The ‘neglected’ chemistry: Fuels and materials preparation in China’s ‘two bombs and one satellite’ project

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Abstract
The ‘two bombs and one satellite’ project was a major achievement of China after 1949 and has since been an important subject in historical and sociological research on science and technology in modern China. However, most accounts of the history or sociology of the project focus on physicists and engineers, rather than the chemists. This study examines the chemists’ work of preparing fuels and materials in the project and their post-project research. By analysing how Chinese scientists engaged in the project, how they understood the relationship between basic and applied research in their scientific practice and how they positioned themselves on issues of science policy, this article offers different and shifting concepts of basic and applied research with cultural variation in the context of China.

Keywords
Bomb project, history of chemistry, global history of science, basic and applied research

I. Introduction: The global history of science and a new perspective on basic and applied research
The ‘two bombs and one satellite’ project was a major achievement of China after 1949 and has since then been an important subject in historical and sociological research on science and technology in modern China. There has been much historical and sociological literature on this big-science project, covering topics ranging from the organizational structure of the project, such as operating mechanisms, science planning and management (Liu et al., 2004) to the work of the Chinese Academy of Sciences (CAS) in the project (Liu, 2019), which captured a lot of historical details, including major decisions on China’s nuclear bomb development; the preparation of nuclear fuel; the design, manufacturing and testing of China’s atomic and hydrogen bombs; and the production factories and test bases (Lewis and Xue, 1991). There were also studies that examined the teacher–student relationships of researchers in the project from the perspective of organizational sociology (Zhang and Fu, 2017), and the inspiration for scientific research and engineering innovation derived from the project, such as the
non-contractual spirit of the scientists (Wu and Shen, 2018).

However, the role of chemists in the project and the chemical dimension of the project have been overlooked. The 23 scientists awarded the Two Bombs and One Satellite Merit Award were mostly physicists who focused on fields such as nuclear physics; applied mechanics; theoretical physics; materials science and structures; control systems and radio; engine technology; and optics. In contrast, chemists participating in the project were little known and did not receive the same recognition as the physicists. This phenomenon also occurred in other major science projects immediately before and during the Cold War era, such as the Manhattan Project, in which attention was focused on physics and engineering. The Cold War has been described as a physicists’ war (Manning and Savelli, 2018: 8), and research on the subsequent impact and legitimacy of atomic energy science has rarely gone beyond the sphere of physics (Creager and Santesmases, 2006).

The scientific and cultural supremacy of physics has continuously asserted itself in different countries. I do not doubt the soundness of the selection of the 23 recipients of the Two Bombs and One Satellite Merit Award or negate the greater priority of the work of physicists, but I aim here to explore the work of chemists in the project.

Why should research on the project pay attention to the work of the chemists who were involved? In recent years, new historiographical perspectives have been used in the study of the history of science.

The first change is the promotion of a new global approach to the history of science, which advocates the exploration of the flow and contextuality of knowledge around the world. The study of science during the Cold War also made new progress and included obvious changes in historiography of science by shifting the main focus from governments’ big-science projects to the circulation of knowledge on the global scale, the transnational development of knowledge and how those factors shaped local decisions (Van Dongen et al., 2015).

In advocating this approach, historians of science explored ways to best place the history of science in the global context (Fan, 2012). This emphasis on the circulation of knowledge from the perspective of the global history of science has been reflected by various new concepts, including the notion of trade in physics, and the contact zones that link knowledge in a situation of asymmetrical power (Galison, 2010).

The second change in the approach to the history of science during the Cold War (including the atomic bomb programmes) is the discussion of the distinction and relationship between pure science, basic science and applied science, which has been neglected in policy studies but has been expounded in more recent literature, driven by the concept of historical legacy in the history of science. While the dichotomy between basic science and applied science or between basic research and applied research is no longer advocated in some fields of research, including STS (science and technology studies) and STI (science, technology and innovation), in which alternative notions such as transdisciplinarity and responsible research have been proposed in place of notions such as pure science and basic science, those concepts are still widely used in science policies and practices in different countries and even in public discourse (Schauz and Kaldewey, 2018). In contrast to STS researchers, historians and philosophers of science attempt to understand the meanings of those concepts and the relationship between contemplative and instrumental forms of knowledge as a pressing problem. What counts as purity in logic, in physics, in chemistry and in biology? How do pure science and applied science differentiate from each other? Does pure science equate to basic science? (Galison, 2008; Dear, 2012).

The distinction between these terms not only indicates the epistemological differences among the fields of science studies but is also closely related with the professional identity work of scientists, scientific institutions and the organizations conducting national research activities in different countries. Moreover, historians of science and STS researchers have also helped to highlight the importance of focusing not only on science policy but also on the characteristics of the evolution of science itself (Creager, 2013). Therefore, research on the history of science in different countries can shed valuable light on important concepts such as pure science, basic science and applied science and improve the discussion of the complex relationship between science and society.
While the global turn in the historiography of science offers a new conceptual framework for the history of science in national and regional contexts, it should be noted that the national or regional history of science remains confined to specific national or regional contexts and that, even though the global perspective on the history of science reveals the generation and circulation of knowledge, it cannot adequately reveal the underlying objects, organisms, texts, people and other targets (McCook, 2013).

