstocks, most inorganic chemicals begin their life as ores and minerals. North Korea has reserves of more than 200 mineral types, many of which are important sources of inorganic precursors required to produce chemical warfare agents (CWAs).[15]

Brine

The production of chlorine and sodium hydroxide by the electrolysis of brine is commonly referred to as the ‘chlor-alkali process’. In 2022, around 100-million tonnes of chlorine were produced worldwide using this process.[16] Chlorine is a key raw material in the production of CWAs as a chlorinating agent in the production of vesicants and important precursors for nerve agents.[17]

15. Choi Kyung-soo, ‘The Mining Industry of North Korea’, Nautilus Institute for Security and Sustainability, NAPSNet Special Report, 4 August 2011, <https://nautilus.org/napsnet/napsnet-special-reports/the-mining-industry-of-north-korea/#axzz2TAJOiCxP>, accessed 6 June 2025.
16. Statista, ‘Market Volume of Chlorine Worldwide from 2015 to 2022, with a Forecast for 2023 to 2030 (in Million Metric Tons)’, 23 May 2025, <https://www.statista.com/statistics/1310477/chlorine-market-volume-worldwide/>, accessed 17 June 2025.
17. R M Black and J M Harrison, ‘The Chemistry of Organophosphorus Chemical Warfare Agents’, in Frank R Hartley (ed.), *The Chemistry of Organophosphorus Compounds: Ter- and Quinque-Valent Phosphorus Acids and Their Derivatives* (Hoboken, NJ: John Wiley and Sons, 1996), pp. 781–840.

Phosphorites (Apatite)

Apatite is the primary mineral in which phosphates are found.[18] It is mined around the world to produce phosphate-based fertiliser. Apatite deposits are common in North Korea and there are many apatite mines. Apatite can be easily converted to white phosphorus by heating in a furnace;[19] the phosphorus can subsequently be converted to phosphorus trichloride by reacting with chlorine.[20] Phosphorus trichloride is a key precursor in the chemistry of CWAs, not only as an important building block for organophosphorus chemicals, but also as a chlorinating agent.

During the preparation of phosphate-based fertilisers from apatite and fluorapatite, hexafluorosilicic acid is produced as a by-product. Neutralisation of hexafluorosilicic with sodium hydroxide gives sodium fluoride.[21] Apatite (including fluorapatite) deposits are common on the Korean Peninsula, and there are several apatite mines in North Korea, notably the Sonam Mine in Cholsan County.[22]

Mirabilite

Mirabilite is a hydrous sodium mineral which is often found in parts of the Korean Peninsula.[23] Mirabilite can be used in the production of sodium sulfide by the carbothermic reduction of sodium sulfate.[24] Sodium sulfide is an important precursor in the synthesis of sulfur mustard, and while not included in the CWC's Annex on Chemicals,[25] is on the AG's list of controlled precursors.[26]

