Exploration and Reflection on a Team-based Collaborative Three-Dimensional Matrix Management Model for Scientific Research Innovation (Postprint)

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Abstract

The National deepening of the science and technology system reform and implementation of the "dual-wheel drive" development strategy presents challenges for the existing research management models of scientific research institutes. The Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, drawing upon its own characteristics and long-term practice, proposes a "three-dimensional matrix research innovation management model based on team collaboration," establishing academic, administrative, and project lines. These three dimensions constitute independent systems while maintaining organic linkage, maximizing synergy among diverse advantageous resources, which is conducive to realizing strategic research objectives. This paper presents a comprehensive overview and analytical discussion of this model in terms of historical background, core mechanisms, safeguard measures, and achieved results.

Full Text

Preamble

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Exploration and Reflection on a Three-Dimensional Matrix Management Model for Scientific Research Innovation Based on Team Collaboration

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Abstract

The deepening reform of China' s scientific and technological management system and the implementation of the "dual-wheel drive"development strategy have posed significant challenges to existing research management models in scientific institutions. Drawing upon its own characteristics and long-term practice, the Institute of Nuclear Energy Safety Technology of the Chinese Academy of Sciences has proposed a "three-dimensional matrix management model for scientific research innovation based on team collaboration." This model establishes three distinct yet organically linked dimensions—academic, administrative, and project lines—that operate as independent systems while maximizing the synergy of diverse advantageous resources to achieve strategic research objectives. This paper summarizes and analyzes this management model from the perspectives of historical background, core mechanisms, supporting measures, and implementation outcomes.

Keywords: team collaboration, three-dimensional matrix, scientific research innovation management model, reform of scientific research management system
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1. Challenges Facing Research Teams Under the Innovation-Driven Development Strategy

The report of the 18th National Congress of the Communist Party of China explicitly stated that "scientific and technological innovation is a strategic support for improving social productivity and comprehensive national strength," emphasizing the need to "implement an innovation-driven development strategy" [1]. At the National Conference on Science and Technology, General Secretary Xi Jinping further stressed the importance of placing scientific and technological innovation in a more prominent position to build China into a world leader in science and technology. He proposed the "dual-wheel drive" strategy of scientific and technological innovation alongside institutional innovation, emphasizing that only by forging a new path of research management innovation can China navigate the deep waters of reform and achieve its innovation goals by 2020 [2,3]. The "13th Five-Year Plan" of the Chinese Academy of Sciences (CAS) noted that CAS is at a critical juncture of reform and leapfrog development, requiring firm commitment to deepening reforms and pooling efforts to promote innovation to achieve the "Four Firsts" goal [4].

Under these national strategic requirements, current management models in research institutions face numerous challenges: resource allocation and evaluation systems cannot adapt to the demands of major outcome-oriented research, and research activities suffer from low-level repetition, homogeneous competition, and fragmented development to varying degrees. There remains a gap between management capabilities and the standards of world-class research institutions. How to reform institutional management systems to align with national innovation strategies has become a critical issue for research teams [5]. As an inno-

vative research unit established in 2011, the Institute of Nuclear Energy Safety Technology (hereafter "INEST") has gradually developed a distinctive three-dimensional matrix innovation management model based on team collaboration to address these challenges, demonstrating its effectiveness and practicality in practice. The following sections introduce and analyze this research innovation management model, hoping to provide insights for China's research management system reform.

2. Three-Dimensional Matrix Management Model for Scientific Research Innovation Based on Team Collaboration

The role of large-scale science models in contemporary scientific research and innovation has become increasingly prominent, with the key lying in the overall coordination of resources to concentrate efforts on major undertakings. However, traditional management models in specific project implementation tend to form temporary or short-term small groups, potentially dispersing resources and hindering the maximization of team effectiveness. Coordinating researchers across multiple units and disciplines, and managing various resources holistically, urgently requires establishing new management models, fostering shared values, strengthening an innovative culture, enhancing cohesion and combat effectiveness, and better accomplishing research tasks to ultimately achieve team objectives.

2.1 Historical Background

The foundation of INEST was the "FDS Team" (www.fds.org.cn) established in 2003. At that time, team members came from multiple institutions, including the Institute of Plasma Physics of CAS, University of Science and Technology of China, Hefei University of Technology, and Anhui University, forming an interdisciplinary collaboration team with diverse academic backgrounds and research experiences. The team primarily undertook projects from the Ministry of Science and Technology, CAS, the National Natural Science Foundation of China, and international multilateral and bilateral cooperation programs, characterized by multi-unit, multi-project, and multi-disciplinary collaboration. The challenges faced in adapting to national needs and research trends, and in exploring a path of independent innovation and sustainable development, are mainly reflected in the following contradictions.