Existing literature on the distinction between basic and applied research or pure and applied science has been mostly focused on countries such as the United States and the United Kingdom, and not much on China. In his paper on Chinese debates about basic research between 1949 and 1966, Wang (2018) interpreted China’s science policy, analysed China’s decision to launch the ‘two bombs and one satellite’ project and discussed basic research and exploratory research. He suggested that the impact of the successful Chinese atomic bomb test in 1964 on Chinese scientists and science policy deserves further examination.

In this study, I examine the chemists’ work in preparing fuels and materials in China’s ‘two bombs and one satellite’ project and their subsequent research after the success of the project in the light of the global history of science and the global circulation of scientific knowledge. In contrast to perspectives such as task-driven big-science organization and the relationship between science and politics, this study focuses on the scientific practice and concepts of the chemists. By analysing how the Chinese scientists engaged in the project understood the relationship between basic and applied research in their scientific practice and how they positioned themselves on issues of science policy, this article aims to offer different and shifting concepts of basic and applied research with cultural variation in the context of China.

2. Radiochemical research and the centralized training of new talent

The manufacture of atomic bombs, hydrogen bombs and missiles requires not only the expertise of physicists in fields such as nuclear reaction and nuclear decay, but also the expertise of chemists in the process of nuclear transformation, such as radioactivity and radioactive elements. The chemists’ specific activities included the preparation, separation, purification and identification of radioactive elements, and the analysis of the properties and behaviours of nuclear transformation products.

The earliest participation by Chinese scientists in China’s atomic energy research was in radiochemical research and the training of researchers.

In the spring of 1953, Qian Sanqiang, a nuclear physicist and then director of the Institute of Modern Physics of CAS, led a study mission on nuclear science research to the Soviet Union and exchanged views on expanding scientific cooperation between the two countries (Editorial Committee of Nuclear Industry of Contemporary China, 1987). In 1955, after the Soviet Union offered help to socialist countries in developing nuclear technology, China made a strategic decision to develop and establish the country’s nuclear industry as soon as possible.

At that time, China did not have researchers engaged in radiochemical research directly, and a number of chemists specializing in structural chemistry and quantum chemistry joined the research on atomic energy. In 1950, the Institute of Modern Physics of CAS was established to focus on nuclear science research, and its main areas of research included experimental nuclear physics, cosmic rays and radiochemistry. Yang Chengzong and Guo Tingzhang, who were responsible for radiochemical and nuclear reactor materials, prepared gram-level uranium oxides with fairly high purity and studied the preparation of heavy water and graphite during China’s first Five-Year Plan period (1953–1957), which paved the way for reactor construction. Guo was a radiochemist and theoretical chemist specializing in quantum chemistry and a pioneer in applying quantum mechanics and statistical mechanics to chemical research. He developed the absolute velocity theory and the effective structure theory of liquids, laying the foundation for the transitional state theory of chemical reactions. He had studied theoretical chemistry at Ohio State University and Utah State University before returning to China and joining the Institute of Physics of CAS in 1950.
Besides sending people to the Soviet Union to study reactor and accelerator technology, theoretical physics and experimental physics in 1955, the Ministry of Education set up a special nuclear education base with a radiochemical lab and a radiochemistry programme to train atomic energy researchers. In April 1955, after Qian Sanqiang returned home from a visit to the Soviet Union, the Ministry of Education appointed a team comprising nuclear physicists Hu Jimin, Yu Fuchun and Zhu Guangya from Zhejiang University, Peking University and Northeastern People’s University (now Jilin University) to prepare for building an Institute of Physics at Peking University. The institute was the first organization dedicated to training nuclear technology talent in China. It was engaged in research and teaching in nuclear physics, making it the first nuclear education base in China as well.

In August 1955, according to the guidelines of the Central Committee of the Communist Party of China (CPC) and at the suggestion of Qian, the Institute of Physics was established at Peking University. It comprised professors from multiple universities and added a radiochemistry programme to the existing nuclear physics programme. Two years later, the Ministry of Education decided to cancel the institute, merge its nuclear physics programme into the Department of Physics and its radiochemistry programme into the Department of Chemistry, and establish the Teaching and Research Office of Radiochemistry (externally referred to as the ‘Teaching and Research Office of the Structure of Matter’) (Department of Technical Physics at Peking University, 1995). Guo Tingzhang concurrently served as deputy director of the Fifth Research Office of the Institute of Physics and director of Teaching and Research Office of Radiochemistry at Peking University (Qian et al., 1957).

In 1958, the two programmes began officially recruiting undergraduates in nuclear physics and radiochemistry. At the same time, chemists engaged in teaching and research on the structure of matter nationwide were transferred for teaching and research in radiochemistry; among them were Wu Zhengkai, Tang Aoqing and Lu Jiaxi. Wu was then directly transferred to the Ministry of Nuclear Industry to serve as chief engineer for the diffusive separation of uranium-235 and uranium-238. The Department of Atomic Energy at Peking University graduated its first class of radiochemistry students in 1957. In the autumn of 1958, it enrolled 93 students into its 5-year radiochemistry programme and 70 into its 4-year programme, in addition to selecting 70 top-performing junior students from different universities to study in the programme. In this way, China established its first higher education programme in radiochemistry at Peking University in 5 years from 1955 to 1960.

