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Organization Strategies of Innovation Forces for the Breakthrough of Key Core Technology in Aero-Engine Industry

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Abstract: Achieving breakthroughs of key core technologies in the aero-engine industry is urgently required for guaranteeing national strategic security, and it demands effective organization of innovation forces. This study first analyzes the major innovation forces and their problems regarding collaborative innovation in the current aero-engine scientific research and production system in China. It subsequently clarifies the roles of relevant forces in the research process of key core technologies, including the government, the Army, the Aero Engine Corporation of China, professional maintenance enterprises, upstream and downstream enterprises, universities, and research institutes. Furthermore, the breakthrough practice should be planned and organized in an overall manner. Additionally, corresponding institutions and mechanisms should be created to encourage the innovation forces to closely align with national strategies. Moreover, the driving role of the demand side should be emphasized, a number of innovation consortia aiming at user needs and product problems should be established by leading enterprises, and an innovation ecosystem should be established relying on major projects.

Key words: aero-engine industry; key core technology; collaborative innovation; innovation consortium; national system mode

1 Introduction

An aero-engine is an extremely complex engineering machinery system involving many disciplines and integrating many cutting-edge technologies. The development level is the concentrated embodiment of national scientific and technological strength, industrial foundation, and comprehensive national strength. With the establishment of Aero Engine Corporation of China (AECC) and the implementation of the National Science and Technology Major Project on Aero-Engines and Gas Turbine, China has made significant progress in the independent research and development (R&D) capability of aero-engines. However, there is still a large gap with the world's top level due to the industry difficulty and its late start-up time.

According to the relevant data of *World Air Forces 2021*, the number of military aircraft in China is less than 1/4 of that of aviation powers. In terms of composition, the second-generation aircraft in China's fighter aircraft accounted for 46.75%, while developed countries have mainly eliminated such aircraft. With the enhancement of Chinese economic strength and international status, some countries regard China as a competitor, and the international situation has changed significantly. National defense strength is the foundation and support of superpower games. To enhance the control of airspace and fully ensure national security, China should break

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through the key core technology of domestic aero-engines the soonest possible, thus to promote the self-control of the aero-engine industry chain and supply chain as well as the self-reliance of science and technology.

Key core technologies refer to the technical system that controls the technical commanding point of the same industry, which plays an irreplaceable, not-easy-to-master and not-easy-to-surpass role [1]. Owing to the extremely high requirements of the intersection of basic knowledge and interdisciplinary knowledge, breaking through the key core technologies of aero-engines must take the form of in-depth cooperation among various innovative forces. For example, turbine disk technology was once a difficulty in the development of the aero-engine in China. The AECC Beijing Institute of Aeronautical Materials formed a joint research team with major engine manufacturers, professional factories, and universities, and finally solved the technical problem of powder turbine disk development in the form of in-depth cooperation. However, the effective organization of innovation forces is a bottleneck problem that needs to be solved urgently in the practice of key core technology research in China [2]. Relevant research as a whole is in its infancy, such as a new national system mode of key core technology research [2,3], industry–education–research deep integration mode [4], innovation ecosystem mode [5], and multi-agent equilibrium [6]. These research results can provide general ideas for the breakthrough of key core technologies of aero-engines, and they are not targeted because they are not closely integrated with the aero-engine industry.

From the practice in China and abroad, a joint research mode led by the government is usually adopted for developing the key core technologies in major scientific and engineering innovation fields related to national development and security, achieving success with professional division of labor and large-scale cooperation within the industry. To provide basic reference for the technology management and R&D layout of relevant industries, this study focuses on the innovation subjects and coordination problems of Chinese aero-engine scientific research and production systems, sorts the role definition of the relevant subjects of aero-engine key core technologies, and suggests organization strategies of the relevant subjects.

