Advances in Disruptive Technologies of Ultrahigh-energetic Materials

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Abstract. Since this century, disruptive innovating technology has developed rapidly and become a significant power of promoting science & technology development and military change, it will also affect energetic materials’ development profoundly. In order to realize the impact of disruptive technologies on energetic materials’ development, based on tracking the disruptive technology progress of energetic materials field at home and abroad, the disruptive technologies of ultrahigh-energetic materials has been reviewed, and the technological trends of metal hydrogen, all-nitrogen compounds, material genome and nuclear-energy are mainly analyzed, these disruptive technologies will greatly promote the innovative development of ultrahigh-energetic materials.

1. Introduction

The word "Disruptive Technology" first appeared in the book "Disruptive technologies: catching the next wave" published by Professor Christensen of harvard business school in 1995 [1]. It is also known as Disruptive innovation and revolutionary Technology. In terms of attributes, disruptive technologies can be either original innovative technologies based on new concepts and principles, or innovative new technologies generated by cross-disciplinary and cross-disciplinary integration of multiple technologies [2-4]. Disruptive technology plays a huge role in promoting the development of science and technology and industrial transformation. The United States, Russia and other powerful countries attach great importance to the development and application of disruptive technology, and regard it as an important grasp and main way to occupy the commanding heights of economy, science and technology, especially national defense and military [5-11]. The US department of defense advanced research projects agency (DARPA) is the world's earliest disruptive technology planning and research institutions, it earlier proposed and mastered many disruptive technology such as the Internet, stealth, GPS and so on [12-17], these greatly improved the US defense capability. Disruptive technology has become the world frontier and research hot spot of science and technology, especially in the field of defense.

Energetic material is an important part of national defense and the key damage and power energy materials for various weapons and equipment, energy is the priority topic of energetic material’s pursuit and development. The energy level of conventional explosive is in \(10^3\) J/g grade commonly,
this can satisfy the energy demand of most weapons and equipments. While the high ultra-speed and efficient damage weapon, large launch vehicle will need energetic material with higher energy, namely ultra-high energy density materials(UHEDM) whose energy density is higher than conventional explosives at least an order of magnitude, this kind of material is known as ultra-high energy energetic material, also known as disruptive energetic material in recent years [18-20]. Now abroad is developing the high kinetic energy weapons (boost-glide, hypersonic, advanced full speed field engines, etc.), ultra-high energy energetic material is gained high attention to by many foreign experts and scholars for it can achieve high energy goal such as powerful propulsion and efficient damage, so it has important reference significance to track and master the status of disruptive technology related to ultra-high energy energetic material, analysis its potential impact on energetic material and the developing trend.

2. Research status

Traditional energetic materials are generally composed of CHON elements, whose energy comes from chemical energy between elements. The CHON explosives based -NO₂ as blasting groups have a maximum theory density of about 2.2 g/cm³ and its maximum explosion energy is only higher about 30% than octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine(HMX) [21-22], the theoretical density of CL-20 appeared at the end of 20th century is 2.03g/cm³ and its detonation speed is up to 9.4km/s, this indicates that the energy of such energetic materials is close to the theoretical limit and has little potential for further improvement.

The application of disruptive technology is a feasible way to greatly improve energy of energetic material and obtain ultra-high energy energetic materials. Combined the research status of disruptive technology in the field of domestic and foreign energy and weapon with the development direction of energetic material, the disruptive technology of ultra-high energy energetic materials mainly is focused in following categories: metallic hydrogen technology, all-nitrogen compound technology, materials genome technology and nuclear power technology.

2.1. Metallic hydrogen technology

Metallic hydrogen has the advantages of large energy storage and no pollution to the environment, it is the highest chemical energy explosive known to date. Its theoretical energy density is up to 216kJ/g, above 40 times than that of TNT (4.5kJ/g), 20 times than hydrogen-oxygen engine used for space shuttle (10 kJ/g) and theoretical specific impulse Isp can reach 1700s [23-24]. It is likely to be a powerful ultra-high energy material and rocket propellant. Metallic hydrogen is also a kind of superconducting material, which has great application prospect in aviation and defense.

