

March 2026

# HIGH-EXPLOSIVES TESTING IN NUCLEAR WEAPONS PROGRAMMES

*Elin Bergner and Sarah Laderman*



**OPEN NUCLEAR  
NETWORK**

A PAX sapiens programme





Open Nuclear Network (ONN), a PAX *sapiens* programme  
Argentinierstrasse 21/9, 1040 Vienna, Austria  
[www.opennuclear.org](http://www.opennuclear.org)



#### Produced for:

Verification Research, Training and Information Centre (VERTIC)  
244–254 Cambridge Heath Road, London E2 9DA, United Kingdom  
[www.vertic.org](http://www.vertic.org)

#### Acknowledgements

The authors would like to thank Marcy R. Fowler, Jaewoo Shin, Raymond Gough, Hugh Chalmers and other experts who prefer not to be named for their reviews. The authors are grateful to the entire ONN team for their support in this work, and to Andreas Persbo for project conception and counsel.



This work was funded as part of a joint project between VERTIC, the James Martin Center for Nonproliferation Studies (CNS) and the Royal United Services Institute (RUSI), which was funded by Global Affairs Canada.



The authors gratefully acknowledge the support of the PAX *sapiens* Foundation, including their assistance with copy-editing and design of this report.

# TABLE OF CONTENTS

<b>Introduction</b>	3
<b>What are high explosives?</b>	4
<b>How are high explosives used?</b>	5
Industry	5
Scientific research and materials diagnostics	5
Conventional military applications	6
<b>How are high explosives used in nuclear weapons?</b>	6
Material composition	7
<b>Why do high explosives need to be tested?</b>	9
Safety in handling, storage and transport	9
Performance validation	9
Material response under extreme conditions	9
Simulation and model validation	10
Production and quality control	10
Ageing and stability assessment	10
Supporting modernisation	11
<b>How are high explosives tested and involved in nuclear testing?</b>	12
Blast tube testing	12
Hydrodynamic and subcritical tests	13
Unique materials, infrastructure and equipment	13
<b>Conclusion</b>	17
<b>Annex A. Control list items (diagnostic equipment)</b>	18

# Introduction

High explosives (HEs) are a foundational component of implosion-type nuclear weapons, enabling the precise implosion required to initiate a nuclear chain reaction. HEs represent a significant step in transforming fissile material into a weaponised device. Although gun-type fission designs can be developed without HE implosion systems, HE-based implosion is central to the compact and efficient weapon designs that underpin most modern arsenals. Despite this, HE testing has received limited systematic attention in open-source analysis.

As part of a larger project funded by Global Affairs Canada, the Verification Research, Training and Information Centre (VERTIC) in cooperation with Open Nuclear Network (ONN), a PAX *sapiens* programme, completed open-source assessments of the Democratic People's Republic of Korea's (DPRK's) nuclear capabilities. These assessments covered: uranium enrichment; operation of the Experimental Light Water Reactor at Yongbyon; and weaponisation facilities and capabilities (to include pit production, beryllium production and HE testing).<sup>1</sup> This paper<sup>2</sup> seeks to ground analysis on the DPRK's and other specific countries' HE testing programmes.<sup>3</sup>

This paper draws on open-source documentation, primarily from US national laboratories and federal testing programmes, as these provide the most detailed publicly available information. This research examines what HEs are; how they are used (both generally and in nuclear weapons); how and why they are tested; and the unique signatures of HE testing. By providing a general overview of HEs and their testing regimes, this paper seeks to aid other open-source researchers by providing a baseline level of information that can be used to analyse states' nuclear weapons programmes, an area that is largely under-researched.

This paper focuses on HE testing rather than production or manufacturing, as testing reflects a state's ability to characterise, qualify and integrate HEs into weapons systems, rather than merely to acquire or synthesise energetic materials. While testing does not indicate production scale or directly reveal the sophistication of an HE formulation, it does provide insight into a state's capacity to generate the experimental data needed to validate models, assess performance and support reliable weaponisation. For the purposes of this analysis, HE testing therefore offers a more meaningful benchmark of weaponisation capability than production alone.

1 Current publications from this project can be found at: [https://linktr.ee/vertic\\_onn\\_project](https://linktr.ee/vertic_onn_project).

2 Parts of this text were drafted using the AI tool ChatGPT. The work was edited, expanded upon or changed by the authors for accuracy, clarity and consistency.

3 The full comparative analysis can be found at: <https://storymaps.arcgis.com/collections/debd98f0c8f9424398488eaf1eeab1bb>.

# What are high explosives?

**HEs are chemical compounds or mixtures that, when initiated, release energy rapidly and intensely through a detonation wave travelling faster than the speed of sound in that medium, which generates immense heat and pressure within microseconds.**<sup>4</sup>

This shockwave delivers sufficient energy to compress and deform materials, causing them to temporarily exhibit fluid-like behaviour under extreme stress.<sup>5</sup> In contrast to HEs which undergo detonation, low explosives (such as black powder or gunpowder) undergo deflagration – a slower combustion process that propagates at subsonic speeds.<sup>6</sup>

HEs are broadly classified into primary explosives and secondary explosives. Primary explosives, or “primaries,” are energetic materials characterised by exceptionally high sensitivity to impact, friction, electrostatic discharge, heat and shock, and they reach detonation almost immediately upon such initiation.<sup>7</sup> Less powerful than secondary explosives, primaries' principal role is to function as the initiating component of a secondary main charge. Secondary explosives, or “secondaries,” are comparatively insensitive to stimuli but have overall greater energy release and are therefore used in larger quantities as the main charge.