Arsenopyrite

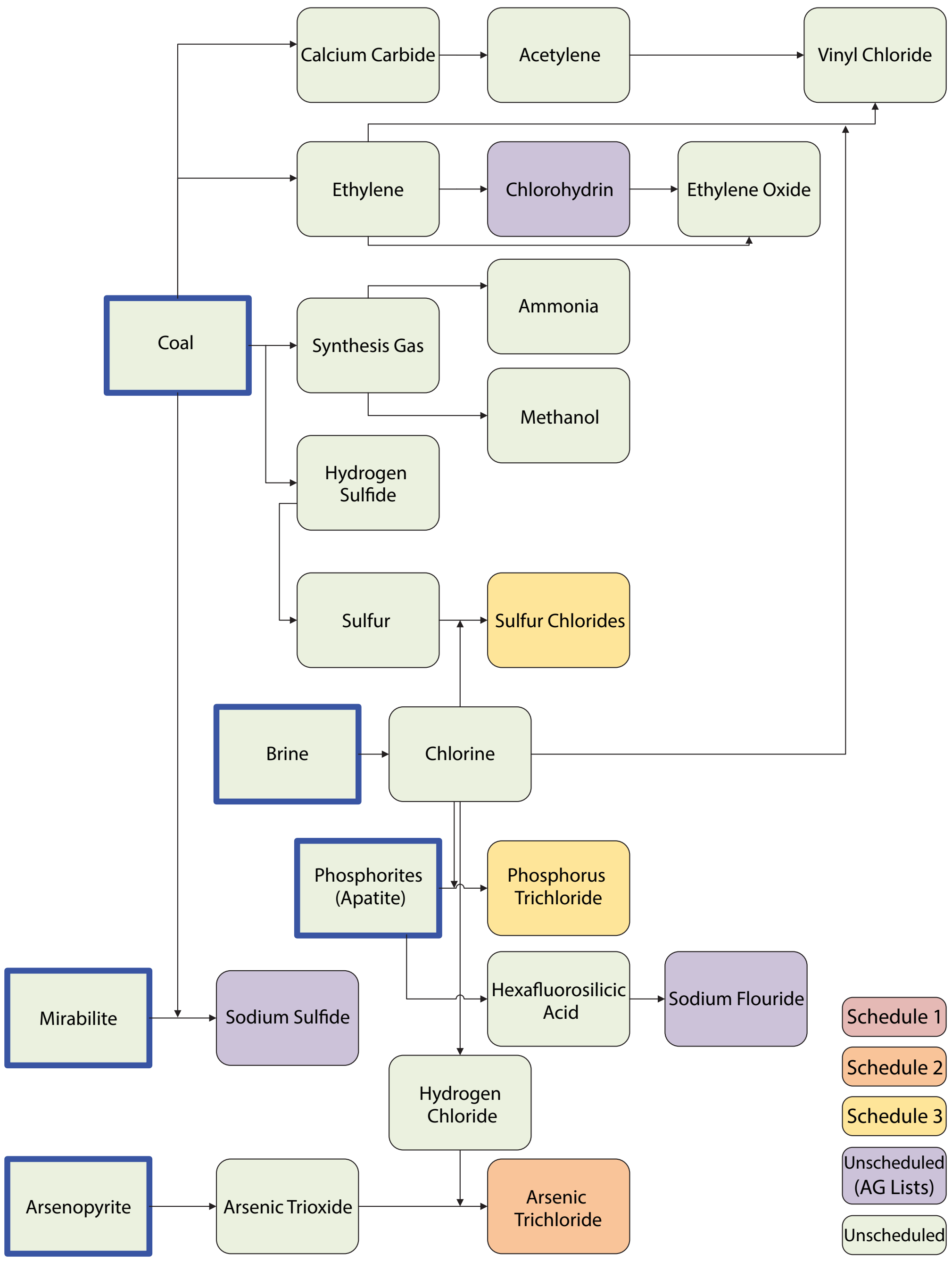
Arsenic is a critical element for lewisite production, and can be found in deposits of arsenopyrite (FeAsS), a sulfide mineral containing arsenic, iron and sulfur.[27] There are many deposits on the Korean Peninsula, and it is mined at the Sangnong mine in North Korea.[28] The key precursor for lewisite is arsenic trichloride, which can be easily produced by the treatment of arsenic trioxide with hydrogen chloride.[29]

18. Zhai Mingguo et al., 'The Geology of North Korea: An Overview', *Earth-Science Reviews* (Vol. 194, 2019), pp. 57–96.
19. Richard E Threlfall, *The Story of 100 years of Phosphorus Making: 1851–1951* (Oldbury: Albright and Wilson Ltd, 1951).
20. Michael B Geeson and Christopher C Cummins, 'Let's Make White Phosphorus Obsolete', *ACS Central Science* (Vol. 6, No. 6, 2020), pp. 848–60.
21. Jean Aigueperse et al., 'Fluorine Compounds, Inorganic', in Fritz Ullmann, *Ullmann's Encyclopedia of Industrial Chemistry* (Weinheim: Wiley-VCH Verlag GmbH & Co, 2022).
22. Choi, 'The Mining Industry of North Korea'; Mindat.org, 'Apatite from Sonam Mine, Posan-dong, Paengnang-myon, Cholsan County, North Pyongan Province, North Korea', <https://www.mindat.org/locentry-547122.html>, accessed 6 June 2025.
23. In Sung Paik et al., 'Traces of Evaporites in Upper Cretaceous Lacustrine Deposits of Korea: Origin and Paleoenvironmental Implications', *Journal of Asian Earth Sciences* (Vol. 30, No. 1, 2007), pp. 93–107.
24. Arnold Frederick Holleman and Nils Wiberg, *Inorganic Chemistry* (San Diego, CA: Academic Press, 2001), p. 622.
25. OPCW, 'Annex on Chemicals', <https://www.opcw.org/chemical-weapons-convention/annexes/annex-chemicals/annex-chemicals>, accessed 30 June 2025.
26. The Australia Group, 'Export Control List: Chemical Weapons Precursors', 21 November 2023, <https://www.dfat.gov.au/publications/minisite/theaustraliagroupnet/site/en/precursors.html>, accessed 6 June 2025.
27. L Szinicz, 'Toxicology of Chemical Warfare Agents', in Ramesh C Gupta (ed.), *Handbook of Toxicology of Chemical Warfare Agents*, Third Edition (where: Academic Press, 2025), pp. 423–46.
28. Mindat.org, 'Arsenopyrite from Sangnong Mine, Sangnong-ni, Suha-myon, Tanchon City, South Hamgyong Province, North Korea', <https://www.mindat.org/locentry-456410.html>, accessed 6 June 2025.
29. Erhard Sirtl and Josef Paulik, 'Method of Producing Highly Pure Arsenic Trichloride', United States, Patent No. US3551099A, 1970, Google Patents, <https:// patents.google.com/patent/US3551099A/en>, accessed 30 June 2025; Sabina C Grund, Kunibert Hanusch and Hans Uwe Wolf, 'Arsenic and Arsenic Compounds', in Ullmann, *Ullmann's Encyclopedia of Industrial Chemistry*.