At present, metallic hydrogen is mainly obtained by high pressure and low temperature technology. A large number of theoretical and experimental studies have been conducted on metallic hydrogen in US, Silvera team [25-26] at Harvard University claimed to have obtained solid metallic hydrogen at a high pressure of 495GPa and an ultra-low temperature of 5.5k since 2017(Figure 1).

![Figure 1. The photographs of hydrogen with increasing pressure](image_url)

In 2019, Loubeyre et al. [27] adopted the diamond anvil technology similar to the "doughnut" ring structure and observed that hydrogen samples absorbed all infrared radiation at a pressure of 425GPa
and a temperature of 80K, indicating that hydrogen electrons happened "band gap closure" and phase transition, becoming metallic hydrogen under such conditions. Xia et al. [28] made use of the high mechanical strength of carbon nanotubes to prepare quasi-one-dimensional "metallic hydrogen" at relatively low pressure (163.5GPa), and they developed corresponding theoretical models. These research results mark continuous breakthrough in the preparation of metallic hydrogen, the diversification of preparation methods and the decreasing pressure need for preparation of metallic hydrogen. However, the conditions of metallic hydrogen' preparation and application are harsh and far from practical application, so many technical and engineering problems need to be solved.

2.2. All-nitrogen compound technology

Theoretical calculations show that the molecular density and energy will increase with addition of nitrogen content in energetic molecules, so theoretical simulation and synthesis research of high-nitrogen compounds have always been an effort direction to pursue UHEDM [29-31]. Klapotke team [32] synthesized dihydroxylammonium 5,5'-bistetrazole-1,1'-dilolate(TKX-50), its detonation velocity reached 9.7km/s and sensitivity (impact sensitivity 20J) was lower than HMX. Zhang qinghua team [33] synthesized [2,2'-bi(1,3,4-oxadiazole)]-5,5'-dinitramide(ICM-101), it exhibited a surprisingly high density(1.99 g. cm$^{-3}$ at 298 K), calculated detonation velocity reached above 9.4km/s, the energy level and sensitivity properties were similar to those of CL-20, but there was no trans-crystal phenomenon and its synthesis cost was low. Zhang et al. [34] found the detonation velocity and detonation pressure of tetranitrodipyrazole annulated with 1, 2, 3, 4-tetrazine(TNDPT) achieved 9.6km •s$^{-1}$ and 44.0GPa respectively, its energy was equivalent to CL-20, but its mechanical sensitivity was significantly lower than CL-20, showing obvious application potential. Although the mechanical sensitivity of these compounds is relatively low, but their energy are basically comparable to CL-20, not reach to the energy level of UHEDM.

All-nitrogen compounds are composed entirely of nitrogen atoms, they provides a possibility for realizing UHEDM, much progress has been made in this field [35-37]. All-nitrogen compounds are mainly divided into ionic type and covalent type. Christe et al. [38] synthesized N$_{5}^{+}$ cationic all-nitrogen compounds in 1999, the theoretical energy density of N$_{5}^{+}$ is about 21kJ/g. Lu Ming team [39] synthesized cyclic-N$_{5}^{-}$ anion ammonium salt and pentazolium series energetic metal salt in 2017, the chemical energy of N$_{5}^{-}$ can reach 46kJ/g, higher than that of N$_{6}^{+}$ and N$_{1}$ (24.9kJ/g). Up to now, more than ten kinds of salt compounds containing N$_{5}^{-}$ have been synthesized [40-42]. However, it should be noted that the energy level of aqueous N$_{5}^{-}$ and pentazole metal salts is not high, and the application of pentazole salt of heavy metals is greatly restricted due to its high mechanical sensitivity or high cost [43]. If all-nitrogen anion and all-nitrogen cation can be effectively assembled, a novel UHEDM may be obtained.