Understanding this distinction helps explain how HEs deliver their effects. Whether a primary or a secondary is involved, detonation always produces extremely high temperatures and pressures very quickly. Because of this, HEs are especially valuable in applications requiring precise and intense energy delivery, such as controlled shock physics experiments and studies of material behaviour under extreme conditions. In nuclear weapons, these explosive characteristics are critical for achieving the precisely timed and symmetric implosion of a fissile pit, which is an essential prerequisite for initiating a nuclear chain reaction in implosion-type designs.<sup>8</sup>

4 Explosives Regulatory Division, *Type E High Explosives*, ERD-G03-01 (Natural Resources Canada, 2014), <https://natural-resources.canada.ca/minerals-mining/explosives-fireworks-ammunition/explosives/type-e-high-explosives>; Jill Gibson, “Sparking Success,” Los Alamos National Library, 9 December 2024, <https://www.lanl.gov/media/publications/national-security-science/1224-sparking-success>.

5 Allan Chen, “Hydrodynamic Experiments Support Stockpile Stewardship,” *Science & Technology Review*, December 2021, <https://str.lnl.gov/past-issues/novemberdecember-2021/hydrodynamic-experiments-support-stockpile-stewardship>.

6 Gibson, “Sparking Success,” See also the appendix of definitions in: Explosives Regulatory Division, *Type E High Explosives*. Note that Type E explosives are not the category usually used in nuclear weapons.

7 Jesse J. Sabatini and Karl D. Oyler, “Recent Advances in the Synthesis of High Explosive Materials,” *Crystals* 6, no. 1 (2016): 5, <https://doi.org/10.3390/cryst6010005>.

8 Early gun-type nuclear weapons, such as the *Little Boy*, relied on conventional propellants to force two pieces of nuclear material together rather than on HE implosion. This approach could only be used with highly enriched uranium, as plutonium's spontaneous fission properties make plutonium impractical in this design.

# How are high explosives used?

Beyond nuclear applications, HEs are used in industry, scientific research and conventional military applications.

## Industry

HEs are crucial for multiple civil and industrial sectors due to their ability to deliver controlled, high-energy force. In the mining and quarrying industries, their efficiency in fracturing rock formations facilitates the extraction of minerals.<sup>9</sup> The oil and gas industry relies on specialised HE devices to pierce well casings during drilling and extraction operations.<sup>10</sup> Similarly, HEs are used in controlled demolition blasting for urban redevelopment and other civil construction purposes.<sup>11</sup>



## Scientific research and materials diagnostics

HEs allow researchers to recreate extreme environments that are otherwise unachievable in a lab setting to study material behaviour under conditions of high pressure, temperature and variable strain over time.<sup>12</sup> These explosive-driven experiments are critical in generating shockwaves used to investigate how materials change internally under extreme pressure and heat; assess structural integrity; and determine the mechanical properties of metals, ceramics and composite materials.<sup>13</sup> Applications include planetary science<sup>14</sup> as well as materials engineering, where HEs help validate equations of state for advanced materials.



## Conventional military applications

HEs are central to the operation of a wide array of conventional weapons systems and remain the primary means by which modern military munitions achieve destructive effect.<sup>15</sup> Most importantly, HEs are employed as the principal explosive fill in a wide range of weapons systems, including artillery shells, mortar rounds, aerial bombs and missile warheads.<sup>16</sup> Secondly, their high detonation velocities and substantial energy release make them particularly effective for armour penetration. In shaped charges, HEs are used to collapse a metal liner into a high-velocity jet capable of penetrating steel or reinforced concrete, rendering them especially effective against armoured vehicles and fortified structures.<sup>17</sup> HEs are also used in spacecraft and space launch systems, including in launcher operation, stage separation, thrust termination and the separation of external tanks or payload structures.<sup>18</sup>



# How are high explosives used in nuclear weapons?

HEs play a fundamental role in both the initiation and functional design of modern fission-type nuclear weapons and in the primary stage of thermonuclear weapons. Within this context, HEs perform a sequence of tightly integrated functions within the implosion system. First, they are incorporated into small electrical devices called detonators, which produce an initial shock to initiate the detonation sequence. Second, the initiating shock from the detonator activates a booster charge of HE, which amplifies and transmits the reaction with sufficient energy to initiate the detonation of the main HE charge.<sup>19</sup> Finally, this main HE charge is arranged symmetrically around a subcritical core (or “pit”) of fissile material (typically weapons-grade plutonium or highly enriched uranium). When detonated, the HE causes the pit to compress, leading to

15 For a comprehensive history of HE use in conventional military applications, see: Headquarters, Department Of The Army, *Military Explosives*, Department Of The Army Technical Manual TM 9-1300-214 (Headquarters, Department Of The Army, 1984), <https://www.epa.gov/sites/default/files/2015-03/documents/9546041.pdf>.

16 *Explosive Weapon Effects* (Geneva International Centre for Humanitarian Demining (GICHD), 2017), <https://www.gichd.org/publications-resources/publications/explosive-weapon-effects/>.

17 Rattin Trushlakov, “Exploring the Strategic Versatility of C-4 in Modern Military Operations,” *Journal of Defense Studies and Resource Management* 11, no. 4 (2023), <https://www.scitechnol.com/abstract/exploring-the-strategic-versatility-of-c4-in-modern-military-operations-24749.html>.

18 Carl S. Gorzynski Jr and J. Norman Maycock, “Explosives and Pyrotechnic Propellants for Use in Long-Term Deep Space Missions,” *Journal of Spacecraft and Rockets*, ahead of print, 23 May 2012, <https://doi.org/10.2514/3.62044>; Juho Lee and Jae-Hung Han, “Separation and Release Devices for Aeronautical and Astronautical Systems: A Review,” *International Journal of Aeronautical and Space Sciences* 26, no. 1 (2025): 131–61, <https://doi.org/10.1007/s42405-024-00802-9>.