2.1.1 Contradiction Between Phased Project Tasks and Long-term Research Mission

Since its establishment, the team has been guided by the mission of "developing advanced nuclear energy technology for a better life," focusing on "ensuring nuclear safety from the source." The team undertakes research projects from different sources with varying specific directions, requiring both the completion of phased project tasks and the accumulation of academic expertise to serve its long-term research mission. This creates a balance between "project" and

"academic" priorities. Overemphasizing projects can lead to "short-sightedness" and focus on short-term gains at the expense of long-term value, while focusing solely on academics makes it impossible to complete project tasks and achieve sustainable research development.

2.1.2 Contradiction Between Multi-Administrative Units and Multi-Disciplinary Collaboration

Team members span multiple administrative units, even across different regions and countries. To accomplish major project tasks, team members need strong collaboration but cannot effectively achieve "harmony in diversity" administratively to ensure consistent progress. Meanwhile, nuclear safety research encompasses frontier theoretical innovation and engineering technology applications, requiring multi-disciplinary collaborative innovation. Moreover, the development of contemporary basic research is transitioning from individual leadership to team collaboration, where researchers need not only interdisciplinary expertise but also comprehensive management and coordination skills. Engineering research tasks often require completion within specific timeframes, and team members exhibit gaps in practical competence and innovation capabilities.

2.2 Model Overview

The three-dimensional matrix management model for scientific research innovation based on team collaboration [Figure 1: see original paper] is built upon an open and inclusive team culture and institutional framework. It establishes three dimensions—academic, administrative, and project lines—with academics as the purpose, administration as the means, and projects as the vehicle. Each dimension forms its own system while organically linking with the others, maximizing the synergy of various advantageous resources to facilitate the achievement of strategic research goals. Any single dimension developed in isolation has limitations: a sole project line pursuing short-term benefits can lead to resource idling and dispersion, while a sole academic line lacking project support inevitably loses competitiveness and support. Only when the three dimensions function as an integrated whole with interconnected integration can core competitiveness be maintained and sustainable development achieved.

2.2.1 Academic Line—Research Laboratories (Academic Research Units)

Based on academic development needs, research laboratories are established as academic research units to accumulate research strength through basic research and promote multi-disciplinary cross-fertilization. The laboratory organization is open, relaxed, and flexible, with members having no strict administrative boundaries, which facilitates academic innovation and frontier exploration, accumulating developmental momentum.

2.2.2 Administrative Line—Executive Departments (Administrative Management Units)

Executive departments are established as daily administrative management

units with rigorous and effective organizational goals. Each executive department has clear and independent work boundaries, and members have explicit administrative relationships to ensure execution efficiency.

2.2.3 Project Line–Project Teams (Task Management Units)

Jointly coordinated project teams serve as task management units. Specific research work is flexibly organized under the leadership of project teams, which concentrate relevant strengths from various executive departments and research laboratories for collaborative breakthrough efforts. This approach effectively optimizes resource allocation, fully leverages team synergy advantages, and generates development momentum.

2.3 Core Mechanisms

Implementing the three-dimensional matrix management model requires genuine overall management of project tasks, focusing on three key stages: scientific decomposition and implementation of project tasks, strict execution according to task requirements to ensure quality, and evaluation and incentive mechanisms after achieving results.

In the first stage, after project initiation, the team decomposes tasks based on project sources and requirements into elements such as research fields, scientific problems to be solved, and necessary software and hardware resources. Depending on the relevance of different project elements, tasks are broken down and reintegrated.

In the second stage, to ensure task execution, the team adopts the Work Breakdown Structure (WBS) method for management, developing work plans that include responsible persons, multi-level sub-task decomposition, milestone events, and deliverables. Executive departments supervise and manage progress, identify potential risks, and make timely adjustments.

In the third stage, results are evaluated and personnel are incentivized to ensure that each project team' s achievements receive fair and objective assessment and that researchers' contributions are fully recognized. Research outcomes include not only traditional papers and patents but also researchers' comprehensive contributions such as task planning and team organization.

2.4 Supporting Measures

2.4.1 Team Culture as the Soul of Development

Culture is the soul of team development, especially in a cross-unit, multidisciplinary team that cannot be managed through conventional administrative means. An innovative culture is needed to unify thinking and generate maximum synergy, while subtle cultural influence can internalize members' sense of responsibility, motivating them to strive consciously for the team' s ultimate mission. Over more than a decade, the FDS culture has been consciously summarized and refined from the team' s traditions, experiences, and lead-

ership philosophy, reflecting unique and distinctive ideological achievements and spiritual strength, such as the team' s "phoenix spirit" of "continuous creation, persistent inheritance, and infinite transcendence." Young talents from different units and fields have converged to create a pluralistic, open, and creative atmosphere, working together with one heart to continuously achieve self-transcendence.