N4, N6, N8, etc. belong to covalent all-nitrogen compounds. Studies have shown that covalent nitrogen has high energy, for example, the formation enthalpy of N4 is 798kJ/mol, its detonation velocity is 15.7km/s and detonation pressure is 125GPa, its ability to accelerate metal is three times HMX [44]. Russia has done lots of works in nitrogen atom-clusters and poly-nitrogen [45-48], cubic gauche polymeric nitrogen(Cg-N) and other solid poly-nitrogen were obtained by using diamond anvil technology. The structure of Cg-N is shown in figure 2, its density can reach 3.9g/cm$^{3}$ and formation enthalpy reach 20.8MJ/mol.
Although all-nitrogen UHEDM has high energy and no pollution to the environment, but its physical and chemical properties, safety properties and detonation properties which are different from traditional energetic materials also bring great challenges to its synthesis, characterization and application.

2.3. Materials genome technology

Materials Genome Initiative (MGI) was announced and implemented by US in 2011, MGI created the new model of material research and development, its three core elements are high-throughput materials calculation, high-throughput material experiment and materials database, through the technology integration and coordination between database, material calculation and material experiment, the materials calculation engineering is expanded to the whole chain of material science, technology and engineering, throughout the whole process of new materials from development to application (figure 3), then improve the materials development speed from discovery to application, also decrease the cost of new Materials development [47-49]. MGI's ultimate goal is to complete the materials "on-demand design" through theoretical simulation and realize the whole process of intelligent manufacturing based on material database, this lays an innovative foundation for the development of new key materials and advanced manufacturing.

MGI provides a new technical way for research and development of new material. Introducing the MGI method into energetic material field and implementing energetic materials genome initiative (EMGI), we can design and screen the molecular structure rapidly and acquire the target molecule with demand performance through identify the "trait gene" of energetic material, combined with high-throughput experiments, the development process of new energetic materials molecules will accelerated greatly. Pan et al. [52] established a functional module of energetic materials database, which can be used to query the basic information such as structure and performance of energetic materials. Zhang [53] proposed the phase goals and specific measures of EMGI, and pointed out that EMGI platform should be composed of four parts: database, design and calculation, preparation and characterization, service and failure evaluation, this structure adds the application elements to three elements of MGI. Tsyshevsky et al. [54] designed several energetic molecules which was expected to
have better comprehensive performance than existing energetic materials using a combination method
similar to the genomic strategy, this method can realize the efficient design of high-energy density
materials. Wang et al. [55] designed and synthesized a new insensitive high explosive (IHE) using the
material genome method (FIG.4): 2,4,6-triamino-5-nitropyrimidine-1,3-dioxide(ICM-102), its
calculated detonation velocity reaches 9.2m/s, impact sensitivity (>60J), friction sensitivity (>360N)
and electrostatic spray sensitivity are closed to those of TATB.

Figure 4. Illustration of possible materials genomes approach of organic explosives(Comparison with
that of organism) and identification of key gene texture(the relation between crystal density and
oxygen balance) [55]

The application of EMGI method in energetic materials field is still in the exploration stage, with
few successful examples, the accumulation of basic energetic materials database and establishment &
improvement of calculation model are in the works at present. However, as an efficient design and
development tool for advanced materials, once the genomic method of energetic materials is
established and applied, it will greatly change the research ideas of energetic materials and subvert the
existing development mode of energetic materials, and finally obtain UHEDM.

2.4. Nuclear power technology
The energy of metallic hydrogen and all-nitrogen compounds is based on chemical energy, their
energy level is generally at the \(10^4 \sim 10^5\) J/g. However, the energy level of physical energy-based
substances can reach above \(10^5\) J/g [56]. Such UHEDM mainly composed of nuclear isomers and
micro-fusion materials.