19 North Atlantic Treaty Organization, *Manual Of Data Requirements And Tests For The Qualification Of Explosive Materials For Military Use*, Aop-7 (Edition 2), Allied Ordnance Publication (2003), <https://www.difesa.it/assets/allegati/1675/c7c7e469-8f1f-4de2-b074-3d0449fcb66f.pdf>.

9 Explosives Regulatory Division, *Type E High Explosives*.

10 Explosives Regulatory Division, *Type E High Explosives*.

11 Eric N. Brown and Dan L. Borovina, “The Trinity High-Explosive Implosion System: The Foundation for Precision Explosive Applications,” *Nuclear Technology* 207, no. sup1 (2021): S204–21, <https://doi.org/10.1080/00295450.2021.1913954>.

12 Gibson, “Sparking Success.”

13 Federica Coppari et al., “Shock Behavior of Materials,” *Journal of Applied Physics* 133, no. 5 (2023): 050401, <https://doi.org/10.1063/5.0143414>.

14 S. I. Blinnikov et al., “Dynamics of Supernova Bounce in Laboratory,” *Physical Review E* 99, no. 3 (2019): 033102, <https://doi.org/10.1103/PhysRevE.99.033102>.

implosion, enabling the release of nuclear energy.<sup>20</sup> For the chain reaction to initiate and sustain, the explosion must deliver a precisely timed, symmetrical, high-pressure compression wave.<sup>21</sup>

In thermonuclear weapons, this fission-based implosion system serves not as the end point but as the initiator of a second, more powerful stage. The energy released from the primary fission explosion is used to compress and ignite a secondary stage containing fusion fuel, typically lithium deuteride.<sup>22</sup> This process, known as radiation implosion, does not rely on HEs to compress the secondary; instead, the high-temperature radiation environment generated by the fission primary is channelled and reflected within the weapon casing to symmetrically compress the fusion stage. Thus, while HEs are essential for initiating the fission primary, the subsequent fusion stage relies on a different set of physical principles to achieve exponentially greater explosive yields.

The integration of HE into a nuclear weapon follows a multistage process. The sequence begins with the chemical synthesis of the constituent compounds, followed by formulation into a moulding powder.<sup>23</sup> This powder is then consolidated under controlled pressure and temperature into a pressed charge, after which the charge undergoes final machining and assembly into the weapon system.

To ensure safety, the main-charge HEs in nuclear weapons must combine low sensitivity to external stimuli with high detonation performance, which is a stringent requirement met by only a limited range of formulations.<sup>24</sup> Modern designs prioritise slightly reduced explosive performance in exchange for markedly enhanced safety and resistance to accidental or sympathetic detonation.<sup>25</sup> Early-generation weapons, such as *Fat Man* and *Little Boy*, employed more sensitive conventional explosives, which could, in principle, still be used in certain nuclear weapon designs.

In sum, HEs are not the ultimate destructive element in nuclear weapons but rather the mechanism that creates the extreme physical conditions necessary to trigger and sustain a supercritical nuclear reaction.

## Material composition

HEs used in nuclear weapons comprise two related but distinct elements: explosive compounds and explosive formulations. Explosive compounds are specific chemical substances with defined energetic properties. In practice, however, nuclear weapons do not use raw explosive compounds alone. Instead, these compounds are incorporated into engineered formulations, often referred to as plastic-bonded explosives (PBXs), which combine one or more energetic compounds with binders and

additives to improve mechanical strength, manufacturability, safety and long-term stability.

Depending on the explosive composition used, HEs can either be conventional (CHE) or insensitive (IHE); the latter of which is more difficult to accidentally detonate but generally produces less energetic output.<sup>26</sup> While there are many formulations of CHE and IHE, this section focuses on the most common ones utilised in nuclear weapons which could be found in open sources.

Two CHE compounds known from open sources to have been used in nuclear weapons are Research Department Explosive (RDX – 1,3,5-trinitro-1,3,5-triazinane) – known to previously or currently be manufactured in France, the United Kingdom and the United States<sup>27</sup> – and High Melting Explosive (HMX – 1,3,5,7-tetranitro-1,3,5,7-tetrazocane) – known to be manufactured in the United States.<sup>28</sup>

The earliest CHE identified in open sources as used in a nuclear weapons programme was Composition B (Comp B), first manufactured by the United Kingdom and later the United States for use in the Manhattan Project.<sup>29</sup> Comp B uses a mixture of RDX and TNT as the explosive compounds.

A commonly used IHE found in open sources is TATB (1,3,5-triamino-2,4,6-trinitrobenzene), found in munitions and weapons systems worldwide, including some, but not all, nuclear weapons.<sup>30</sup> TATB is one of the most stable IHEs as it does not undergo the thermal sequence of deflagration-to-detonation (DDT), which means it does not readily explode even if exposed to heat or fire, a unique property that makes it highly resistant to accidental initiation.<sup>31</sup> Notably, TATB is also used in civilian applications, such as deep oil well explorations.<sup>32</sup>

Another HE in the process of being introduced into the US nuclear programme is LLM-105 (2,6-diamino-3,5-dinitropyrazine-1-oxide). As the principal constituent of the LX-21 formulation, it is the first novel explosive to be integrated into a US nuclear warhead without the use of full-scale underground testing.<sup>33</sup> It appears to be intended primarily for booster applications<sup>34</sup> and is described in open-source documentation solely as an “IHE candidate,” a designation that renders its precise classification uncertain.<sup>35</sup> Notably, LLM-105 exhibits greater energetic output than TATB with a similar level of insensitivity and safety.<sup>36</sup>