In 1958, after the passing away of Guo, Qian recommended Xu Guangxian for the position of director of the Teaching and Research Office of Radiochemistry after referring to the personnel archives of Peking University. Xu received his PhD in physical chemistry from Columbia University in 1951 and was engaged in quantum chemistry. Later, for the better management of confidential programmes, the CPC committee of Peking University demerged nuclear physics from the Department of Physics and radiochemistry from the Department of Chemistry to form the Department of Atomic Energy. In January 1959, Xu was appointed as deputy director of the department while concurrently serving as director of the Teaching and Research Office of Fuel Chemistry. In 1960, for reasons of secrecy, the Department of Atomic Energy was renamed as the Department of Technical Physics.

What did China do in the field of radiochemistry when it began its atomic energy research programme? Taking the Department of Atomic Energy/Technical Physics at Peking University as an example, Liu Yuanfang and others, under the guidance of associate professor Neferdorf (an expert from the Soviet Union), carried out research on hot atom chemistry and isotope exchange and actively prepared for teaching and experimental work in radiochemistry. Sun Yiliang and Zheng Shuhui conducted research on radioanalytical chemistry. Xiao Lun, a US-trained radiochemist, worked at the Atomic Energy Research Institute and spent a year teaching radiochemistry at Peking University.

Xu Guangxian’s first task in the Department of Atomic Energy was to teach students an introductory course in nuclear physics. When he returned to China in 1951, he brought with him some books on
radiochemistry and nuclear physics. Using those books as references, Xu prepared his lectures for the introductory course, covering radioactive decay and its laws, the composition and structure of the nucleus, reactors and accelerators, among other things (Xu, 1959). Gao Hongcheng, a professor in the Department of Technical Physics, recalled that Xu’s teaching also included the laws of radioactive decay and new terms and concepts such as actinium, uranium, decay and fission, which took students into the world of radiochemistry.

In radiochemistry, although China received help from the Soviet Union, it was of not much use in China’s nuclear research because it had little to do with applied research tasks such as the development of nuclear fuel, atomic bombs and nuclear reactors. The Soviet radiochemistry expert Neferdorf, in his communication with Chinese chemists, ‘actually did not provide full information. What he focused on was hot-atom chemistry, an area of basic research of radiochemistry which has nothing to do with the atomic bomb’ (Ye et al., 2013: 91). When Chinese scientists attended international academic conferences organized by the Joint Institute for Nuclear Research and visited the nuclear research base in Moscow, the Soviet side also closely guarded information related to atomic bomb development. Therefore, the Soviet Union did not offer much practical help. Chinese chemists realized that the effort to study radiochemistry and train urgently needed talent should focus on areas directly related to nuclear fuels such as uranium, thorium and plutonium (that is, nuclear fuel chemistry). As the extraction and preparation of nuclear fuels was the key to atomic energy, chemists devoted most of their attention to that work. At the same time, students of nuclear physics at Peking University studied not only the introductory course on nuclear physics but also principal chemistry courses, such as physical chemistry, complex chemistry and nuclear fuel extraction.

Overall, the radiochemical research work in China’s ‘two bombs and one satellite’ project was carried out by chemists with physical chemistry and quantum chemistry backgrounds. They not only took it upon themselves to conduct research into nuclear fuel chemistry but also trained a number of researchers in the field. In other words, a lot of chemists had to change their research fields by entering a field they were less familiar with. When they had to make a choice between a national task and their personal interest in science, and between the autonomy of science research and service to the country, how did these chemists respond?

3. Theory attached to practice: The extraction and separation of nuclear fuel

Nuclear fuel extraction mainly involves three production lines: uranium, plutonium and thermonuclear fuels. The development of atomic energy, semiconductor and rocket technologies requires a large amount of nuclear fuel. The preparation of uranium, plutonium and thermonuclear fuels is the most basic and extremely important part in the development of atomic bombs, hydrogen bombs and missiles, and is also a huge project. The uranium and plutonium fuels for atomic bombs and the lithium-6 deuteride-based thermonuclear fuel for hydrogen bombs all require complicated processes involving ore smelting and the extraction and separation of radioisotopes. The content of uranium in natural ores that can be used to make atomic bombs is very low. Because of the very low levels of plutonium in uranium ores, plutonium also requires separation and purification by chemists before being used as nuclear fuel.

There are two routes for making atomic bombs, the first being fuelled by uranium. China’s first atomic bomb was made of uranium-235. The first step to make a uranium bomb is to find uranium ores and extract uranium from them in a process called ‘pretreatment’. Pure uranium thus extracted is 0.72% uranium-235 and 99.28% uranium-238. As uranium-235 used to make atomic bombs needs to have a concentration of 99%, it has to be separated from uranium-238. After the separation of the radioisotopes, it needs to be restored to metal, which is then used to make atomic bombs. China was not rich in uranium which occurred mostly in small and medium-sized mines with other elements such as phosphorus, sulphur, and non-ferrous and rare metals. Therefore, uranium had to be extracted from the natural ores and then purified to uranium-235. The chemists’ work in this effort was to analyse the
presence of uranium in ores, then extract uranium from the ores by pretreatment, and then separate uranium-235 from uranium-238 to serve as a raw material for atomic bombs. In addition, they needed to separate uranium, plutonium (or thorium) and other valuable elements in a process called ‘post-treatment’, which enables researchers to not only recover and reuse the remaining and newly generated fissile materials and thus improve the utilization of uranium resources but also to use newly generated fissile fuels: plutonium-239 and plutonium-241.