2.4.1. Nuclear isomer technology: Nuclear isomer refers to a class of substances with the same atomic
number and two or more different energy nuclides. When the nuclide in higher energy excited state
changes to lower energy state nuclide, it will release energy with the release level of more than \(10^5\) J/g
[56-57]. Nuclear isomer not only don’t produce residual nuclear radiation, but also has high energy
and the energy can be controlled to release, so it can realize the low-yield and miniaturization of
nuclear weapons. Low-yield weapons made from nuclear isomers are considered as the
fourth-generation nuclear weapons and no longer considered as mass destruction weapons. They can
be used not only directly as highly destructive "conventional weapons", but also as "clean" triggers for
hydrogen bombs, thus they have many military and political advantages. Both non-nuclear countries
and nuclear powers are actively developing and utilizing nuclear isomer using advanced technologies
and new principles, the development of nuclear isomer technology is expected to promote the
disruptive development of UHEDM.

US department of defense(DOD) included UHEDM technology in the list of priority to
development of S&T and military key technology, especially regarded the nuclear isomer technology
as a key technology of high energy density materials development, it regarded nuclear isomer as an
important high energy density storage medium. They have studied the production of Hf\(^{178m2}\) and its
application in gamma ray weapons (i.e., hafnium bullet), also studied Os187, Y186, Ta180, etc. Cline et al. [58] studied the energy release control method of nuclides to obtain the required energy level. As a new concept energy material, in addition to being used as energetic materials, the potential applications of nuclear isomers include energy storage, advanced propulsion systems, gamma-ray laser weapon and explosive devices, etc [59-61].

2.4.2. Micro-fusion technology. Similar to nuclear isomer technology, micro-fusion technology is also used to obtain energy and weapons at the conventional level, the energy released by this micro-fusion is around 10^8 J/g [62-64]. As early as 2008, DARPA launched the "chip-sized high-energy atom beam" program, which studies the microchip-sized nuclear fusion technologies and devices to obtain mini-nuclear bombs. In 2013, American researchers used a powerful laser to hit a bean-sized target, triggering its nuclear fusion reaction and releasing a energy of 10^8 J within 1s [65]. This mini-nuclear bombs prepared by micro-fusion technology have the characteristics of adjustable explosive yield, integrated strategy and tactics, high strike accuracy and low equipment maintenance cost. In early 2019, the United States has developed the B61-12 low-yield airborne nuclear bomb (mini-nuke) with less than 1000 tons of yield, which has a destructive capability beyond the reach of conventional warheads. The cross-section structure of mini-nuke is shown in figure 5.

![Figure 5. Mini-Nuke Cross Section [66]](image)

In addition to permanent energy and miniature nuclear bombs, micro-nuclear fusion technology can also be used in fields such as permanent power propulsion systems [67], it has an unlimited development potential.

3. Conclusion
Energetic materials will continue to develop in the direction of higher energy, lower sensitivity and better application performance. The energy potential of CHON conventional energetic materials is already very small, and it is extremely difficult to increase the energy of energetic materials in multiples especially in order of magnitude. The application of disruptive technologies in the field of energetic materials will provide a good approach and opportunity for the development of UHEDM, scholars engaged in the research of energetic materials should actively pay attention to and track the research trends and development directions of disruptive technologies in the field of energetic materials. At present, several ultra-high energy disruptive technologies that should be focused on and worked on mainly include :(1) metallic hydrogen technology, including its synthesis conditions, storage and application technology; (2) all-nitrogen compound technology, including molecular design, synthesis and application technology; (3) material genome technology, including database establishment technology, high-throughput computing and high-throughput material experiment technology; (4) nuclear power technology, such as nuclear isomers and micro-fusion. Once these technologies make progress and gain practical application in the field of energetic materials, they will greatly enhance the energy of energetic material and drive disruptive changes in weapons and
ammunitions.