2.4.2 Institutional System as the Cornerstone of Management
To unify behavioral norms and improve management efficiency, the team has established a comprehensive institutional system covering almost all matters. Additionally, it has independently developed the CROSS (Collaborative Research Organization Support System) platform for nuclear energy information research, utilizing new-generation information technologies such as the Internet of Things, big data, and cloud computing to achieve "institutional process informatization and process information systematization." The CROSS platform has enabled intelligent implementation of the three-dimensional matrix management model, creating great convenience for timely communication and collaborative innovation among all parties implementing research plans. The platform won first place among the "Top Ten Excellent Cases of CAS Research Informatization" and was selected for two consecutive editions of the "China Research Informatization Blue Book" jointly compiled by seven ministries. Team members have also been recognized as National Excellent Chief Information Officers for their outstanding performance in research and management informatization.

2.4.3 Multi-Dimensional Evaluation to Stimulate Innovation Vitality
The team has developed a multi-dimensional evaluation mechanism that assesses individuals from perspectives including superiors, peers, subordinates, and independent reviewers, covering ethics, competence, diligence, performance, and integrity. The evaluation balances process and results, emphasizing both visible research outcomes (papers, patents) and milestone achievements during the research process, ensuring comprehensive coverage so that everyone' s work is included in the evaluation system with fully public results to ensure fairness and guidance. The evaluation also balances quantitative and qualitative aspects, emphasizing both quantitative research performance and collaborative capabilities (including management achievements and team spirit), making the assessment comprehensive rather than one-sidedly emphasizing research performance.

3. Implementation Outcomes of the Three-Dimensional Matrix Management Model

The team has consistently applied the three-dimensional matrix management model to respond to national trends and strategic needs, making new contributions. It has led more than 200 major projects and tasks with total funding exceeding 1 billion RMB, conducting research in nuclear energy neutron physics and safety theory, lead-based fission reactor engineering, fusion nuclear technology and materials, and interdisciplinary nuclear technology applications. The team has achieved deep integration of "research, education, and indus-

try," producing world-leading original scientific and technological achievements. It has published over 1,000 academic papers and received more than 10 national and provincial/ministerial science and technology awards, including the National Natural Science Award (Second Class), National Science and Technology Progress Award (First Class), National Energy Science and Technology Progress Award (First Class), and China Nuclear Energy Association Science and Technology Award (First Class). The institute' s human, financial, and material resources have achieved an order-of-magnitude growth within five years.

3.1 Upholding Academic Innovation to Achieve Scientific Breakthroughs

For many years, the team has remained committed to the goal of "ensuring nuclear safety from the source," conducting systematic research on fundamental scientific and technical issues in advanced nuclear energy physics and safety, achieving breakthroughs in frontier theoretical innovation with significant international impact. The team created a precise modeling theory and computational method for multi-process direct coupling in complex systems for neutron transport, proposing for the first time an integrated irregular modeling concept combining surface-volume mixing and characteristic decomposition. It constructed a physical model coupling probabilistic and deterministic methods with adaptive transition zones, developed a fast coarse-mesh nodal SN method and characteristic pre-judgment probabilistic transport method in curvilinear coordinate systems, and achieved a leap from discrete isolated processes to multi-scale full-process coupling in neutron transport calculations, making precise and efficient 3D nuclear design and safety evaluation of complex nuclear systems a reality. Based on these theoretical achievements, the team independently developed the SuperMC super Monte Carlo nuclear simulation software system, which has been deployed in over 50 countries, selected as reference software by the ITER Organization (the world's largest energy science and technology cooperation program), and evaluated by international experts as "representing major progress in neutronics in recent years," "making significant contributions to neutronics-related research," and being "one of the leading teams in international neutronics." Six papers have been selected as ESI Global Top 1% Highly Cited Papers, the team published the first Nature paper in the field of thermonuclear reactor safety, and released the world' s first monograph on "Fusion Neutronics." The theoretical research achievements won the 2016 National Natural Science Award (Second Class).

