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An Exploration on Certain Issues of the Safety During the Terrestrial Trial of the Power Source of Space Nuclear Reactors.

Technical paper submitted by China

1. Introduction

The power source of space nuclear reactors is a device which supplies power to space vehicles by converting the thermal energy generated from the fission in the nuclear reactor into electric energy. The power source of a nuclear reactor is, under normal conditions, made up with the reactor, the thermal-electric conversion system, the heat discharge system, the shadow shield and the automatic control system.

Together with the advance in science and technology, the pace of the exploration into the deep space by mankind has also become faster. The top priority issue that has to be resolved for the exploration into the deep space is the supply of power. Since the solar constant in the deep space is significant reduced, it is almost impossible to use the technology of solar power, hence nuclear power supply becomes the only inevitable choice under the current technological conditions, while the requirement for high power supply by the mission of exploration into the deep space dictates that power supply by nuclear reactor becomes the only practical choice.

In the process of development, the space nuclear reactor power source will normally undergo trials of generation on the ground. The space nuclear reactor power source is, during the terrestrial trial, similar to an ordinary critical assembly and a research reactor, and must meet the standards contained in the current laws and regulations for critical assemblies and research reactors. However, unlike a reactor on the earth, a space nuclear reactor power source operates in different working conditions, and is subjected to numerous limitations in terms of size and quality. A number of systems cannot adopt redundancy and diversity designs. In order to develop a working environment and conditions that are as similar as possible to those that it works in, the prototype for the trials on the ground should not undergo major modifications either. Hence, such a power source has numerous special attributes compared to the ordinary critical assemblies and research reactors, and the safety issue involved merits further discussions.

2. The Current Laws, Regulations and Standards

The current Chinese laws, regulations and standards relating to research reactors exist mainly on the following four levels:

State legislature, i.e. The Radioactive Pollution Control Law of the People's Republic of China;

Administrative regulations: i.e. Safety Supervision and Management Regulations of the People's Republic of China for Civilian Nuclear Facilities;

Regulations of competent authorities: i.e. the No. 2 Implementation Details of Civilian Nuclear Facilities' Safety Supervision and Management Ordinance Rules – the Safety Supervision of Nuclear Facilities; the No. 3 Implementation Details of Civilian Nuclear Facilities' Safety Supervision and Management Ordinance Rules – the Rules for the Application for and Issuance of the Safety Permits for Research Reactors; the Safety Rules for the Design of Research Reactors; the Safety Rules for the Operation of Research Reactors; the Methods for the Control of the Training Assessment and Qualification Review of the Operators of Research Reactors; the Rules for the Management of the Radioactive Protection of Nuclear Facilities.

Nuclear Safety Guidance: i.e. the Management of the Operation of Research Reactors; the Management of Critical Assemblies and Trials; The Application and Modification of Research Reactors and the Decommissioning of Research Reactors and Critical Assemblies.

Apart from the above documents, China National Nuclear Security Administration has also issued for reference purposes a number of technical documents on research reactors. These documents form the current system of laws and regulations for nuclear safety of research reactors. This system of laws, regulations and standards covers essentially everything contained in the safety standards for research reactors as recommended by the International Atomic Energy Agency, and thereby are capable of supporting and securing the development of the device for terrestrial trials of the power source of space nuclear reactor.

3. Reactivity

Since (the reactor) operates in the space, it is recommendable to use solid moderator materials, such as zirconium hydride, graphite, etc. for space nuclear reactor power source with thermal neutron spectrum. Should the working temperature change, the density of the solid moderator material will remain almost unchanged, which can easily cause the co-efficiency of the reactive temperature of the moderator materials to become positive, thereby rendering the power co-efficiency of the whole reactor positive. This is what happened to the power source of Space Nuclear Reactor TOPAZ-II.

In terms of safety, the positive reactivity co-efficiency is not in the interests of the smooth operation of the reactor, and finds it difficult to automatically recover once deviation from operation occurs. However a positive co-efficiency of reactive temperature is not necessarily an out-and-out drawback so far as the power source of space nuclear reactors are concerned. The power source of space nuclear reactors with positive co-efficiency of reactive temperature has a smaller residual reactivity under cold conditions than in the initial operation. As far as space nuclear reactors are concerned, a major design problem is the critical safety issue that occurs at the time the reactor crashes onto the earth when the launch vehicle malfunctions during launch (the reactor remains cold during this stage). As long as the life span of the core of the reactor and the requirement for reactivity control are the same, it is easier to avoid the above basic design errors, as the residual reactivity of the cold power source of the space nuclear reactor with positive reactive temperature co-efficiency is relatively small.

Another advantage of the reactors with a system of positive reactive temperature is that all the reactivity control systems can function as a shut-down system individually, and are in a better position to meet the prescribed limits and conditions for effectiveness, speed of movements and shutdown margins, and therefore meeting the requirements for the design of the control system of the reactor as contained in the laws, regulations and standards.

In order to support the protection against the transience of different reactors, laws, regulations and standards will generally require that inherent safety attributes incorporated in the design. A concrete example is to use the materials and the choice of the geometric shape of the core to allow it to have transient negative temperature co-efficiency. As far as the power source of the space nuclear reactors is concerned, the choice of solid uranium as its fuel will ensure that the reactive temperature co-efficiency of the fuel remains negative, i.e. to have transient negative reactive co-efficiency, and thereby meeting the requirements of the laws, regulations and standards.