References
[1] Christensen C.M. 1995 *Disruptive technologies: catching the next wave*. Harvard Business Review
[2] WANG Zhi-yong, DANG Xiao-ling, LIU Chang-li, et al. 2015 Characteristics of disruptive technology and international research survey *National Defence Science & Technology* 36(3) 14-7
[3] BAO Wei-min, WANG Feng-wei, XI Long, et al. 2017 Outlook on the disruptive technology revolution and the future trend—Changing the game rule, subverting the traditional thoughts, promoting the reform and development *THING TANK: Theory & Practice* 2(6) 31-3
[4] LI Zheng, LIU Chun-ping, LUO Hui. 2016 Analysis of essence and nurturing of disruptive technology: highlighting basic science researches behind disruptive technology *Global Science Technology and Economy Outlook* 31(10) 53-9
[5] LI Jing, WANG Yong, ZHENG Bin. 2017 Research progress in development of new materials for wearable equipment in foreign countries *Journal of Ordnance Equipment Engineering* 38(12) 142-5
[6] Lemnios Z. J. 2009 *National Defense Industrial Association Disruptive Technologies Conference* ADA517382
[7] LI Yan-qing, MA Xiao-cheng, SUN Xing-cun. 2017 US DOD pushes the development skeleton of disruptive technologies *Navy Equipment* 4 15-7
[8] Ajey Lele. 2019 *Disruptive Technologies for the Militaries and Security* Springer Nature Singapore Ltd.
[9] Wagen C.M. 2012 *Twenty-First century defense and disruptive innovation* ADA563406XAB
[10] Alessandro B., John Erkoyuncu, Paul C., Filomeno Martina, et al. 2017 A review of Additive Manufacturing technology and Cost Estimation techniques for the defense sector *CIRP Journal of Manufacturing Science and Technology* 19 117-28
[11] FANG Yong. 2018 the momentous movement of world weapon equipment and military technology development *The Science & Technology of China* 2 48-53
[12] CHEN yin, LIU Meng-yuan. 2017 The development status and revelation of foreign disruptive technology *The Journal of china army to civil* 9 60-3
[13] Marshall P. 2008 DARPA progress towards affordable, dense and content focused tactical edge networks *IEEE Military Communications Conference*
[14] David T.M., Joseph S.N. 2015 *Defense 2045: Assessing the future security environment and implications for defense policymakers* US Centre for strategic & international studies
[15] ZHANG Bo, ZHANG Lin, WANG Wen-feng, et al. 2018 Analysis of US Army Disruptive Technology Management *Tactical Missile Technology* 1 60-4
[16] DOU Chao, DAI Tao, LI Xiaoxuan1, et al. 2018 Research on DARPA’s Disruptive Technological Innovation Mechanism: Based on the Perspective of SNM Theory *Science of Science and Management of S.& T.* 39(6) 99-108
[17] YUAN Cheng. 2017 The research development of DARPA important a vigation programs *Science & Technology of China* 7 8-11
[18] Jennifer A, Ciezak J. 2016 *Disruptive Energetics-Fundamental Science for the Future* US Army ARL
[19] PENG Cui-zhi, FAN Xue-kun, FAN Xi-ping, et al. 2017 Review on foreign disruptive energetic materials *OSEC the first congress of weapon engineering*
[20] PENG Cui-zhi, ZHENG Bin, QIN Jian, et al. 2018 Disruptive energetic materials- The high-risk/ high-respond forward stratagem foundation materials *Chinese Journal of Energetic Materials* 26(3) 198-200
[21] DONG Hai-shan. 2004 The development and countermeasure of high energy density materials *The chinese Journal of energetic materials* 12(Supplement) 1-12
[22] ZHANG Yong-li, YANG Hui-qun. 2012 Review on new energetic materials Journal of Sichuan Ordnance 2 125-34
[23] Thierschmann M.1991 Comparison of Super-High-Energy-Propulsion-Systems Based on Metallic Hydrogen Propellant for ES to LEO Space Transportation N91-22154/9/XAD