- 26 United States Government Accountability Office, “National Nuclear Security Administration: Explosives Program Is Mitigating Some Supply Chain Risks but Should Take Additional Actions to Enhance Resiliency,” Report to Congressional Committees GAO-25-107016 (2025), <https://files.gao.gov/reports/GAO-25-107016/index.html>.
- 27 Henry Abadin et al., “Production, Import/Export, Use, and Disposal,” in *Toxicological Profile for RDX*, (Agency for Toxic Substances and Disease Registry (US), 2012), <https://www.ncbi.nlm.nih.gov/books/NBK154153/>; Brown and Borovina, “The Trinity High-Explosive Implosion System,” 2021.
- 28 Agency for Toxic Substances and Disease Registry (US), “Production, Import, Use, and Disposal,” in *Toxicological Profile for HMX* (Agency for Toxic Substances and Disease Registry (US), 1997), <https://www.ncbi.nlm.nih.gov/books/NBK596098/>.
- 29 Eric N. Brown and Dan L. Borovina, “The Trinity High-Explosive Implosion System: The Foundation for Precision Explosive Applications,” *Nuclear Technology* 207, no. sup1 (2021): S204–21, <https://doi.org/10.1080/00295450.2021.1913954>.
- 30 Anne M. Stark, “Hot Stuff: A New Thermal Pathway for a High Explosive,” 28 February 2024, <https://www.llnl.gov/article/50911/hot-stuff-new-thermal-pathway-high-explosive>.
- 31 Stark, “Hot Stuff,” Gibson, “Sparking Success.”
- 32 Veera M. Boddu et al., “2,4,6-Triamino-1,3,5-Trinitrobenzene (TATB) and TATB-Based Formulations—A Review,” *Journal of Hazardous Materials* 181, no. 1 (2010): 1–8, <https://doi.org/10.1016/j.jhazmat.2010.04.120>.
- 33 Margaret Davis and Ben Kennedy, “Three Decades of Explosive Innovation,” *Science & Technology Review*, August 2021, <https://str.llnl.gov/past-issues/august-2021/three-decades-explosive-innovation>.
- 34 A booster application refers to the use of a small HE charge that strengthens and transfers the detonation from the initiator to the main explosive system.
- 35 “Extending the Life of a Workhorse Warhead,” *S&TR*, November 2018, <https://str.llnl.gov/sites/str/files/2024-04/10.18.1.pdf>.
- 36 T D Tran et al., *Characterization of 2,6-Diamino-3,5-Dinitropyrazine-1-Oxide (LLM-105) as an Insensitive High Explosive Material*, n.d.

20 The NSS staff, “Pit Production Explained,” Los Alamos National Laboratory, 13 December 2021, <https://www.lanl.gov/media/publications/national-security-science/1221-pit-production-explained>.

21 Samuel Glasstone and Philip J. Dolan, “General Principles of Nuclear Explosions,” in *The Effects of Nuclear Weapons* (United States Department of Defense and the United States Department of Energy, 1977), <https://www.atomicarchive.com/resources/documents/effects/glasstone-dolan/chapter1.html>; Gibson, “Sparking Success.”

22 Sarah Scoles, “Behind the Scenes at a U.S. Factory Building New Nuclear Bombs,” *Scientific American*, 1 December 2023, <https://www.scientificamerican.com/article/behind-the-scenes-at-a-u-s-factory-building-new-nuclear-bombs/>.

23 C.B. Skidmore et al., *Aging and PBX 9502*, (Los Alamos National Laboratory, n.d.), accessed 26 September 2025, [https://digital.library.unt.edu/ark%3A/67531/metadc678756/m2/1/high\\_res\\_d/296629.pdf](https://digital.library.unt.edu/ark%3A/67531/metadc678756/m2/1/high_res_d/296629.pdf).

24 Yi Wang et al., “Accelerating the Discovery of Insensitive High-Energy-Density Materials by a Materials Genome Approach,” *Nature Communications* 9, no. 1 (2018): 2444, <https://doi.org/10.1038/s41467-018-04897-z>.

25 A sympathetic detonation occurs when the detonation of one explosive charge unintentionally triggers the detonation of a nearby explosive due to transmitted shock, heat or fragment impact, without direct initiation.

# Why do high explosives need to be tested?

HEs must undergo rigorous testing to ensure they are safe, effective and reliable across a range of operational scenarios. Testing validates performance and reinforces weapons modelling efforts and long-term stockpile stewardship.



## Safety in handling, storage and transport

HE materials must be tested to ensure they can be safely handled, stored and transported without risk of accidental initiation, burning or detonation (essentially any unintended event) due to thermal stimuli, electrostatic discharge or mechanical shock.<sup>37</sup>



## Performance validation

Testing is essential to verify that HE formulations meet stringent specifications for detonation velocity, peak pressure, brisance (shattering power) and energy release in nuclear warheads.<sup>38</sup> Importantly, with the cessation of full-scale nuclear testing, HE testing has become even more central to assuring the performance of legacy and modern warheads.<sup>39</sup> Subcritical and hydrodynamic tests simulate implosion physics using fissile materials or surrogates in sufficiently small quantities to prevent a sustained critical chain reaction. These experiments are fundamental to understanding how systems and materials perform under operational conditions. Experiments are conducted using sophisticated diagnostics to confirm that the HE behaves as predicted and meets the stringent specifications for warhead designs.<sup>40</sup>