Arsenic trioxide is released when the mineral arsenopyrite is heated,[30] and incidentally is used to treat acute promyelocytic leukaemia and as such is included on the WHO Model List of Essential Medicines.[31]

Some of the most important industrial processes to produce the feedstock chemicals needed for the main CWAs are summarised in Figure 2.

Figure 2: Important Upstream and Downstream Processing of Coal to Produce Key Precursors for CW Production



Source: The Project Anthracite Team.
Note: Naturally occurring materials and minerals are represented by the blue rectangles.

30. *Ibid*.
31. World Health Organization, 'Model List of Essential Medicines: 22nd List, 2021', 30 September 2021, <https://www.who.int/publications/i/item/WHO-MHP-HPS-EML-2021.02>, accessed 26 June 2025.

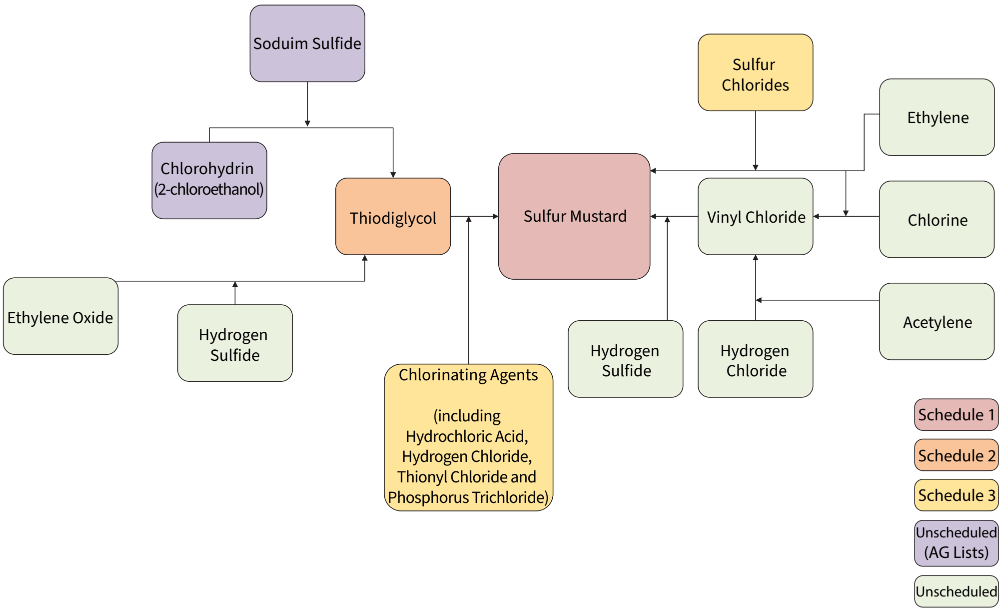
Production Routes of Chemical Warfare Agents

Sulfur Mustard (HD)

Sulfur mustard is a CWA that was first used in the First World War, and has most recently been used by the Islamic State in Syria.[32] Classed as a vesicant (blister agent), it causes both severe chemical burns on contact with skin, eyes and respiratory tissues and significant chronic health issues, including a predisposition to cancer.

Chemically, sulfur mustard or bis(2-chloroethyl)sulfide is a chlorinated organosulfur compound with the formula $(ClCH_2CH_2)_2S$. Figure 3 shows its most common routes of production.

Figure 3: The Most Common Production Routes for Sulfur Mustard



Source: The Project Anthracite Team.

32. Organisation for the Prohibition of Chemical Weapons (OPCW), 'Fourth Report by the OPCW Investigation and Identification Team Pursuant to Paragraph 10 of Decision C-SS-4/DEC.3 "Addressing the Threat from Chemical Weapons Use" Marea (Syrian Arab Republic) – 1 September 2015', S/2255/2024, 22 February 2024, <https://www.opcw.org/sites/default/files/documents/2024/02/s-2255-2024%28e%29.pdf>, accessed 6 June 2025.