2 Composition of innovation subject and collaborative innovation of aero-engine scientific research and production system

2.1 Current status of innovation subject composition

After decades of development, China's aero-engine industry has formed a scientific research and production system covering three links: R&D and design, processing and manufacturing, operation and maintenance. (1) The R&D and design link is divided into basic pre-research, subsystem design, integrated design of complete machine, and other sub links. The major participants are units in the AECC system, aviation universities, and related scientific research institutions. (2) The processing and manufacturing link involves sub links such as raw materials, parts and components, and complete machine integration. In addition to the units in the AECC system, the participants also include enterprises outside the system and scientific research institutes. (3) The main body of operation is the Army, and that of maintenance includes the maintenance enterprises subordinate to AECC and the professional maintenance enterprises. It is worth mentioning that under the background of promoting the combination of military and civilian functions, with the gradual construction of the scientific research system under the idea of "small core, large cooperation, specialization, and openness," many private enterprises have been attracted to participate in the aero-engine industry chain. They have intensively developed in subdivided fields, achieved product specialization and differentiation, and injected vitality into the development of the aero-engine industry. The composition of the major innovative bodies of China's aero-engine scientific research and production system is illustrated in Fig. 1.

2.2 Problems in collaborative innovation

Aero-engine products are a special kind of industrial products. The key to their development is not to master a single technology, but to integrate various technologies. The breakthrough of key core technologies is not in a single field, but a collective breakthrough in the field of technology in all links, which requires smooth connection and close coordination between the main bodies of all links. However, under the current mechanism in China, there are many phenomena such as "management islet," "data islet", and "technology islet" in the aero-engine scientific research and production system, resulting in insufficient connectivity of all links and difficult realization of overall efficiency.

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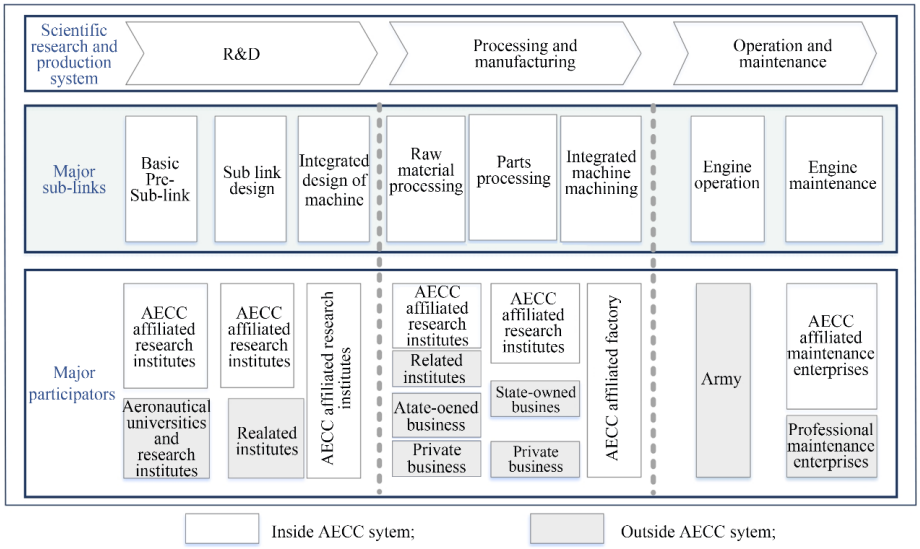

Fig. 1. Composition of innovative subjects in China's aero-engine scientific research and production system.

First, in terms of the "management islet" of scientific research plans, China has not established a department in charge that comprehensively manages the innovative development of the aero-engine industry, and the corresponding regulatory responsibilities are scattered in related ministries and commissions of the Central government and the Army. This "management fragmentation" situation can easily cause management departments to focus solely on their own parts. Hence, there may be competition and game between various departments, which is not conducive to the overall situation and coordination of the chain to carry out scientific plan, resource supply, and coordinated management, and it is difficult to form an innovative joint force to the greatest extent.

Second, regarding the "data islet" of major links, information sharing in R&D design, processing and manufacturing, operation and maintenance is the basis for efficient collaboration among innovation entities. Owing to the management system, the phenomenon of "data islet" between links is more prominent at present. (1) "Data islet" in R&D, design, processing and manufacturing can be summarized as follows. Chinese aero-engine design institutes are separated from the manufacturers, which makes it difficult to share information in the design and manufacturing links in time. A situation may arise in which the designer does not know the process capability and does not grasp the realization of the process, while the manufacture does not understand the design criteria or intent, and so on. (2) "Data islet" in design, manufacturing, and maintenance. The R&D, design, processing and manufacturing of aero-engines in China are mainly undertaken by the industrial department (e.g., AECC), while maintenance is mostly undertaken by equipment support enterprises managed by the military. This leads to a large amount of maintenance data and professional knowledge, which have accumulated in the maintenance support link for a long time, but cannot effectively feed the improvement, upgrading, and new research of models, thus restricting the improvement of the independent R&D level and service support ability.