## Material response under extreme conditions

Materials testing with HE enables researchers to understand how various materials comprising the non-nuclear components of a weapon behave under explosive loading, including how debris is formed. When detonated, HEs generate shockwaves that compress and heat materials to extreme conditions, often inducing phase transitions or deformation in microseconds.<sup>41</sup>

37 Headquarters, Department Of The Army, *Military Explosives*; Gibson, "Sparking Success."

38 Headquarters, Department Of The Army, *Military Explosives*.

39 Chen, "Hydrodynamic Experiments Support Stockpile Stewardship."

40 Gibson, "Sparking Success."

41 Chen, "Hydrodynamic Experiments Support Stockpile Stewardship."



## Simulation and model validation

Data from HE tests are indispensable for validating computer simulations of nuclear warhead detonations. Modern stockpile stewardship relies heavily on high-fidelity modelling, and accurate predictions require precise experimental benchmarks.<sup>42</sup> Diagnostics such as flash x-ray (FXR) imaging, radiography and interferometry allow scientists to capture detonating systems on microsecond time-scales, which is then used to calibrate and verify computational codes.<sup>43</sup> Such data-driven simulations, in conjunction with subcritical and hydrodynamic testing, have enabled the US to qualify and integrate new HE formulations in nuclear warheads without the need to resume full-scale underground nuclear testing.<sup>44</sup> Other nuclear-armed states may have pursued comparable approaches, but open sources do not confirm similar HE formulation changes. However, since ending nuclear explosive testing, several states have developed or are in the process of developing new nuclear-capable warhead designs.<sup>45</sup>



## Production and quality control

Testing also plays a vital role in quality assurance throughout the HE lifecycle. This includes post-synthesis chemical characterisation, mechanical assessment after machining and functional testing of fully assembled components.<sup>46</sup>



## Ageing and stability assessment

HE testing is not static and must evolve across both the material's and programme's lifecycle:

1. **Development stage:** Tests focus on chemical stability, safety thresholds and whether new formulations meet desired velocity and power targets.
2. **Maturation phase:** Larger-scale detonations assess how HE performs under operational conditions.
3. **Ageing and surveillance:** Long-term tests evaluate how HE formulations age over decades, maintaining safety and performance despite material degradation.

Over time, HE materials may degrade chemically or physically, potentially affecting performance and safety. Testing aged samples allows scientists to assess whether properties such as detonation velocity or sensitivity have

42 "Dual Success for DARHT Test," ahead of print, 7 December 2009, <https://doi.org/10.1063/PT.5.023904>.

43 Chen, "Hydrodynamic Experiments Support Stockpile Stewardship"; "Dual Success for DARHT Test".

44 Davis and Kennedy, "Three Decades of Explosive Innovation."

45 See for example: Hans M. Kristensen et al., "United Kingdom Nuclear Weapons, 2024," *Bulletin of the Atomic Scientists* 80, no. 6 (2024): 394–407, <https://doi.org/10.1080/00963402.2024.2420550>; Ministry of Defence, *Delivering the UK's Nuclear Deterrent as a National Endeavour*, CP 1058 (2024), [https://assets.publishing.service.gov.uk/media/671b8641956d9b52e8c6d276/Defence\\_Nuclear\\_Enterprise\\_Command\\_Paper.pdf](https://assets.publishing.service.gov.uk/media/671b8641956d9b52e8c6d276/Defence_Nuclear_Enterprise_Command_Paper.pdf).

46 Gibson, "Sparking Success."

changed due to environmental exposure or material fatigue.<sup>47</sup>

Ageing may occur naturally or be induced under accelerated conditions such as elevated temperatures to assess stability, predict performance and analyse its interaction with surrounding non-HE material such as the chemical binders that are mixed with HEs to create the final explosive mixture.<sup>48</sup>

Degradation can produce new chemical forms with altered sensitivities, making ageing studies critical for safety and reliability.<sup>49</sup> HEs used in nuclear weapons are further subjected to intense radiation environments and are therefore tested to ensure resistance to radiation-induced degradation or sensitivity changes.<sup>50</sup>



## Supporting modernisation

Ongoing testing supports the development of new HE materials with improved safety, manufacturability or tailored detonation properties. This includes synthesising novel compounds, evaluating their energetic profiles and confirming their suitability for current or future systems.<sup>51</sup> For HEs used in nuclear weapons, ongoing tests focus on developing new IHE compounds that retain the low sensitivity of TATB while achieving energy outputs approaching those of CHE such as HMX.<sup>52</sup> It also allows nations to overcome supply chain constraints by developing explosives that do not require ingredients from other states, thereby reducing vulnerability to disruptions arising from changes in the geopolitical environment.<sup>53</sup>

## How are high explosives tested and involved in nuclear testing?

HEs undergo a multi-phase qualification process that begins with characterisation of their chemical, physical and mechanical properties, including hardness, density and heat of explosion.<sup>54</sup> This is followed by hazard evaluation, starting with small-scale sensitivity and safety assessments and advancing to full-scale performance trials and diagnostic experiments to validate their suitability for operational use. Early tests involve exposing HE samples to stimuli such as heat, friction, impact and electrostatic discharge to determine thresholds for initiation all the way up to detonation and ensure safe handling and transport.<sup>55</sup> These include, amongst others, hammer tests, cook-off tests (heating until ignition) and skid tests simulating abrasive impact during transit.<sup>56</sup>