Levenstein Route

Sulfur mustard can be prepared by treating ethylene with sulfur monochloride (disulfur dichloride, CASRN 10025-67-9).[33] Other similar routes from ethylene using sulfur chlorides are also reported in literature.[34] The utility of sulfur monochloride as a precursor in the production of CWs is reflected by its inclusion in Schedule 3 (3.B.12) of the CWC's Annex on Chemicals.[35]

Meyer Process

Thiodiglycol is one of the most useful precursors for the synthesis of sulfur mustard, and as can be seen in Figure 3, many of the routes outlined proceed via thiodiglycol. It is a Schedule 2 (2.B.13) in the CWC's Annex on Chemicals[36] and can be converted efficiently to sulfur mustard in high yield and purity using a range of chlorinating agents, via the process reported by Meyer.[37] Similar synthetic methods are reported in literature using concentrated hydrochloric acid, hydrogen chloride gas, thionyl chloride, phosphorus trichloride or sulfur chlorides.[38]

Ethylene Oxide Route

Ethylene oxide has widespread industrial uses and can also be a useful precursor to produce sulfur mustard via thiodiglycol. Ethylene oxide can be converted to thiodiglycol by treating with hydrogen sulfide – several methods are published in patents and literature.[39]

Chlorohydrin Route

Ethylene is readily converted into chlorohydrin (2-chloroethanol) by treating it with hypochlorous acid.[40] Chlorohydrin can subsequently be converted to thiodiglycol by treatment with sodium sulfide. Although chlorohydrin is not included in the CWC Annex on Chemicals, it is included in the Australia Group's (AG) control list for chemical weapons precursors.

33. R Malhotra, K Ganesan, K Sugendran and R V Swamy, 'Chemistry and Toxicology of Sulphur Mustard: A Review', *Defence Science Journal* (Vol. 49, No. 2, 1999), pp. 97–116.
34. C Despretz, 'Sur les propriétés du gaz sulfureux chloré' ['On the Properties of Chlorinated Sulfur Dioxide'], *Annales de chimie et de physique* (Vol. 21, 1822), p. 428; J B Contant, E B Hartshorn and G O Richardson, 'The Mechanism of the Reaction Between Ethylene and Sulfur Chloride', *Journal of the American Chemical Society*, (Vol. 42, No. 585, 1920), pp. 585–95; Reynold C Fuson and William E Parham, 'Process', *Journal of Organic Chemistry* (Vol. 11, 1946), p. 499.
35. OPCW, 'Annex on Chemicals: Schedule 3', <https://www.opcw.org/chemical-weapons-convention/annexes/annex-chemicals/schedule-3>, accessed 6 June 2025.
36. OPCW, 'Annex on Chemicals: Schedule 2', <https://www.opcw.org/chemical-weapons-convention/annexes/annex-chemicals/schedule-2>, accessed 6 June 2025.
37. Victor Meyer, 'Uber thiodiglykol Verbindungen. Berichte der Deutschen Chemischer Gesellschaft' ['About Thiodiglycol Compounds. Reports of the German Checmical Society'], German Chemical Society, (Vol. xix, No. 3, 1886), pp. 3259–65.
38. Hans Thacher Clarke, 'Synthesis of 4-alkyl-1,4-thiazans', *Journal of the Chemical Society* (Vol. 101, 1912), pp. 1583–90; W Steinkoff, J Herold and J Stohr, 'Uber das Ttiodiglykolchlorid und einige abkommlinge desselben' ['On Thiodiglycol Chloride and Some Derivatives Thereof'], *Chemische Berichte* (Vol. 53, 1920), pp. 1007–12; S J Lundin, *Verification of Dual-Use Chemicals Under the Chemical Weapon Convention: The Case of Thiodiglycol* (Oxford: Oxford University Press, 1991), p. 4.
39. Alexis Tchitchibabine, *Procédé d'obtention des thioéthylèneglycols [Process for Obtaining Thioethylene Glycols]* (French Patent No. FR769216, 1934), French Ministry of Commerce and Industry, <https://data.inpi.fr/brevets/FR769216?q=#FR769216>, accessed 30 June 2025; Malhotra et al., 'Chemistry and Toxicology of Sulphur Mustard'.
40. Gordon Y T Liu et al., 'Chlorohydrins', in Ullmann, *Ullmann's Encyclopedia of Industrial Chemistry*.