Third, the "technological islet" of scientific research achievements can be summarized as follows. (1) The "technology islet" in the AECC system. The AECC attaches great importance to the sharing of scientific and technological information and the transformation of achievements. It has taken a series of relevant measures, such as building an information sharing platform for scientific and technological achievements, realizing the information sharing between scientific achievements and related intellectual property rights, and providing services such as scientific and technological achievements information inquiry and screening, which has promoted the achievements of directly affiliated units to self-enforce and transform. However, due to the barriers caused by the business competition between various units and the strict confidentiality requirements of military enterprises, the promotion and transformation rate of various research results to other enterprises and the whole industry is low [7]. (2) "Technology islet" between industry, university, and research. Although the AECC has actively promoted and made progress in industry–university–research cooperation, owing to the incentive mechanism for transformation of scientific and technological achievements for universities and scientific research institutions, and other factors, the current system and mechanism to support achievement transformation industry is still not smooth. Most of the scientific and technological achievements in basic research, such as inventions, patents, papers, and so on, led by universities and scientific research institutions, cannot meet the needs of the industry.

3 Related subjects of tackling key core technologies of aero-engines

Aero-engines are related to national development and defense security. Tackling key core technologies is a typical mission-oriented task, which should coordinate and organize industry elite forces based on the national system model. The major bodies involved in this mission include the government, the military, R&D institutions, enterprises inside the AECC system, upstream/downstream enterprises outside the system, professional maintenance enterprises, universities, and scientific research institutions. There are differences in the main interest demands of various participants and their role positioning in tackling the key core technologies (Fig. 2).

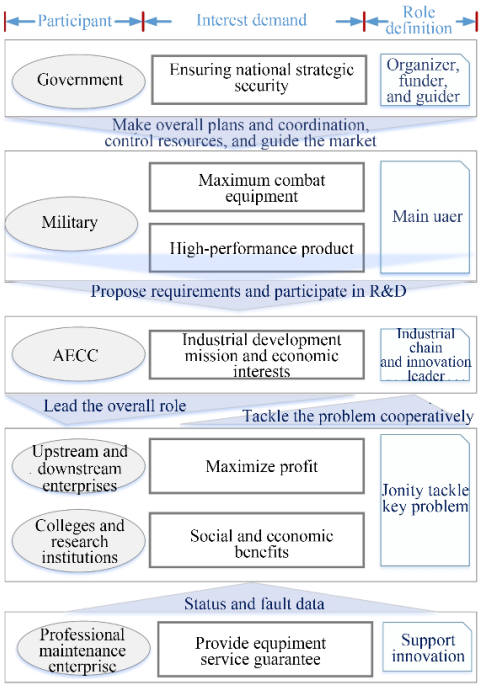

Fig. 2. Interest demands and role definition of participants for developing key core aero-engine technology in China.

3.1 Government

The interests of the government are to ensure national strategic security and enhance airspace control. The government has a strong ability of overall planning and coordination and a wide range of resources at its disposal. It should be the organizer and sponsor of tackling key core technologies of aero-engines. However, such technologies are highly complex. The performance and reliability can only be improved through continuous trial-and-error and testing in industrial practice, through accumulation, analysis, and feedback application of many empirical data. Therefore, the government should also play an active role in the construction of application markets, encourage relevant users to use domestic aero-engines, and constantly drive the breakthrough and improvement of key core technologies in use.

3.2 The military

The military is the main user of domestic aero-engines, and the relevant demand is an important basis for the development of the industry. One of the military's key responsibilities in the process of independent innovation development of aero-engines is to scientifically put forward military needs and accurately tow industrial development. Generally, military users require manufacturers to provide technologically advanced aero-engines, and to pursue high combat performance and reliability. The military should collect and analyze the problems of aero-engines exposed in the process of combat readiness training or combat in a timely manner, provide timely and accurately feed back to the industrial department, jointly research and propose improvement suggestions, and steadily promote the improvement/modification and new research of aero-engines.