Performance evaluation is done through detonation tests measuring key characteristics like detonation velocity, pressure output, shattering power and symmetry.<sup>57</sup> Large-scale experiments use advanced diagnostics such as FXR, which can provide a stop-motion photo of an explosion and provide data on, for example, implosion symmetry.<sup>58</sup> Other diagnostics may include Photon Doppler Velocimetry (PDV) – to capture real-time data on the velocity of surfaces or particles moving at extreme speeds (typically 0.1 m/s to over 50 km/s) during an explosive event – and Broadband Laser Ranging (BLR) – to create an interference pattern indicating the movement of fragments during the detonation.<sup>59</sup>

## Blast tube testing

Blast tube facilities use a carefully configured explosive charge to produce a controlled shock. The HE charge itself is not being characterised; instead, the facility studies how the resulting blast wave interacts with targets and instrumentation. Long, modular tubes (often hundreds of metres in total length that can be configured in varying diameters and geometries to achieve specific peak pressures, durations and shapes) are arranged so engineers can reproduce specific operational environments with fewer calibration shots.<sup>60</sup> Explosive charges are placed at one end of the tube and the resulting blast wave propagates down the length to the other exit, where it interacts with test articles or instruments to record, for example, how weapons-related materials, assemblies and subsystems deform, fragment, heat or fail under specified peak pressures and durations, enabling assessment of material interaction with explosive-driven loads relevant to weapon systems.

47 Lawrence Livermore National Laboratory, "New Life for a Legacy Warhead," *Science & Technology Review*, November 2018, <https://str.llnl.gov/sites/str/files/2024-04/10.18.pdf>.

48 S. Drell and R. Jeanloz, Signatures of Aging, JSR-97-320 (JASON, 1998), <https://irp.fas.org/agency/dod/jason/aging.pdf>.

49 *Scientists Solve the 50-Year Mystery of Widely Used High Explosive TATB* | Physical and Life Sciences Directorate, 18 June 2025, <https://pls.llnl.gov/article/53031/scientists-solve-50-year-mystery-widely-used-high-explosive-tatb>.

50 C.B. Skidmore, et al., *Aging and PBX 9502* (Los Alamos National Laboratory, n.d.), accessed 26 September 2025, [https://digital.library.unt.edu/ark%3A/67531/metadc678756/m2/1/high\\_res\\_d/296629.pdf](https://digital.library.unt.edu/ark%3A/67531/metadc678756/m2/1/high_res_d/296629.pdf).

51 Gibson, "Sparking Success."

52 Wang et al., "Accelerating the Discovery of Insensitive High-Energy-Density Materials by a Materials Genome Approach."

53 *Explosives Program Is Mitigating Some Supply Chain Risks but Should Take Additional Actions to Enhance Resiliency*, GAO-25-107016 (National Nuclear Security Administration, 2025), <https://files.gao.gov/reports/GAO-25-107016/index.html>.

54 For a step-by-step insight into the HE testing process as conducted by NATO, see: *Manual Of Data Requirements And Tests For The Qualification Of Explosive Materials For Military Use*.

55 Gibson, "Sparking Success."

56 Gibson, "Sparking Success."

57 Headquarters, Department Of The Army, *Military Explosives*.

58 Ann Parker, "X-Ray Machine Does Double Duty," *Science & Technology Review*, August 2018, <https://str.llnl.gov/past-issues/julyaugust-2018/x-ray-machine-does-double-duty>.

59 Chen, "Hydrodynamic Experiments Support Stockpile Stewardship."

60 "Blast Tube Facility," Sandia National Laboratories, accessed 30 July 2025, <https://www.sandia.gov/vqsec/facilities/blasttube/>.

An example of this type of facility is the large-scale blast tube operated at Sandia National Laboratories, which can accommodate charges of over a ton of HE. This blast tube testing facility is currently part of a two-year project to simulate conditions that a nuclear weapon re-entering the Earth's atmosphere could experience if another nuclear weapon exploded nearby.<sup>61</sup>

## Hydrodynamic and subcritical tests

In the absence of routine nuclear explosive testing, the only HE-driven experiments with nuclear-weapons-related assemblies are hydrodynamic and subcritical tests, which are performed to maintain the viability of nuclear weapons without resorting to underground nuclear testing, enabling scientists to predict nuclear weapons performance with high precision.<sup>62</sup>

In hydrodynamic tests, HEs are used to drive the implosion of a non-nuclear duplicate of a nuclear warhead made from surrogate materials. The implosion process is then compared with computer-generated predictions. These tests involve enclosing an inert (non-fissile) material within the HE (specifically for tests that are not subcritical).<sup>63</sup> During a hydrodynamic test, numerous processes occur simultaneously, including physical and chemical reactions, debris dispersal and interactions between different components. The aim is to examine the entire integrated system, comparing experimental results with simulations to improve the accuracy of assessments concerning the conditions that trigger a nuclear device's primary.<sup>64</sup>

Hydrodynamic testing also supports preparations for subcritical tests. While similar in design, subcritical tests use small quantities of fissile material instead of inert material, arranged in configurations that prevent the assembly from becoming critical.<sup>65</sup> Plutonium and uranium exhibit different behaviours than inert surrogates, making these tests beneficial to the production of more accurate models.<sup>66</sup> Subcritical experiments are resource intensive; each costs tens of millions of dollars, takes three to five years to plan and involves hundreds of specialists and a wide range of materials. Hydrodynamic testing is therefore a key step in preparing for these complex, costly experiments.