Vinyl Chloride Route

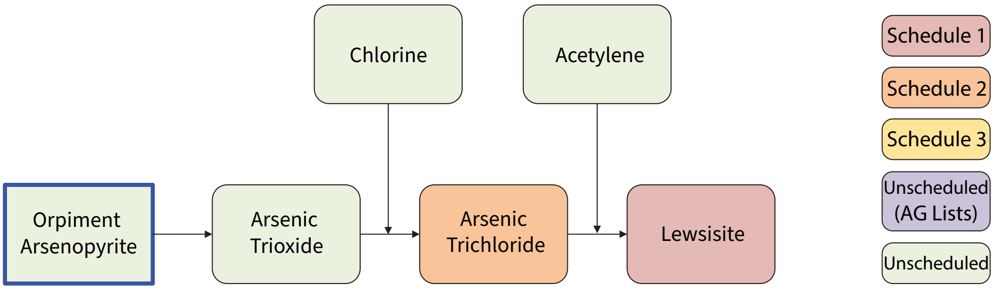
Another notable production method for sulfur mustard was reported by Dupont chemists in 1945,[41] where vinyl chloride was treated with hydrogen sulfide to give sulfur mustard.

Lewisite

Lewisite (or lewisite 1) is an organoarsenical compound (2-chlorovinyldichloroarsine) produced by the US, Japan, Germany[42] and the former Soviet Union[43] for use as a CWA. It is a vesicant (blister agent) and included on Schedule 1 of the CWC's Annex on Chemicals.[44]

It is produced by a catalytically mediated reaction of arsenic trichloride with acetylene, which produces lewisite in <85% yield, with two significant impurities which are themselves vesicants. They are included in Schedule 1 of the CWC's Annex on Chemicals: lewisite 2 (bis(2-chlorovinyl) chloroarsine) and lewisite 3 (tris(2-chlorovinyl) arsine).[45]

Figure 4: The Most Common Production Route for Lewisite



Source: The Project Anthracite Team.
Note: Naturally occurring materials and minerals are represented by the blue rectangles.

Nitrogen Mustards

The first production of nitrogen mustards occurred in the 1920s, when they were looked at as potential CWAs.[46] Like sulfur mustard and Lewisite, nitrogen mustards are vesicants and their chemical structure shares similarities with sulfur mustard. They are one of the few CW agents which have a legitimate use; HN2 was used as one of the first chemotherapeutic agents for the treatment of cancer and is still used today in oncology.[47]

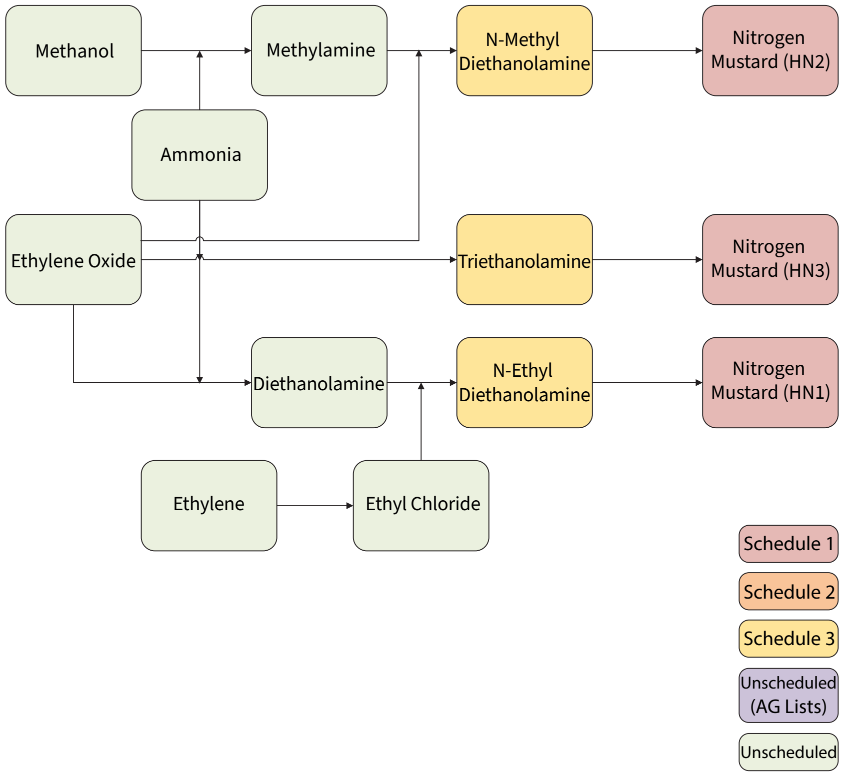
41. Malhotra et al., 'Chemistry and Toxicology of Sulphur Mustard'.
42. Jon Mitchell, 'A Drop in the Ocean: The Sea-Dumping of Chemical Weapons in Okinawa', *Europe solidaire sans frontières*, 27 July 2013.
43. Alicia Sanders-Zakre, 'Russia Destroys Last Chemical Weapons', *Arms Control Today*, November 2017, <https://www.armscontrol.org/act/2017-11/news/russia-destroys-last-chemical-weapons>, accessed 6 June 2025.
44. OPCW, 'Annex on Chemicals: Schedule 1', <https://www.opcw.org/chemical-weapons-convention/annexes/annex-chemicals/schedule-1>, accessed 6 June 2025.
45. *Ibid*.
46. Center for Disease Control and Prevention, US Department of Health & Human Services, 'Nitrogen Mustard Chemical Factsheet', 6 September 2024, <https://emergency.cdc.gov/agent/nitrogenmustard/basics/facts.asp>, accessed 6 June 2025.
47. Martin S Highley et al., 'The Nitrogen Mustards', *Pharmacological Reviews* (Vol. 74, No. 3, 2022), pp. 552–99; Jianan Sun et al., 'Design and Synthesis of Chromone-Nitrogen Mustard Derivatives and Evaluation of Anti-Breast Cancer