3.3 AECC

The AECC is the national aero-engine development team and the leader of the aero-engine industry chain, shoulders the historical mission of independent innovation and development of the industry, and is focused on

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realizing the commercial value of products. The AECC undertakes important major functions in R&D and design, processing and manufacturing, and maintenance and support, and is actually in a monopoly position in the whole machine integration. As a leading enterprise of the industry and owner of the industrial chain, the AECC should know the bottleneck of industrial development better than other subjects. Therefore, in the process of industrial independent innovation and development, the AECC should actively play its leading role, build a national strategic scientific and technological force, guide other subjects to conduct collaborative research on the tasks and goals of key core technology innovation, and lead the integration and innovation of the industrial chain.

3.4 Professional maintenance enterprises

The professional maintenance enterprise is an important force in the Chinese aero-engine industry system and has accumulated extensive state and fault data in the maintenance process. Feeding these maintenance data and knowledge back to model improvement/modification and new research will substantially improve the aero-engine development level. The increase in the intensity of practical training has produced much aero-engine equipment loss data, which should be fed back to the R&D, design, processing, and manufacturing links in a timely manner. All the industrial systems of the world's aero-engine powers have the characteristics of design–manufacturing–maintenance integration, which provides a basic guarantee for the timely sharing and accommodation of data in major links.

3.5 Upstream/downstream enterprises

According to the theory of value chain division of labor, in the era of global division of labor, the innovation and development of any industry requires not only the "traction" of large enterprises, but also the technical support of upstream/downstream enterprises [8]. The same is true of the aero-engine industry. The research on key core technologies requires a high degree of collaboration between the AECC and "specialized, refined, special, and new" enterprises outside the AECC system that have technological advantages in the relevant subdivisions of the industrial chain. Furthermore, a collaborative technological innovation system led by large enterprises and promoted by the aforementioned enterprises should be established the soonest possible. In recent years, with the accelerated release of military aero-engine demand, many excellent private enterprises have entered the aero-engine field. In view of the great difficulty and high risk in the development of aero-engines, private enterprises mostly enter the field from the aspects of materials and parts, actively undertake the task of model research and production, and has become an important supplier in the field of aviation power [9].

3.6 Universities and scientific research institutes

Universities and scientific research institutes are the basic forces of scientific research and an important base for talent training. They shoulder the important task of national public science and technology supply and provide innovative technical support for enterprises. The basic research and key core technology research of aero-engines are mainly undertaken by relevant universities (such as Northwestern Polytechnical University, Beihang University, Nanjing University of Aeronautics and Astronautics, Shanghai Jiao Tong University, Harbin Institute of Technology, and Tsinghua University) and research institutes subordinate to the Chinese Academy of Sciences (such as the Institute of Engineering Thermophysics, Chinese Academy of Sciences). With the development of a new-generation or new-concept engine as the main research goal, it is necessary to explore new working principles, design ideas, design concepts, new materials, new processes and new engine technologies, and verify the engineering application prospects through experimental principle, digital simulation, and other methods. The interest demands of universities and scientific research institutions include social and economic interests. The latter refers to the direct or indirect economic benefits generated by the output of technological innovation.

4 Organization strategy of key core technology research subjects of Aero-engine

The certification process of military suppliers is strict and complex, and it often takes many years from pre-research to final batch production review. Once the batch production review is passed, the two sides will form a long-term and stable cooperative relationship. Therefore, the aviation engine industry has high barriers regarding qualification, technology, and customer conversion costs, which directly leads to the relatively stable competition pattern of suppliers in the industrial system and relatively few market participants. China's aero-engine industry is still in the "follow-up" stage, with relatively definite market demand and a clear technical route. Based on the attributes and characteristics of the aero-engine industry, the government has adopted a centralized and strategic

planning model to develop key core technologies, with remarkable results. At this stage, under the technological paradigm of China's aero-engine industry, this organizational model is less likely to have signal distortion and resource mismatch and has institutional and economic rationality [10].