While the Soviet Union provided assistance in many important processes and shared valuable experience in nuclear weapon development, it withheld some key techniques. After the Soviet Union stopped its assistance in 1958, China had to entirely rely on itself for the extraction and preparation of nuclear fuels. In the production of uranium-235, for example, China could not make key equipment required for the fluorination of uranium and isotope separation, and lacked important techniques. The Soviet Union kept its diffusive separation technology for uranium and in many cases provided only process parameters, without explanation. For the production of plutonium-239, the Soviet Union stopped the supply of key components after the water treatment and fluorination of uranium ores. China could not make those components, and its post-treatment process was backward as well. Even the design of the factory conducting uranium–plutonium separation had not been completed (Liu et al., 2004: 193–194).

Chinese chemists began officially and comprehensively getting involved in the charging and preparation of nuclear fuels in 1958 after the Soviet Union stopped its aid to China in atomic energy. Five chemical research institutes of CAS, including the Institute of Organic Chemistry and the Institute of Chemistry, reached a collaborative agreement on atomic energy. The agreement identified priorities for systematic study, including uranium and thorium chemistry, organic extractants, ion-exchange resins and metal corrosion chemistry, which covered a number of chemical issues relating to the pretreatment and post-treatment of nuclear fuels and the separation and preparation of stable isotopes of lithium and borohydride. Chemists at Peking University and the Institute of Atomic Energy also joined the work on nuclear fuel preparation.

Mined uranium ores were subjected to a series of processes, including beneficiation, crushing, leaching, extraction, ion exchange and roasting to produce a product called ‘yellowcake’, which was then converted to uranium tetrafluoride and then to uranium hexafluoride through hydrofluorination or extraction. Uranium hexafluoride has a low boiling point and can be gasified and made into nuclear fuel through the diffusive separation and enrichment of uranium. The extraction and diffusive separation processes were developed mainly by chemists.

In 1960, the Institute of Organic Chemistry of CAS organized a team of more than 60 researchers and workers and began the extraction of nuclear fuel. Xu Guangxian of Peking University worked on the chemical separation and nuclear fuel separation of uranium-235 and uranium-238, and at the same time he taught the separation chemistry course for graduate and undergraduate students of the radiochemistry and inorganic chemistry programmes of the Department of Technical Physics at Peking University. At that time, extraction chemistry was not a well-established discipline. There were confusing explanations of the mechanisms of extraction, and there was no extraction chemistry textbook, either. More importantly, extraction chemistry at that time was only an analytical method for element separation. Although much progress was made internationally in the extraction of inorganic substances, there was a lack of systematic theorization for nuclear fuel extraction (Xu, 1962). Therefore, Xu initially worked on the extraction classification system and extraction mechanisms. On that base, he developed the separation method for uranium-235 and uranium-238 and explored the efficiency and mechanisms of the synergistic extraction of uranium and hafnium with different extraction agents.

The research team at the Institute of Organic Chemistry that was responsible for nuclear fuel extraction also started its work with a focus on the solvent extraction of uranium. In 1961, the team invited Xu to give lectures on the classification of organic extraction agents (Yuan, 1961). After that, the research team was divided into three groups tasked to prepare three kinds of extractants: acidic organophosphorus extractants, neutral organophosphorus extractants and amine extractants. In addition, another group was responsible for the performance of
different extractants. Later on, the team was expanded to include graduates in specialties such as inorganic chemistry, analytical chemistry, radiochemistry and chemical engineering.

Among them, Lu Xiyan led the group for acidic organophosphorus extractants and improved the traditional method of alcoholysis of phosphorus pentoxide. Inspired by the phosphorylation reaction in nucleic acid synthesis discovered by Alexander Todd at the University of Cambridge, Lu and his team successfully synthesized the extractant P-204 with high purity (Zhu and Gao, 2018: 40). Xu Yuanyao and his amine extractants team not only prepared the extractant N-235 through a series of reactions such as ammonia solution, dehydration and ammonification based on mixed fatty acids, but also performed component analysis of the mixture. One year later, the team at the Institute of Organic Chemistry prepared the extractants P-204 and N-235 and successfully applied them to the preliminary extraction of uranium (Zhu and Gao, 2018: 37). Eventually, on 29 November 1963, the factory in Hengyang produced qualified uranium hexafluoride, providing a key raw material for uranium enrichment.

In the chemical pretreatment of uranium ores, the preparation of ammonium diuranate and the gaseous-diffusion-based enrichment of uranium were also important steps in extracting uranium. In order to precipitate ammonium diuranate without sulphate radicals from uranium sulphate solution, the Changchun Institute of Applied Chemistry systematically investigated the mechanism of sulphate radicals entering ammonium diuranate and the processing of amine ion exchange to produce sulphate-radical-free ammonium diuranate. In addition, the institute prepared uranium tetrafluoride from uranium dioxide using three methods by thermolysis-based purification of uranium and achieved a recovery rate comparable to the level reported at the second Geneva International Conference from May 1961 to July 1962 (Liu, 2019). They also prepared uranium hexafluoride by fluorination and submitted a crystallized sample of uranium hexafluoride to the Second Ministry of Machine-Building Industry, an administrative department for the bomb. The Institute of Chemistry carried out research on subjects including reaction dynamics, the sintering of uranium tetrafluoride and impurities in uranium tetrafluoride. Wu Zhengkai participated in gaseous-diffusion-based uranium enrichment in 1960 and 1961. He was responsible for the preparation of uranium hexoxide, including the engineering conditions for uranium enrichment. Cao Benxi, a chemist, in cooperation with Wu, made a special contribution to the chemical separation of uranium hexafluoride and plutonium.