The synthesis of nitrogen mustards is relatively straightforward and can be obtained from chlorination of the corresponding ethanolamine precursor, for example, triethanolamine can be converted to nitrogen mustard (HN3) by the treatment of triethanolamine with thionyl chloride.

The ethanolamine precursors are all included on Schedule 3 of the CWC's Annex on Chemicals.[48] Despite being easily converted to Schedule 1 CW agents, the ethanolamines find wide industrial applications. Indeed, triethanolamine, the key precursor for nitrogen mustard (HN3), has multiple industrial uses and is common in most homes as it is included in the formulation of many personal care products. As such it has the highest trading volume of all the scheduled chemicals in the CWC's Annex on Chemicals.[49] As a result, it was placed in Schedule 3 rather than Schedule 2 of the Annex.

Production of ethanolamines is relatively simple. For instance, triethanolamine can be produced on an industrial scale by the reaction of ethylene oxide with aqueous ammonia.[50]

Figure 5: The Most Common Production Routes for Nitrogen Mustards



Source: The Project Anthracite Team.

Activity', Journal of Enzyme Inhibition and Medical Chemistry (Vol. 37, No. 1, 2022), pp. 431-44; OPCW, 'Annex on Chemicals: Schedule 1'.

48. OPCW, 'Annex on Chemicals: Schedule 3'.
49. OPCW, 'Most Traded Scheduled Chemicals', 2022, <https://www.opcw.org/sites/default/files/documents/2021/12/Most%20Traded%20Scheduled%20Chemicals%202022%20%28MTSC%29.pdf> accessed 17 June 2025.
50. World Health Organization International Agency for Research on Cancer, 'Triethanolamine', *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, (Vol 77, 2000), p. 381–401.

Nerve Agents

Organophosphorus nerve agents are a class of highly toxic chemical compounds developed for warfare that disrupt the normal functioning of the nervous system, with potentially fatal consequences. Nerve agents interfere with the transmission of nerve impulses by inhibiting the enzyme acetylcholinesterase, which is essential for muscle control. They were discovered during pesticide research by Germany in the period immediately before the Second World War.[51]

Tabun (GA)
Tabun (GA) is the simplest of the G-series nerve agents to synthesise due to the availability of a range of suitable precursors. As is shown in Figure 6, it can be produced from either phosphorus trichloride or phosphorus oxychloride as the principal phosphorus containing starting materials (both are included in Schedule 3 of the Annex).[52] As shown in Figure 2, phosphorus trichloride can be readily obtained from apatite by the treatment of white phosphorus with chlorine.[53]

Phosphorus oxychloride is the most convenient precursor for Tabun and can be obtained by chlorinating phosphorus trichloride further to phosphorus pentachloride, which is subsequently reacted with phosphorus pentoxide (to give phosphorus oxychloride).[54]

Dimethylamine (DMA), which is required for the synthesis of Tabun, can be readily obtained from ammonia on an industrial scale through a catalytic reaction with methanol at elevated temperatures and high pressure.[55]

Sarin (GB), Soman (GD) and Cyclosarin (GF)
The manufacturing processes to produce Sarin (GB), Soman (GD) and Cyclosarin (GF) nerve agents are complicated by the requirement to introduce a phosphorus-carbon bond, which results in additional synthetic steps and precursors.[56]

A key precursor in the production of these G-series nerve agents is methylphosphonyl dichloride (DC), which can be prepared in a multistep synthesis from phosphorus trichloride.[57] Methylphosphonic dichloride, on reaction with hydrogen fluoride, can be converted to the Schedule 1 precursor methylphosphonic difluoride (DF), which can subsequently easily be converted to the corresponding G-series nerve agent by treatment with the corresponding alcohol, as is shown in Figure 6.