[24] Silvera I.F., Cole J.W. 2010 Metallic hydrogen: The most powerful rocket fuel yet to exist Journal of Physics: Conference Series 215(17) 1-9
[25] Dias R., Silvera I.F. 2017 Observation of the Wigner-Huntington transition to metallic hydrogen Science 355(6326) 715-8
[26] Silvera I.F., Dias R. 2018 Metallic hydrogen Condensed Matter 30 254003
[27] Loubeyre P, Occelli F, Dumas P. 2019 Observation of a first order phase transition to metal hydrogen near 425 GPa arXiv preprint 1906:05634
[28] Xia Yueyuan, Yang Bo, Yin Fan, et al. 2019 Hydrogen Confined in a Single Wall Carbon Nanotube Becomes a Metallic and Superconductive Nanowire under High Pressure Nano Lett 19(4) 2537-42
[29] PENG Cui-zhi, FAN Xi-ping, REN Xiao-xue. 2011 The development status analysis of foreign ultra-high energetic materials Journal of Winged Missle 7 92-5
[30] HAN Zhi-yue, YAO Qian, YANG Yue-zhen, et al. 2016 Review on synthetic methods of nitrogen-rich compounds[J]. Journal of Ordnance Equipment Engineering 37(11) 119-23
[31] Keshavarz M.H., Abadi Y. H., Esmaeilpour K. D., et al. 2018 Novel high-nitrogen content energetic compounds with high detonation and combustion performance for use in Plastic Bonded Explosives (PBXs) and Composite Solid Propellants Central European Journal of Energetic Materials 15(2) 364-75
[32] Fischer N., Fischer D., Klapotke T.M., et al. 2012 Pushing the limits of energetic materials—the synthesis and characterization of dihydroxylammonium 5,5'-bisterazole-1,1'-dolate J Mater Chem 22 20418–22
[33] Zhang Wenquan, Zhang Jiaheng, Qi Xiujuan, et al. 2017 A promising high energy density material Nature Communications 1 1-7
[34] ZHANG Ji-chuan, WANG Zhen-yuan, WANG Bin-shen, et al. 2018 Fused-ring nitrogen-rich heterocycles as energetic materials: maintaining a fine balance between performance and stability Chinese Journal of Energetic Materials(Hanneng Cailiao) 26(11) 983-90
[35] LI Yu-chuan, PANG Si-ping. 2012 Progress of all-nitrogen ultrahigh-energetic materials Chinese Journal of Explosives & Propellant 35(1) 1-8
[36] LU Ming. 2017 The understanding on the energy level of all-nitrogen anion N₅⁺ metal-free salt Chinese Journal of Energetic Materials 25(7) 530-2
[37] XU Cheng, BI Fuqiang, GE Zhongxue, et al. 2012 Research progress of polynitrogen anion N₅⁻ Chemical Industry and engineering progress 31(9) 2019-24
[38] Christie K.O., Wilson W.W., Sheehy J. A., et al. 1999 N₅⁺: a novel homolectic polynitrogen ion as a high energy density material Angew. Chem., Int. Ed. 38 2004-9
[39] Zhang Chong, Sun Chengguo, Hu Bingcheng, et al. 2017 Synthesis and characterization of the pentazolate anion cyclo-N₅⁻ in (N₅)₃(H₂O)₅(NH₄)₃Cl Science 355(6323) 374-6
[40] Xu Yuangang, Wang Qian, Shen Cheng, et al. 2017 A series of energetic metal pentazolate hydrates Nature 549(7670) 78-92
[41] Xu, Yuangang, Qiuhan Lin, and Ming Lu. 2018 recent advances in the syntheses and properties of polynitrogen pentazolate anion cyclo-N₅⁻ and its derivatives Chemical Society reviews
[42] Tian Lili, Xu Yuangang, Lin Qiuhan, et al. 2019 Syntheses of Energetic cyclo-Pentazolate Salts Chemistry-An Asian Journal 14(16) 2877-82
[43] LU Ming. 2018 Thinking on the density and energy level of all-nitrogen anion N₅⁻ metal salt Chinese Journal of Energetic Materials 26(5) 373-6
[44] HUANG Hui,WANG Ze-shan,HAUNG Heng-jian. 2005 Researches and progresses of novel energetic materials Chinese Journal of Explosives & Propellants 28(4) 9-13
[45] Eremets M.I., Gavriliiuk A. G., Trojan I. A., et al. 2004 Single-bonded cubic form of nitrogen
Nature Materials 3(8) 558-63