To establish an efficient collaborative research mechanism, the government needs to open up the management, data, and technology islets in the existing scientific research and production system. Based on the role positioning of various subjects, these should be encouraged to give full play to their due role and build a community of interests around the key research goals. Specifically, the government needs to conduct a comprehensive planning and overall layout of technological research from the top, guide and stimulate the consensual actions of relevant subjects through institutional arrangements and mechanism design, provide traction power through the release of demand-side market, and carry out collaborative research work with innovation consortia as the major organization form and major projects as the carrier.

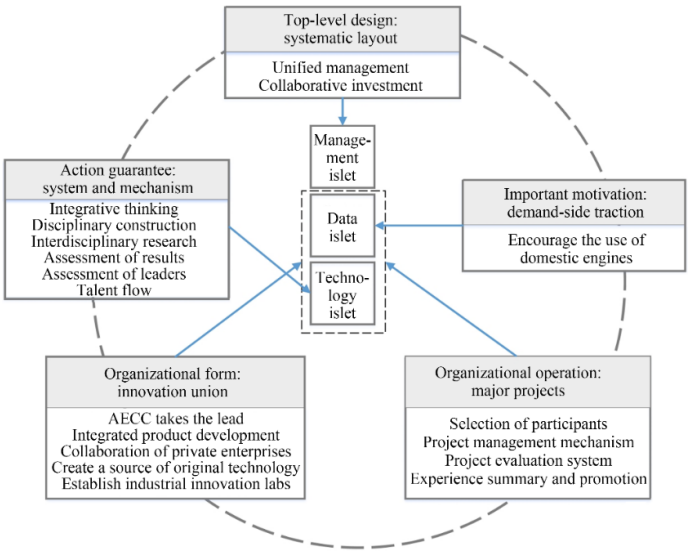

Fig. 3. Organizational strategy of research subjects for core aero-engine technologies in China.

4.1 Making overall arrangements and scientific layout for key core technology research based on the overall view and collaborative view

Overall and collaborative views of the independent innovation and development of the aero-engine industry should be established as well as focus on the integration and innovation of the industrial chain, and form a systematic layout of key core technology research with focus, gradient, and hierarchy. It is suggested to establish a competent department to comprehensively plan and manage the development of aero-engines, systematically plan and focus on guiding the key core technology research work. It is necessary to realize the linkage of management departments responsible for supervision, and effectively connect with various national science and technology plans to reflect the collaborative investment of the industrial chain. Duplicative and inefficient layout and eliminate multiple channels of repeated funding for the same technical field should be avoided as well as "faults" and "gaps" in the direction of important technical fields. For example, after the completion of basic research in the field of aero-engine materials, if there is a lack of process technology research connecting the application of models, new material technology will often be shelved or even interrupted. The focus of key resource investment and eliminate the situation of average investment and purposeless investment should be maintained.

4.2 Considering the different interest demands of all kinds of innovation subjects, designing systems and mechanisms that effectively guide and encourage all kinds of subjects to actively and closely connect with the national strategy

Efforts should be made to change the competitive thinking of the existing policy system to integrated thinking, and guide all kinds of subjects to form scientific cognition and consensus on the collaborative research of key core technologies of aero-engine. Additionally, it is necessary to form an innovation joint force to the greatest extent. It is suggested to set up the first-class discipline of aerospace power science and technology, establish the national laboratory of aerospace power, comprehensively build the discipline talent training system, and improve the speed and quantity of high-quality and high-end talent training. For aerodynamics, engineering thermophysics,

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mechanics, electronics, automatic control, and other disciplines involved in aero-engine development, we should explore and realize the connection from basic to applied research and then to industrialization, and support and promote interdisciplinary research. We should encourage basic aeronautical scientific research to meet major national needs and strengthen the engineering orientation of papers, patents, and other research results. A talent flow mechanism should be built between universities, scientific research institutions, and enterprises, to support scientific researchers to work part time in enterprises. It is also necessary to effectively impose the national will on the management level of enterprises, improve the assessment mechanism of enterprise leaders, and drive attention to key core technology research. For cross-tenure projects, we should pay attention to the continuity of assessment project support, implement the tolerant failure mechanism of due diligence and exemption, and cultivate strategic leaders with entrepreneurship [11].