51. Sarah Everts, 'The Nazi Origins of Deadly Nerve Gases', *Chemical & Engineering News*, 17 October 2016, <https://cen.acs.org/articles/94/i41/Nazi-origins-deadly-nerve-gases.html>, accessed 30 June 2025.
52. OPCW, 'Annex on Chemicals: Schedule 3'.
53. N N Greenwood and A Earnshaw, *Chemistry of the Elements*, Second edition (Oxford: Butterworth-Heinemann, 1997).
54. Gerhard Bettermann et al., 'Phosphorus Compounds, Inorganic', in Ullmann, *Ullmann's Encyclopedia of Industrial Chemistry*.
55. D Corbin, R Schwarz and G C Sonnichsen, 'Methylamines Synthesis: A Review', *Catalysis Today* (Vol. 37, 1997), pp. 71–102.
56. Black and Harrison, 'The Chemistry of Organophosphorus Chemical Warfare Agents'.
57. Robert Engel, *The Synthesis of Carbon-Phosphorus Bonds*, Second edition (Boca Raton, FL: CRC Press, 2003).

Both the Schedule 2 methylphosphonyl dichloride and the Schedule 1 methylphosphonyl difluoride are key precursors for the synthesis of G-agents. While the difluoride has no other use other than the synthesis of G-agents (hence its inclusion on Schedule 1), the dichloride can be used for the synthesis of some pesticides.

V-Agent Production

VX[58] is the best known of the V-series nerve agents. Originating from pesticide research at ICI, it was developed further at Porton Down in England during the early 1950s.[59]

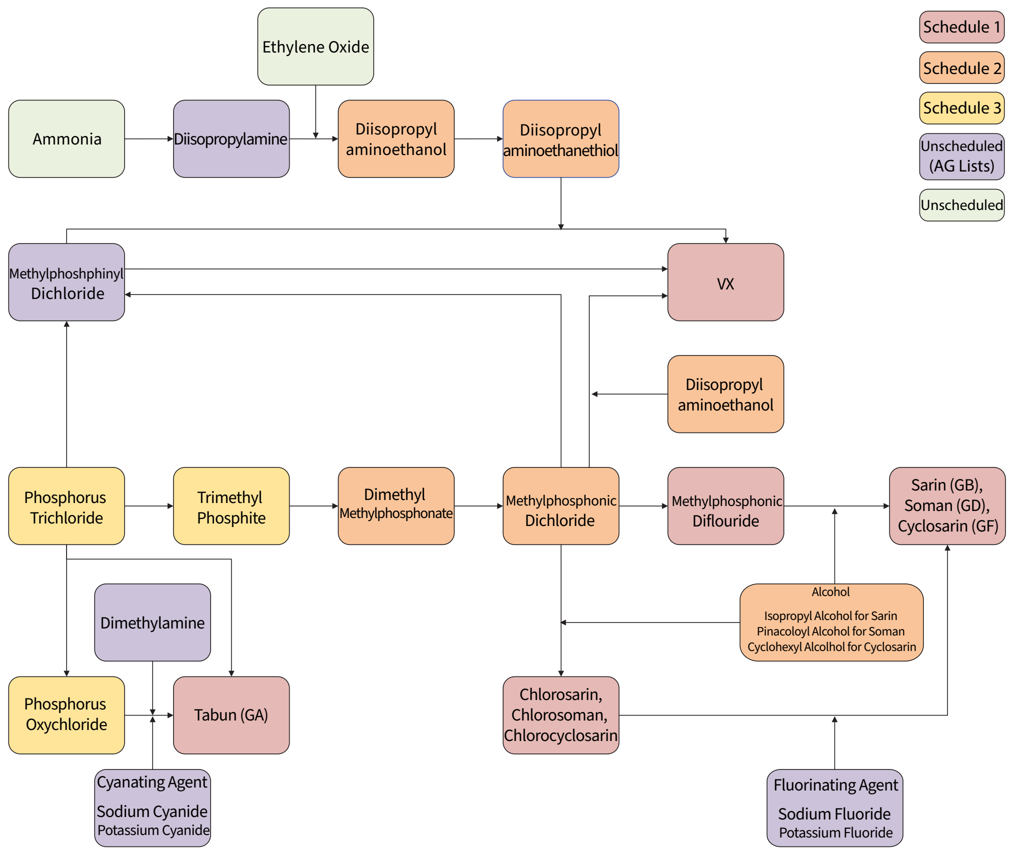
Almost all reported routes to produce V-agents depend on the availability of methylphosponous dichloride, which can be prepared by the methylation of phosporus trichloride.