3.2 Coordinating Advantageous Resources to Overcome Engineering Challenges

One of the team' s long-term research goals is advanced nuclear energy engineering and technology research, which requires establishing an efficient and cooperative team that fully leverages its academic accumulation in nuclear energy neutron physics theory. Under the guidance of engineering projects, the team

integrates advantageous academic strengths from various laboratories and flexibly configures execution units to ensure smooth project implementation. Under this management model, the team innovatively designed the world' s first compact dual-mode critical and subcritical lead-based experimental reactor "Qilin" (CLEAR-I), which has passed international authoritative professional evaluation. The design has been selected as a representative Chinese achievement in official technical reports of the International Atomic Energy Agency (IAEA) and the Generation IV International Forum (GIF). Based on independent design of advanced reactors, the team has achieved breakthroughs in core materials and key equipment, establishing an internationally leading large-scale liquid heavy metal lead alloy technology comprehensive experimental loop KYLIN-II, which has conducted over 10,000 hours of experiments to obtain core data on materials, thermal hydraulics, and key equipment performance for lead-based reactor construction licensing. The team has also completed the main development of the lead-based digital simulation reactor CLEAR-V, physical experimental reactor CLEAR-0, and engineering experimental reactor CLEAR-S, demonstrating its technical foundation for lead-based reactor engineering implementation. The team developed China Low Activation Martensitic steel (CLAM) for fusion applications, reaching industrial-scale smelting and processing levels and being recognized as "one of the world' s three major low activation steels." After seven years of dedicated breakthrough efforts, the team built the high-intensity deuterium-tritium fusion neutron source HINEG, producing 6.4$\times10^{12}$ n/s fusion neutrons, ranking first among similar operating facilities worldwide. Utilizing innovative particle transport modeling and computational methods, the team established a refined dynamic human radiation model for tumor patients, solving the problem of rapid and accurate calculation of internal radiation dose, and led the development of China' s first intensity-modulated precision radiotherapy planning system certified under new national standards, an achievement selected as one of the "2016 China' s Major Technical Advances."

3.3 "Mentor Group" Joint Training of Innovative Talents

Based on its multi-disciplinary characteristics, the team created a unique "mentor group" joint training model. Graduate students work not under a single supervisor but receive joint guidance from multiple mentors based on project needs and their personal characteristics. The team provides all graduate students with opportunities to engage in part-time management work, allowing them to absorb excellent capabilities and qualities from the mentor group through training in different projects and positions, broadening their horizons, perfecting their research character, and enhancing their comprehensive qualities. This approach is also applied to young staff training. With an average age of about 30, the team is young, active, passionate, and combat-effective but lacks knowledge accumulation and practical experience. Lead-based fission reactor engineering research requires collaborative work among researchers from different backgrounds such as reactor design, nuclear materials, and radiation protection, demanding high team spirit and experience in large-scale scientific project management. These

qualities are cultivated from the moment young staff join the team. Under this talent training model, the team has grown from fewer than 50 people to over 500, training more than 200 master' s and doctoral students. Over 30 team members hold positions in international academic organizations, and more than 20 doctoral students have been invited to give keynote speeches at major international conferences. Numerous graduates have become backbone forces in renowned universities, research institutions, and enterprises at home and abroad. The vast majority of members undertake major national research projects, with per capita annual research funding approaching one million RMB, providing a solid talent reserve for China' s nuclear energy science development.

4. Reflections and Recommendations

How to adhere to the "dual-wheel drive" strategy of scientific and technological innovation and institutional innovation to accomplish the historic mission of the "Four Firsts"? As CAS President Bai Chunli stated: the organization model and management system of research activities are the core issues of scientific and technological system reform and the most fundamental and critical problems that have long affected and constrained CAS reform and development [7]. CAS has formulated and implemented the "Pioneer Action Plan," leading a new wave of research management reform in scientific institutions. Based on INEST' s experience, we offer several suggestions regarding research activity organization and management models:

(1) In the era of large-scale science, collaboration is fundamental to development. Major scientific achievements do not solely depend on investment in funding and human resources; the key is to break away from traditional solo or small-group research models and concentrate forces to accomplish major undertakings, thereby maximizing the input-output ratio of research investment.

(2) Emphasize the cultivation of research management talent. Establishing a rigorous and effective management team is as important as the research team itself. A good management team understands the different nature and requirements of research work and can effectively coordinate various resources. If efficient collaboration is the key, then a good management team is the core that understands and can effectively coordinate these resources.

(3) INEST' s research management model has its own characteristics but also reflects common challenges faced by most research institutes, offering good scalability. Several research teams could be selected as pilots for promotion and practical improvement, helping to fully utilize CAS' s various advantageous research forces and attempt collaborative innovation across the entire academy.

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Note: Figure translations are in progress. See original paper for figures.