[46] Lempert D.B., Nechiporenko G.N., Soglasnova S.I. 2009 Energetic potential of compositions based on high-enthalpy polynitrogen compounds Combustion, Explosion, and Shock Waves 45(2) 160-8

[47] Zarko V. E. 2010 Searching for ways to create energetic materials based on polynitrogen compounds (review) Combustion, Explosion, and Shock Waves 46(2) 121-31

[48] Smirnov A., Lempert D., Pivina T., et al. 2011 Basic characteristics for estimation polynitrogen compounds efficiency Central European Journal of Energetic Materials 8(4) 233-47

[49] Prachi Patel. 2011 Materials Genome Initiative and energy MRS Bulletin 36(12) 964-6

[50] Jain A.,Ong S.P.,Hautier G., et al. 2013 Commentary: The Materials Project: A materials genome approach to accelerating materials innovation APL Materials 1 011002

[51] WANG Hong, XIANG Yong, XIANG Xiao-dong, et al. 2015 Materials genome enables research and development revolution Chinese Journal of Science and Technology Innovation Herald 33(10) 13-9

[52] PAN Fu-bin, WANG Dong-lei, YANG liu, et al. 2015 The design and development of energetic materials genome database GF-A0211853G

[53] ZHANG Chao-yang. 2016 The new mode of energetic materials development—Energetic Materials Genome Initiative(EMGI) Chinese Journal of Energetic Materials 24(6) 520-2

[54] Tyshevsky R., Pagoria P., Smirnov A. S., et al. 2017 Comprehensive end-to-end design of novel high energy density materials: II. Computational modeling and predictions J. Phys. Chem. C 121 23865–74

[55] Wang Yi, Liu Yuji, Song Siwei, et al. 2018 Accelerating the discovery of insensitive high-energy-density materials by a materials genome approach Nature Communications 9 2444

[56] Poppe C.H., Weiss M.s., Anderson J.D. 1992 Nuclear isomers as ultra-high-energy-density materials DE93009520

[57] GAO Xiao-min. 2005 The Development Progress of Nuclear Isomer 178Hf2m---One of the Resources of Future Nuclear Weapon GF-A0090482

[58] Cline D., Hayes A.B., Wu C.Y. 2005 Nuclear structure implications for controlled energy release of isomers Journal of Modern Optics 52(16) 2411-22

[59] Hartouni, E.P. 2008 An Assessment of Nuclear Isomers as an Energy Storage Medium LLNL-Proc-409454

[60] Blott R., Koppel C., Jansen F., et al. 2012 Space fission nuclear power - A roadmap for Europe Proceedings of the International Astronautical Congress

[61] YAO Zi-xiu, JIN Xu, LI Jian-ming, et al. 2017 Current development of disruptive material technology and its potential impact on traditional energy Oil Science & Technology forum 3 45-9

[62] Science popularization. 2014 US nuclear fusion technology acquiring breakthrough and creating a “mini-sun” Nongcun Diangong 22(6) 50

[63] Alastair S. M., Shon P., Kevin L. B., et al. 2016 A simulation-based and analytic analysis of the off-Hugoniot response of alternative inertial confinement fusion ablators and materials High Energy Density Physics 20 23-8

[64] Winterberg F. 2019 Coriolis force-assisted inertial confinement fusion Laser and Particle Beams 37(1) 55-60

[65] Labaune C, Baccou C, Depierreux S, et al. 2013 Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma Nature Communications 4 2506

[66] Winterberg F. Mini-fission-fusion-fission explosions(mini-nukes). 2004 A third way towards the controlled release of nuclear energy by fission and fusion Zeitschrift fuer Naturforschung, A: Physical Sciences 599(6) 325-36

[67] Winterberg F. 2014 To Mars in Weeks by Thermonuclear Microbomb Propulsion Journal of Propulsion and Power 30(6) 1480-4