4.3 Focusing the traction of the demand side on the development of key core technologies and encouraging users to use domestic engines

Considering engine performance requirements, users' concerns regarding the reliability of domestic engines, and the limitations of development policies and management measures in related fields, the domestic demand potential of China's aero-engines has not been effectively transformed into the R&D power of key core technologies of domestic aero-engines [2]. It is generally believed that the traction effect of the demand side is crucial to the R&D of key core technologies in the industry, which is mainly reflected in two aspects: (1) providing testing and application scenarios for key core technologies, constantly conducting trial-and-error and testing in flight practice, and accumulating empirical data to help continuously improve performance; (2) realizing the industrial value of key core technologies through product transformation and large-scale application. The government should pay attention to the traction effect of the demand side and encourage users to use domestic engines. The expanded use and iterative updating of domestic engines and their supporting products can be promoted in the form of legislation [12]. In this way, key technology breakthroughs, sample scale application, and industrial ecosystem cultivation are closely combined, and the stability and reliability of core products and technologies are continuously improved through the market release on the demand side, so as to fundamentally ensure the key core technology breakthroughs of aero-engines.

4.4 Highlighting the guiding role of leading enterprises and building several innovative consortia facing user needs and product problems

The industry leader leads technological innovation in implementing the national system [13]. AECC shoulders the major national mission and has rich innovation resources. In the process of collaborative research on key core technologies, its leading role should be strengthened in target and task determination, research organization, achievement transformation and application. A number of government–industry–education–research– application innovation consortia that integrate interaction, close collaboration, and win-win cooperation should be established through collaboration of universities, scientific research institutes, upstream/downstream enterprises, and so on, and by focusing on specific needs of users and product specific problems. We should also implement collaborative innovation guided by industrialization and integrate basic and application research [14] to build an integrated product development mode of aero-engine throughout the lifecycle. AECC should be encouraged to explore and build a collaborative mechanism of resource opening and capacity sharing for upstream / downstream enterprises, especially private enterprises. The ability improvement of enterprises should be supported in the direction of subdivision technologies and they should be integrated into the innovation joint research system led by leading enterprises. We should learn from successful experiences at home and abroad, support key enterprises and scientific research institutions to jointly conduct key core technology research of aero-engines, and encourage the AECC to strengthen original innovation and establish industrial innovation laboratories to promote the efficient transformation of basic research to applied research and applied research to industrial technology.

4.5 Building an innovation ecosystem by focusing on major projects and exploring new mechanisms of project management

Major projects for tackling key core technologies of aero-engines are significant for integrating resources of the whole industry, building an efficient collaborative ecosystem that integrates government, industry, universities, research institutes, and application, and realizing the integration and innovation of the industrial chain [15]. In the selection of major project participants, we should pay attention to the specialized private technology enterprises

with strong strength in the upstream and downstream of the industrial chain, so as to build a mission-oriented innovation ecosystem that is led by large-scale leading enterprises and promoted by specialized private enterprises. New project management mechanisms that adapt to it should be explored to provide guarantee for the high-quality implementation of major projects and the reliable promotion of technological breakthroughs. To avoid the fragmentation of responsibilities and improve the initiative of relevant subjects, a scientific, reasonable, comprehensive, hierarchical, and quantitative evaluation index system should be established by combining expert evaluation and basic data monitoring, so as to conduct major project performance evaluation, enhance the trust of project members, and ensure the scientific and objective evaluation. The experience and lessons in the operation of major projects should be summarized in a timely manner, the corresponding system and mechanism improved, and key reference provided for the operation and improvement of the national major project system.

5 Conclusion

The breakthrough of the key core technologies of aero-engine needs to concentrate the strengths of the industry, coordinate various participants including the government, industry, universities, research institutes, and application, and establish an organization mode of jointly tackling problems with clear division of labor, different emphasis, and complementarity. The government stands at the overall level to conduct systematic plan and scientific layout, strengthens relevant institutional arrangements and mechanism design, and adopts various technological innovation policy tools to guide the desired behaviors of various subjects in the research system.

In the key core technology research practice of aero-engines, how to implement the key points of the proposed organizational strategy and how the government guides through the combination of policy tools are the key content of future research and the exploration direction of industrial practice.

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