At the time, plutonium provided a route to a fissile isotope without the energy-intensive requirement for high levels of isotopic enrichment that are essential with uranium. In fact, China initially considered plutonium for its nuclear programme but postponed the plutonium route and focused on uranium enrichment in the early 1960s when it experienced 3 years of famine. In contrast to uranium fuel, which involves a high raw-material separation cost, the preparation of plutonium fuel is much cheaper because plutonium-239 can be obtained through post-treatment from the solution in which uranium rods are dissolved in a reactor. Although technically it is easier to prepare plutonium than to prepare high-concentration uranium, the design of a plutonium bomb is more difficult than the design of a uranium bomb. Plutonium present in the world today is almost entirely synthetic in origin. The exceptions are trace amounts that occur occasionally together with uranium ores. It must therefore be produced in reactors. In order to separate the plutonium, the final product of the reactor must be chemically treated (that is, through post-treatment).

At that time, China had established the No. 404 factory for post-treatment. In assisting China, the Soviet Union introduced the precipitation method used in the post-treatment process, which involved precipitating one element while leaving the other element in the solution, thus separating uranium and plutonium. However, after precipitation, filtration was required, which would release a lot of radioactive wastewater, and refiltration was required if the filtered liquid was not clean enough, thus further increasing the amount of wastewater generated. The Second Ministry of Machine-Building Industry convened a top-secret meeting in Yan’er Island in Qingdao to discuss whether the project should continue to use the precipitation method or develop other methods. Both Xu Guangxian and the scientists at Tsinghua University strongly supported the extraction method. Xu had carried out research on
the chemical extraction of nuclear fuels for 5 years, and the scientists at Tsinghua University also had filtration devices. The ministry eventually decided to adopt the extraction method and then build a post-treatment factory, headed by Hou Debang’s student and chemical engineer Jiang Shengjie (Ye et al., 2013: 97). The ministry assigned the basic research tasks in the extraction-based separation of plutonium to Xu Guangxian and his colleagues. After the post-treatment factory was established, its processing not only substantially reduced waste but also significantly reduced costs in comparison with existing methods in foreign countries. China’s second atomic bomb, which was successfully tested in December 1968, was made of plutonium.

In the preparation of thermonuclear fuel for hydrogen bombs, lithium-6 deuteride is an important material. In March 1967, the Institute of Organic Chemistry began examining a new process for the separation of lithium isotopes. More than 40 scientists and technicians, in collaboration with relevant factories ministered by the Second Ministry of Machine-Building Industry, in the course of several years and on the basis of a large amount of experimental research, synthesized a total of more than 200 extractants and identified extraction tasks with high extraction efficiency and practical value from thousands of extraction systems. In 1960, CAS also organized several chemistry institutes to solve multiple key analytical and testing problems relating to nuclear fuel extraction and preparation, nuclear testing and nuclear materials using a diversity of methods. They included, for example, the determination of several impurities in metal uranium and its compounds, the analysis of trace uranium in nuclear industrial wastewater, the analysis of various gases emitted from the production of uranium hexafluoride, and the analysis of ultrapure reagents in nuclear fuel processes.

The involvement of Chinese scientists in the nuclear weapon programme in the late 1954 would soon expand and have profound impacts on the debate over basic and applied research (Wang, 2018). After that, scientists had discussions about whether scientific research should be for science’s sake or in the service of production. Some institutions, such as CAS and Tsinghua University, also had debates on those topics, while emphasizing planned scientific activity and calling for respect for and reliance on scientists in scientific decision-making.

In 1955, Guo Moruo, in his report to the conference on the establishment of the academic divisions of CAS, noted that the primary shortcoming of the academy’s leadership work was the failure to seriously examine the practical needs of the country in forming its research plans, and he called for giving full scope to the initiative and creativity of scientists and relying on scientists to advance scientific work (Guo, 1955). In the discussion on the purpose of scientific research, Yan Jici, director of the Division of Technical Sciences of CAS, observed that, while transforming scientists, it was also important to respect scientists and believe in their ability to do well in their fields of research (Yan, 1957). Scientists interpreted ‘attaching theory with practice’ as ‘starting out from practice, then theorizing, and then attaching the theory with the practice’, which served as an important guideline for scientific research, and conveyed the message that theories could be advanced with practice.

After shifting to the practical work of nuclear fuel extraction and enrichment, chemists began adjusting ‘theories’ by identifying their areas of strength and using them in the service of national needs for example, Xu Guangxian leveraged his expertise in clathrate chemistry to find extraction methods suitable for nuclear fuel separation and laid the theoretical foundation for the preparation of extractants of nuclear fuel. Yuan Chengye, who had specialized in pharmaceutical chemistry and polypeptides, focused his research on amine extractants and led a group dedicated to research on the structures and functions of extractants. These practices also helped refine theories. Leveraging their scientific expertise and driven by their pursuit of scientific truth, the scientists advanced China’s ‘two bombs and one satellite’ project and achieved success through their technological achievements, rather than recognition from the scientific community.

After the success of the project, the chemists turned to apply the technologies used in the project to serve civil society and broke new ground. Xu Guangxian applied extraction chemistry to the extraction and separation of rare-earth elements and
then theoretically explored the electron structures, chemical bonds and clusters of rare-earth polynu-
clear complexes from the perspective of coordination chemistry and quantum chemistry. Yuan
Chengye applied the extractants developed in the bomb project to the separation of rare-earth and non-
errous metals and conducted research on biologi-
cally active organophosphates based on neutral organophosphorus extractants.