## Unique materials, infrastructure and equipment

Testing HE safely and precisely requires specialised infrastructure, including firing sites and chambers and specialised diagnostic equipment. As this paper is part of a larger project that seeks to ground analysis on the DPRK's and other specific countries' HE testing programmes, this section draws together the observable elements that could indicate a facility is testing HE for possible use in its nuclear programme. Imagery analysis specifically identifying certain

indicators can be found in the accompanying project publications.<sup>67</sup>

### Firing sites and chambers

Concrete bunkers and contained firing vessels with blast protection and shrapnel mitigation systems are necessary due to the extreme pressures involved. This may include both indoor and outdoor sites.<sup>68</sup> For example, the US hydrodynamic testing facility BEEF has a 10-acre fenced compound which features a control bunker, a camera bunker, a firing pad and associated control and diagnostic systems.<sup>69</sup> Visual analysis of this site can be found in the accompanying project publications.<sup>70</sup>

Blast tube systems are a distinctive infrastructure element for HE research. They require secure sites with reinforced containment, remotely operated systems for charge placement and extensive hazard mitigation to manage risks from explosives, hazardous materials and potential debris. Modular designs allow the tubes to be reconfigured to meet different programme requirements.<sup>71</sup> While blast tube systems do not necessarily indicate testing of HE itself, they provide context into a state's larger programme of using HE in materials testing, which often includes missiles and/or nuclear weapons.

### Specialised diagnostics

Specialised diagnostic equipment, such as high-speed FXR, PDV and BLR provide high-resolution imaging of high-speed or explosion-driven events, offering insight into parameters such as detonation velocity and implosion symmetry.<sup>72</sup>

They continue to evolve through technological improvements, expanding the quality and range of data that can be collected. Although FXR technology was first developed in the United States during the mid-twentieth century, its capabilities were limited to producing a single image during an explosive test.<sup>73</sup> Only in recent years has it become possible to capture two frames within a single experiment. This advance is expected to yield a significantly deeper understanding of implosion processes, including those relevant to nuclear weapon primaries. This evolution illustrates that such diagnostic capabilities may be very different across countries, depending on the maturity of their technological development.

While this equipment does not lend itself to imagery analysis, which was the focus of this project, these specialised items might be found during analysis of import/export data and could indicate a robust HE testing programme (more information can be found in the "Export-controlled items" section below).

61 Sandia National Laboratories, "Researchers Simulate Shock Waves Nuclear Weapons Could Face Using a Blast Tube," Interesting Engineering, accessed 30 July 2025, <https://interestingengineering.com/videos/researchers-simulate-shock-waves-nuclear-weapons-could-face-using-a-blast-tube>.

62 "Dual Success for DARHT Test"; R.J. Hemley and D.I. Meiron, *Hydrodynamic and Nuclear Experiments*, JSR-11-340 (JASON, 2011), <https://irp.fas.org/agency/dod/jason/index.html>.

63 Parker, "X-Ray Machine Does Double Duty."

64 Chen, "Hydrodynamic Experiments Support Stockpile Stewardship."

65 Chen, "Hydrodynamic Experiments Support Stockpile Stewardship."

66 Neal Singer, "Scorpius Images to Test Nuclear Stockpile Simulations", *News Releases*, n.d., accessed 16 January 2026, [https://newsreleases.sandia.gov/stockpile\\_simulations/](https://newsreleases.sandia.gov/stockpile_simulations/).

67 The full comparative analysis can be found at: <https://storymaps.arcgis.com/collections/debd98f0c8f9424398488eaf1eeab1bb>.

68 Gibson, "Sparking Success."

69 Nevada National Security Site, "Big Explosives Experimental Facility (BEEF)", Nevada National Security Site, accessed 3 January 2025, <https://nss.gov/mission/stockpile-stewardship-program/big-explosives-experimental-facility-beef/>.

70 The full comparative analysis can be found at: <https://storymaps.arcgis.com/collections/debd98f0c8f9424398488eaf1eeab1bb>.

71 Sandia National Laboratories, "Blast Tube Facility."

72 Parker, "X-Ray Machine Does Double Duty"; Chen, "Hydrodynamic Experiments Support Stockpile Stewardship."

73 Parker, "X-Ray Machine Does Double Duty."

## Nuclear-specific testing infrastructure

While HEs require specialised sites and infrastructure for storage and testing, there are no consistently distinctive physical features available in open sources that clearly differentiate HE facilities used for conventional purposes from those associated with nuclear weapons programmes. In practice, nuclear-related HE testing sites are most often distinguished by their context, such as co-location with known nuclear facilities, rather than by unique, externally observable structural characteristics. Additional indicators may include heightened security arrangements or the presence of large-scale diagnostic systems, such as FXR installations, although such features are not always visible or attributable through open-source or remote observation alone.

## Export-controlled items

HE compositions relevant to nuclear weapons are primarily controlled under national and supranational legally binding export control lists, such as the EU Common Military List<sup>74</sup> and the United States International Traffic in Arms Regulations,<sup>75</sup> where they are treated as military energetic materials.

By contrast, the diagnostic equipment used to test HEs is typically regulated under national and supranational dual-use control lists, including the EU Dual-Use Regulation Annex I<sup>76</sup> and the US Export Administration Regulations (EAR),<sup>77</sup> reflecting their civilian applicability.

At the multilateral level, the Nuclear Suppliers Group (NSG) addresses both categories through its *Guidelines for Transfers of Nuclear-Related Dual-Use Equipment, Materials, Software, and Related Technology*.<sup>78</sup> While not legally binding in itself, the guidelines are implemented through the domestic export control legislation of participating states and provide a harmonised framework for identifying and controlling technologies and materials recognised as enabling nuclear weapons-relevant capabilities when their performance exceeds defined control thresholds.

Some of these systems fall under other export control regimes, however, as this is not the focus of this paper, the EU, US and NSG regimes are used simply as illustrative examples, not a comprehensive list. Further research on this area is recommended to provide a comprehensive view of this aspect of HE-related equipment.