Methylphosponous dichloride undergoes alcoholysis with ethanol to form the corresponding phosponite which is subsequently transesterified with N,N-diisopropylaminoethanol to produce the Schedule 1 mixed phosphonite O-(2-Diisopropylaminoethyl) O'-ethyl methylphosphonite, commonly referred to as QL, which is a key precursor for the binary VX.[60]

The required N,N-diisopropylaminoethanol can be readily produced from ammonia and proceeds via diisopropylamine,[61] as shown in Figure 6.

58. Black and Harrison, 'The Chemistry of Organophosphorus Chemical Warfare Agents'.
59. Toni Leikas, 'VX 1952', Bertin Environics, 11 November 2020, <https://www.environics.fi/blog/vx-1952/>, accessed 1 July 2025.
60. US Army, 'QL (Diisopropyl Aminoethylmethyl Phosphonite)', RCMD Factsheet, <https://www.cma.army.mil/ql-diisopropyl-aminoethylmethyl-phosphonite/>, accessed 6 June 2025.
61. Karl Löffler, 'Über eine neue Bildungsweise primärer und sekundärer Amine aus Ketonen' ['About a New Way of Forming Primary and Secondary Amines from Ketones'], *Berichte der Deutschen Chemischen Gesellschaft* (Vol. 43, No. 21, 1910), pp. 2031–35.

Figure 6: The Most Common Production Routes for Nerve Agents



Source: The Project Anthracite Team.

Conclusions

This paper has explored the key basic raw materials, processes and precursors required to support a CW programme. It has specifically considered upstream and downstream chemical processing and assessed their relevance to subsequent precursor and CWA production.

An earlier study assessed that North Korea has between 2,500 and 5,000 tons of legacy CWs,[62] but the study did not determine if they were produced as part of an indigenous production capability.

The chemical processes outlined in this paper support an assessment that North Korea could gain access to an important toolkit of precursors from basic industrial process that originate either from North Korea's vast coal resources or its mineral deposits, and such basic industrial processes are essential for a functioning chemical industry.

62. John V Parachini, 'Assessing North Korea's Chemical and Biological Weapons Capabilities and Prioritizing Countermeasures', RAND, 17 January 2018, <https://www.rand.org/pubs/testimonies/CT486.html>, accessed 10 July 2025.

The chemistry indicates a strong likelihood that North Korea has access to the key precursors and chemical feedstocks that would allow sustained production of sulfur mustard. Figure 2 highlights how many of these key precursors can be readily obtained from downstream processing of coal and other mineral deposits.

Similarly, the key precursor and chemical feedstocks required for the sustained production of nitrogen mustards and lewisite can also be readily obtained from downstream processing of coal and other mineral deposits.

This paper also identifies a reasonable likelihood that North Korea has all the key industrial feedstocks and raw materials to produce the precursors required to support the production of G-series and V-series agents. The significant requirement for more complex organic chemicals means that a mature chemical industry would be required, of which there is only limited evidence. As such, subsequent OSINT work will be required to make a robust assessment of North Korea's capability to produce G-series and V-series agents.

This paper makes a convincing case for exploring open-source research, trade data, remote sensing and optical imagery to map the industrial processes and production routes described in this paper to sites in North Korea. This will allow for a robust, multisource assessment of North Korea's chemical industry capabilities, and to what extend they could support a CW programme.

About the Authors

This report was authored by members of the RUSI Project Anthracite Team, who provide varying levels of input to the reports produced by the project.[63] The team includes the following:

Lennie Phillips is Senior Research Fellow, Chemical Weapons in RUSI's Proliferation and Nuclear Policy research team.

Sean Corbett is a Senior Associate Fellow at RUSI.

David Crouch is a Senior Associate Fellow at RUSI.

Jack Crawford is a Research Fellow in RUSI's Proliferation and Nuclear Policy research team.

63. RUSI, 'Project Anthracite'.

Gareth Williams is a Senior Associate Fellow with RUSI's Proliferation and Nuclear Policy research team.

Hailey Wingo is a Researcher at VERTIC.

Nathan Hunt is an independent contractor.

Stephen Mercado is an independent contractor.

Yuseong Choi is an independent contractor.

Gianguiseppe Pili is an Associate Fellow at RUSI and an Assistant Professor in the Intelligence Analysis Program at James Madison University.

Samuel Rooker is a student in the Intelligence Analysis Program of James Madison University.

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