4. Tasks leading disciplines:
Fluorocarbon and fluorine materials

China’s long-term national science and technology plan introduced in 1956 put forward the slogan ‘tasks leading disciplines’, which gave consideration to both applied research and basic research. The last of the 12 key tasks specified in the plan was ‘investiga-
tions into some basic theoretical problems in the modern natural sciences’. After more scientists became involved in the nuclear programme in 1958, ‘tasks leading disciplines’ became a potent slogan encouraging chemists to shift their work areas to serving national tasks.

As I have mentioned, the extraction and enrichment of uranium for atomic bombs required the fluorination of uranium and uranium enrichment through gaseous diffusion, which involved processes that needed ero-
sion- and radiation-resistant materials and special lubricants. Artificial satellites making also needed special materials for temperature control. All these needed support from fluorine chemistry and industry.

At that time, fluorine chemistry was not yet developed in China (few chemists were engaged in this field), and organic fluorine chemistry was an emerging discipline even globally. Recognition of organic fluorine chemistry as a large and important area of chemistry was only possible in the 1950s (Krespan, 1960). Moreover, due to the need for confidentiality, there was no open-source information internationally about the methods of preparation of new fluoride materials such as fluororubber and fluororesin.

It is a long way from basic research in fluorine chemistry to the production of fluororubber, which requires rigorous research and much effort, and this points to the outstanding success of China’s national defence task at that time (Zhu and Huang, 2015: 113).

Jiang Xikui, a chemist at the Institute of Chemistry of CAS, who conducted some basic theoretical research on organic fluorine chemistry in the United States, served as the head of the fluororubber task-
force, and his team successfully prepared No. 1 fluororubber in September 1959. In the autumn of 1960, Chen Qingyun, who previously studied organic fluorine chemistry in the Soviet Union, joined the Institute of Chemistry and became a member of the fluororubber taskforce. The fluororubber had two components. One component required electro-
lysis and a very difficult process of preparation and could not be used for production. Therefore, the team had to shift to a different route of synthesis. After Chen Qingyun joined the team, he developed a new means of fluororubber preparation and eventually identified the best conditions for the preparation of hexafluoropropylene, providing a basis for the subsequent large-scale production of the substance in 3 years. Then the team successfully prepared fluororubber No. 2 and No. 3, which supported national defence projects. The new method that the team invented then is still used today worldwide, rather than the electrolysis method. Later, the Institute of Chemistry and the Shanghai Institute of Organic Chemistry ran research projects on fluoride materials. As the required materials were not availa-
ble in Beijing but in Shanghai, CAS decided to trans-
fer all related tasks of the Institute of Chemistry to Shanghai. As a result, Chen Qingyun followed the taskforce led by Jiang Xikui to the Shanghai Institute of Organic Chemistry.

As bromine and chlorine have isotopes and fluo-
rine does not, turning uranium into uranium fluo-
ride and separating uranium isotopes through gaseous diffusion based on uranium fluoride is the best way to obtain enriched uranium. This also repre-
vented the biggest challenge in making atomic bombs. The purpose of gaseous diffusion was to separate gaseous uranium hexafluoride through gaseous barrier diffusion. As one individual separation component had only a very limited separation capability, the entire system needed thousands of separation components.
The biggest problems relating to the diffusion process were erosion and clogging. For the entire project, infrastructure and equipment installation was only a small part of the work. Because uranium hexafluoride is highly corrosive, the lubricant used in the diffuser must have high corrosion resistance and be inflammable, despite high-speed friction. Therefore, the gaseous diffusion process required the equipment, especially the pumps, to be resistant to high temperatures and highly corrosive uranium hexafluoride. Traditional lubricants would combust under the heat generated by high-speed friction. At the time, there were new lubricants in the form of fluorocarbons that were both lubricating and inflammable. The properties of the fluorocarbons coincided with those required for materials used in handling uranium hexafluoride. However, when the Soviet Union withdrew its experts, they took away this lubricant as well. The search for better ways of synthesizing fluorocarbons had been pursued intensively during World War II (Krespan, 1960).

In November 1960, the Institute of Organic Chemistry was assigned the task of developing the lubricant. Huang Weiyuan, a chemist specializing in steroid chemistry, used his analytical expertise in organic compounds to analyse the structure of the lubricant with infrared spectrometers and eventually determined the appropriate conditions for the preparation of fluorocarbon. In addition, the institute also synthesized materials required to be corrosion and radiation resistant (those materials would be used in the diffusive separation equipment, including gaskets, spacers and valves) and constructed the production workshop.

The Changchun Institute of Applied Chemistry, based on its research on the preparation of fluorine at medium and high temperatures, completed the research on the phase equilibrium and best process conditions for the conversion from uranium difluoride to uranium tetrafluoride. In the production of uranium hexafluoride from uranium tetrafluoride using the low-temperature process designed by the Soviet Union, the fluoride of uranium experienced sintering. The Institute of Chemistry of CAS was tasked to address this issue and finally clarified the mechanism for the elimination of the sintering phenomenon.

Fluorine compounds, especially fluorine-containing polymers, have excellent thermal and chemical stability. These materials with special properties were used in various components, such as sealing sheets and temperature control coatings, in China’s first artificial satellite. Temperature control of artificial satellites was an important emerging technology that required various new materials, including special temperature control coating. The Institute of Organic Chemistry developed a special organic coating, which was applied to the internal surfaces of artificial satellites for heat insulation. In addition, the institute was the only one capable of developing organic thermal control coating in China. Its organic coating was used in an experimental communications satellite successfully launched by China in 1984 and met the temperature control requirements for various parts of the satellite.