The diagnostics discussed in this paper<sup>79</sup> that are subject to dual-use controls include:<sup>80</sup>

- FXR and radiographic systems;
- High-speed imaging equipment (including streak, framing and fast-gated cameras);
- Laser-based interferometry and velocimetry, such as PDV, high-pressure shock gauges and quartz transducers; and
- Contained firing vessels.

Although none of these systems are inherently nuclear specific or exclusively military, their regulation reflects their role in producing data that enables model validation and implosion-relevant experimentation, which underpins the development and maintenance of nuclear weapons capabilities in the absence of full-scale nuclear explosive testing. Consequently, the acquisition of such diagnostics above defined performance thresholds can provide analytically significant indicators of a state's capacity to support advanced nuclear weapons-related development and modernisation.

74 Common Military List of the European Union, Pub. L. No. 24 February 2025, Official Journal of the European Union, [https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:C\\_202501499&utm](https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:C_202501499&utm).

75 International Traffic in Arms Regulations (ITAR), Code of Federal Regulations § 22 CFR Parts 120–130 (2026), <https://www.govinfo.gov/content/pkg/CFR-2025-title22-vol1/pdf/CFR-2025-title22-vol1-part121.pdf>.

76 Regulation (EU) 2021/821 on the Control of Exports, Brokering, Technical Assistance, Transit and Transfer of Dual-Use Items (Annex I), Official Journal of the European Union § Annex I, [https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L\\_202502003](https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202502003).

77 Export Administration Regulations (EAR), 15 CFR Parts 730–774, Code of Federal Regulations § Part 774—The Commerce Control List, <https://www.govinfo.gov/content/pkg/CFR-2025-title15-vol3/pdf/CFR-2025-title15-vol3-part774.pdf>.

78 *Guidelines for Transfers of Nuclear-Related Dual-Use Equipment, Materials, Software, and Related Technology (NSG Part II)* (Nuclear Suppliers Group, 2025), <https://nuclearsuppliersgroup.org/en/guidelines/nsg-guidelines/guidelines-part-2>.

79 While BLR is not explicitly listed in current export control regimes, it is technically adjacent to controlled laser-based measurement techniques and may fall within regulatory scope depending on system design and performance characteristics.

80 An item-based list with reference to specific entries in the control regimes mentioned above can be found in Annex A.

## Conclusion

Since they are used in civilian and military contexts, HEs occupy an ambiguous position yet they are necessary for the manufacture of nuclear weapons. As this paper has shown, the fact that a state possesses HEs is not analytically significant, the key indicator is the state's ability to test and diagnose HEs in conditions relevant to nuclear weaponisation. HE testing provides the bridge between material availability and functional weapon capability.

In the absence of full-scale nuclear explosive testing, HE testing has assumed an even greater role in sustaining and modernising nuclear arsenals. Through hydrodynamic and subcritical experiments, advanced diagnostics and lifecycle testing, states are able to refine implosion symmetry, validate simulation codes and qualify new materials. These activities demand specialised infrastructure, highly controlled environments and sophisticated diagnostic equipment, all of which could leave distinctive signatures. As a result, HE testing capacity offers a key data point for assessing the maturity of a nuclear weapons programme.

From an open-source monitoring perspective, this creates both challenges and opportunities. Many HE-related materials, facilities and diagnostics have legitimate civilian or conventional military applications, complicating assessments. However, when viewed holistically – considering co-location with nuclear facilities and specialised diagnostics – HE testing can provide meaningful indicators of weaponisation progress and stockpile stewardship activities.

**By consolidating technical knowledge on HE composition and testing rationales, methodologies and infrastructure, this paper seeks to lower the analytical barrier for researchers examining nuclear weaponisation pathways. Understanding HE testing does not yield definitive answers in isolation, but it sharpens the questions that policymakers, analysts and verification practitioners can ask when assessing a state's nuclear trajectory.**

## Annex A. Control list items (diagnostic equipment)

This annex maps the principal categories of diagnostic equipment discussed in this paper to their corresponding entries on a selection of non-comprehensive international export control lists. The references are drawn from the NSG Guidelines Part 2 (Dual-Use List), the European Union Dual-Use Regulation Annex I, and the US EAR Commerce Control List (CCL).

- **Flash X-ray and pulsed radiography systems (FXR)**
  - NSG: 5.B.1
  - EU Dual-Use Annex I: 3A201.c
  - US EAR/CCL: 3A201.c
- **High-speed imaging equipment (streak, framing and fast-gated cameras and shutters)**
  - NSG: 5.B.3
  - EU Dual-Use Annex I: 6A203
  - US EAR/CCL: 6A203 (and 6A293 for certain high-speed digital cameras)
- **Laser-based velocity interferometry (including PDV)**
  - NSG: 5.B.5.a
  - EU Dual-Use Annex I: 6A225
  - US EAR/CCL: 6A225
- **Shock pressure gauges (>10 GPa)**
  - NSG: 5.B.5.b
  - EU Dual-Use Annex I: 6A226.a
  - US EAR/CCL: 6A226.a
- **Quartz pressure transducers (>10 GPa)**
  - NSG: 5.B.5.c
  - EU Dual-Use Annex I: 6A226.b
  - US EAR/CCL: 6A226.b
- **Explosive containment vessels enabling diagnostic data extraction**
  - NSG: 5.B.7
  - EU Dual-Use Annex I: 1B234
  - US EAR/CCL: 1B234



**OPEN NUCLEAR  
NETWORK**

A PAX *sapiens* programme

**VERTIC**