Scientific research has its intrinsic nature. Attaching theory with practice may not be a distinguishing strategy to achieve breakthroughs, especially in frontier and emerging technologies, which require comprehensive theoretical support as well as skills and experimental research. In exploring the conditions for preparing No. 1 fluororubber, Chen Qingyun leveraged his experience in making hexafluoroacetone, which played a key role in his effort to prepare hexafluoropropylene. On this basis, he kept on exploring and refining specific reactions.

Despite the strong support offered by the Institute of Chemistry to fluorine chemical research and the ample research force, fluorine chemistry still needed basic theories to make advances because it was a new area of chemical research. Thanks to the guideline of the strategy of ‘tasks leading disciplines’, China’s chemists always conducted their practical work with an idea of developing fundamental theories as well. For example, Jiang Xikui and Chen Qingyun, in their research on fluororubber, also carried out research on related basic theories and discovered the halophilic reaction, which was one of the earliest reactions discovered by Chinese chemists.

After the completion of the ‘two bombs and one satellite’ project, the Institute of Organic Chemistry established a research lab for fluorine chemistry. In its effort to explore civilian applications of fluorine chemistry, the lab developed chromium fog inhibitors.
for electroplating factories. During this research, it discovered a fluorine ether group chain with a unique structure, which paved the way to the development of a series of reactions and reagents named with the family names of participating chemists. In the 1990s, those findings were collectively referred as ‘Shanghai fluorine chemistry’ by international chemistry community. This exemplary case of the transition from state-sponsored applied research to basic research was regarded as evidence of the success of the concept of tasks leading disciplines. In addition, in their subsequent research activities, the chemists at the Institute of Organic Chemistry were always thinking about how to combine basic research and applied research and make better use of fluorine chemistry.

5. Exploratory research: The development of high-energy fuels

Qian Sanqiang regarded basic research as ‘exploratory research’. Besides his belief that scientific research is the exploration of truth and that exploratory research holds an important position in technological innovation over the long term, he emphasized basic research’s precedence over technology. The theoretical research team of the Institute of Atomic Energy first explored and preliminarily researched the mechanism of the hydrogen bomb and its possible structures, which was considered to be an essential step in the early phase of the theoretical exploration of the hydrogen bomb.

What exploratory research did the chemists carry out? In August 1958, the Scientific Planning Committee of the State Council pointed out in its report on the implementation of the 12-year scientific plan that research on artificial satellites would accelerate a series of fields of research, including high-energy fuel. High-energy fuel and high-performance materials are essential to rockets, missiles and satellites. Qian Xuesen, a chief scientist of China’s missile programme, once vividly observed that ‘Everything is ready except the east wind’, in which ‘east wind’ was a metaphor for high-energy fuel. China’s missile development was driven by both basic research and applied research from the very start, and CAS led the ‘exploratory research’. CAS had to explore from scratch and focus on high-energy fuel instead of conventional fuels. All the four institutes of chemical research under CAS were assigned research tasks on high-energy fuel, and the two institutes in Shanghai and Dalian even set up experimental bases in mountainous areas.

What high-energy fuel uses as its raw material was part of the exploratory work of CAS. Qian Xuesen learned from US journals about boron hydride being used as a solid propellant with higher energy density than conventional fuels. However, boron hydride fuel was difficult to prepare and was an area rarely explored in China. Even the international academic community initially researched it mainly out of a theoretical interest. A greater difficulty came from the facts that the preparation of borane required a high-vacuum environment and the compounds were explosive, thus having very high requirements for experimental instruments and equipment. After a lot of effort, Huang Weiyuan and his colleagues successfully synthesized boron hydride in a remotely controlled glass device. However, the US announced that toxic boron hydride could not be directly used as high-energy fuel. Instead, a liquid fuel called helium fluorine was a prospective solution. After that, the Institute of Organic Chemistry made improvements based on boron hydride and eventually prepared helium fluorine fuel.

Along with exploratory research on the preparation of high-energy fuel, several institutes of chemical research under CAS developed a high-energy explosive to trigger the hydrogen bomb and also developed the cohesiveness of solid propellant and burning rate modifier. For example, the Institute of Applied Chemistry was assigned the task of developing liquid Thiokol, and the Lanzhou Institute of Chemical Physics put in place an entire research system covering a full range of subjects, including explosive synthesis, analysis and testing; moulding charges; amplification testing; and detonation theory. More than 150 researchers were transferred from other institutes to the Lanzhou Institute of Chemical Physics, accounting for 43% of its total staff. The institute’s research results were later used in China’s first hydrogen bomb.

The exploratory research conducted by chemists on high-energy fuel was basic research in a new field
with the ultimate purpose of technological realization. Although the hydrogen bomb was successfully tested, significant resources and time were wasted by following the US route due to lack of experience. While some exploratory work achieved applications, the subsequent basic research did not follow up. In 1972, for example, the high-energy explosive unit of the Lanzhou Institute of Chemical Physics was merged into military production departments, including half of the institute’s fixed assets and one-third of the institute’s research personnel. Exploratory research results that were confidential were either eventually transferred to military production departments or left unpublished. Although the contributing chemists received recognition from the state in the form of accolades such as national defence medals, they did not receive wide acknowledgement from the scientific community, which was indeed regrettable.

Science has its own evolution. It is an investigative enterprise that requires inputs of technology, operations, experiments and apparatus as well as fundamental concepts and theoretical explanations. Viewing science as an investigative enterprise rather than an explanatory one is emphasized by scholars of the philosophy of scientific practice in their discussions on the structure of scientific development. The ‘two bombs and one satellite’ project is a case in point. Small factories were set up at research institutes because of the concept of ‘institute–factory’ advocated in the project for integrating scientific research, production and application. Those factories played a positive role in accelerating the independent development and design of raw materials and apparatus used in chemical research and chemical research’s translation to chemical engineering.

6. Situated basic and applied research in the context of national tasks

The debate on whether there is a dichotomy between applied and basic research or a distinction between the internal and external development of science is not helpful in examining the structure of science. Science evolved in its practice. Understanding the meanings of the concepts of applied and basic research in both local and global contexts is a pressing problem to be addressed in the history and philosophy of science. The global turn in the history of science not only provides an expansion of geographical scope but also requires the exploration of the temporal-spatial and dynamic characteristics of the spread of science and placing national or regional science in the global context.

It should be noted that this study is not meant to be a comprehensive survey of the work of chemists in the ‘two bombs and one satellite’ project or a discussion of the relationship between ideology and science, but a case study on the neglected activities of chemists in a historically significant project. I focus on how those chemists both in academia and in the task-oriented national context have had to position themselves and their work in a complex field. In such cases, we need to examine how the chemists understand the relation between basic and applied research.

In the project, Chinese chemists shifted from their previous research to fields related to the project, especially radiochemistry, nuclear fuel chemistry, fluorine materials and high-energy fuel. That shift not only accelerated the circulation of related chemical knowledge worldwide but also created new fields of research and new scientific knowledge, such as extraction chemistry and fluorine chemistry. Robert Merton’s account of the ethos of science is a sociological account consistent with the definition of scientific success as the locus of reliable knowledge of nature (Richardson, 2004). The social dimension of scientific knowledge does not disrupt the epistemic privilege of science. Disinterestedness and the universality of science are the foundation of scientific knowledge’s global circulation. The work on the chemical reactions and theories of phosphorus chemistry and fluorine chemistry developed by Chinese chemists after the project showed its continuity on the basis of the principal theory, mechanism and techniques of nuclear fuel extraction. And the new chemical knowledge was circulated to other parts of the world after the recovery of China’s international exchanges.

In his research on the social direction of science, Kitcher (2011: 260–264) argued that there is no absolute standard for the significance of research projects; nor is there any standard for ‘good’ research, apart from subjective preference. The only non-arbitrary approach to defend judgements concerning research
agendas in the absence of absolute standards is to establish collective preferences democratically. However, his proposal was criticized for the excessive idealism of his well-ordered science. The government-regulated research in the project undoubtedly sacrificed the autonomy and subjectivity of scientists, but, on the other hand, the administrators and scientists had their own responses to that situation.

Promoting applied research through basic research and driving theoretical investigations through national tasks was a unique understanding of scientists in the ‘two bombs and one satellite’ project about the relationship between basic and applied research. They integrated those two sides in their scientific practice. Basic research as understood by the chemists was closer to theoretical research, while applied research referred to the specific programme tasks assigned by the country.

From attaching theory with practice to conducting exploratory research, the chemists were always looking for zones where basic research and applied research could be integrated. After their shift to ‘practical’ research work, they achieved their autonomy by regulating the ‘theory’ and working in areas where they had advantages. When working on technological realization, they remained committed to theoretical exploration. After the success of the project, the scientists, in their subsequent research, remained focused on how to integrate basic and applied research. In the fields of fluorine chemistry and extraction chemistry, for example, the chemists first explored how to put the research results developed in military programmes into civil uses. Even after they regained their autonomy in basic research in the 1980s, chemists were still committed to applying the high-efficiency chemical reactions developed in fluorine chemistry to the synthesis of new compounds that would benefit the world’s well-being.

Mertonian norms of science offer a way to analyse how the chemists continuously regulated and handled the tension between planned research and the autonomy of science. Departing from the definition of the Mertonian norm of disinterestedness, the chemists understood the disinterestedness of research in terms of serving China’s national interests. In contrast to recognition earned from the scientific community in pure science, technological realization served as an alternative recognition of the research work in the project. Despite this, the chemists always maintained the norm of universalism of pure science. During the ‘Great Leap Forward’ period (1958–1960), Xu Guangxian led the uranium separation work. In response to a reported extraordinary rise in uranium enrichment, he repeated the same experiments for more than 50 days to validate the results, despite the wishes of other team members to report the progress to the CPC Beijing municipal committee (Ye et al., 2013: 98–99). In addition, while technological realization itself was a form of recognition of scientists participating in the project, the scientists also valued recognition from the scientific community for their work. Therefore, the slogan ‘tasks leading disciplines’ was well received by the scientists because they found balance between working in planned research and pursuing science for science’s sake. In 1959, the journal *Atomic Energy Science and Technology* was established, which not only promoted academic communication but also satisfied the wishes of the scientists to get recognition from the scientific community.

Therefore, revisiting the relation of basic and applied research in the context of China’s ‘two bombs and one satellite’ project by focusing on the scientific practice of the chemists may offer a different understanding of the inherent tension between basic and applied science.

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