4. The Control System

The control of the power source of space nuclear reactors working in the universe is accomplished through remote control, and will experience a certain amount of the time delay, and, as a result, the control system should be highly automatic. During the trials on the ground, the control system of the trial platform should also be involved in the control of the reactor together with the reactor's own control system, and the former should have an even higher level of authorisation in order to meet the safety requirements and increase the safety margins.

During the initial stage of the terrestrial trial, the control system of the launch pad is used to complete the ignition, operation and shutdown. The reactor's own control system can go into operation once all the features and the operation procedures of the reactor are known so as to realise the complete simulation of the real working environment. However, the protection system of the launch pad continues to be in the working state and maintain manual shutdown throughout this process.

To test the capacity of the protection system of the power source of the space nuclear reactor, different adjustment values of the safety system can be set for the reactor's own protection system and that of the launch pad. As long as safety is not compromised, the self-protection system can be activated first to accomplish shutdown and other manoeuvres. Should the self-protection system fail to function, or the result of the function does not meet the requirement, the protection system of the pad can be activated to ensure that the reactor remains safe.

5. The Cooling of the Reactor's Core

During terrestrial trials, the complete power source system should be placed in a vacuum chamber. The thermo energy from the reactor core after that which is converted into electric energy is channelled into the radiator through the cooling system, and projected onto the interior walls of the vacuum chamber, and then discharged into the terminal heat sink via the cooling water jacket outside the vacuum chamber.

Compared to research reactors whose cores are immersed in coolants, the prototype of the power source of space nuclear reactors does not have the capacity for natural circulation, and its own thermo energy is also quite limited. Nevertheless, the thermo power of the power source of space nuclear reactor is relatively small, and will be able to keep the temperature within the limit of safety by ventilating the residual heat through radiation even if the coolant is completely lost. In order to increase the capacity of ventilation when the loss of circulation and coolant occurs, helium gas can be pumped into the vacuum chamber to increase the heat transmission from the reactor's core into the vacuum chamber.

The cooling water jacket outside the vacuum chamber is the key device to pump the heat from the reactor's core into the terminal heat sink. When the cooling water jacket is missing or the cooling water is lost, the accumulation of heat inside the vacuum chamber can be prevented by sprinkling on the exterior wall of the vacuum chamber to increase the capacity for heat transmission.

6. Radioactivity Containment

As far as ordinary reactors go, their shields that contain the radioactive materials include the fuel matrix, the fuel shell and primary circuit heat transmission system. The power source of some of the space nuclear reactors has fewer shields to contain the radioactive materials. Let's use once again TOPAZ-II as an example. Its power source system uses thermionic as the means for heat-electricity conversion. If the fission gas continues to accumulate, it will make the shield shell inflate causing short circuits between projection end and the receiving end during the operation, and end up causing the failure of the power source system. Hence, the power source system of TOPAZ-II needs to release the fission gas from the component terminal. Under such circumstances, the fuel shell and the primary circuit heat transmission system will be able to function as a shield for the radioactive materials.

During the terrestrial trial, the power source is placed completely in the vacuum chamber, and the fission gas released is collected by an sealed collector and then released into the filtering ventilation system. Should the collection system brake down or crack, the fission gas will be released into the vacuum chamber to be further discharged into the filtering ventilation system via the vacuuming system. If the melting of the fuel exceeds the limit of design, which is rare in occurring, the vacuum chamber and the bio-cover outside the vacuum chamber will function as the shield to contain the melted materials.

During the terrestrial trial, the vacuum chamber which contains the terrestrial prototype of the power source of space nuclear reactors will also be placed in a sealed workshop. The design of the sealed workshop must meet the requirements of the laws and regulations to form the last shield that seal up and separate the radioactive materials and prevent or mitigate the unplanned leaking of radioactive materials into the atmosphere.

7. Conclusion

The power source of space nuclear reactors plays a role that cannot be substituted in the mission of deep space exploration. Though it has numerous unique attributes compared to land-based reactors, the requirements of the current laws, regulations and standards can be fulfilled and safety can be assured by increasing the appropriate systems and facilities during trials on the ground.

When safety analysis is carried out for the terrestrial trials of the power source of space nuclear reactors, one would propose to use the analysis method that combines certainty and probability, and to make sure that the rate of various failures is kept at the reasonable minimum level. It is also proposed that special laws, regulations and standards be developed for the power source of space nuclear reactor, and special requirements be made to reflect its speciality to ensure the successful achievement of the safety targets. We would call on the rest of the world to strengthen the development of the safety technologies for the power source of space nuclear reactor and their cooperation in order to improve the safety technologies together and use the power source of the space nuclear reactor in a better and safer manner.

空间核反应堆电源地面试验时若干安全问题的探讨

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1、引言

空间核反应堆电源是将核反应堆中裂变反应产生的热能转换成电能为航天器供电的装置。空间核反应堆电源一般由反应堆、热电转换系统、热排放系统、阴影屏蔽和自动控制系统等组成。

随着科技的进步，人类深空探测的步伐逐步加快，而深空探测首先要解决航天器的能源供给问题。由于深远空间的太阳常数显著减小，使得太阳能电源技术几乎不可使用，核电源是目前技术条件下的必然选择。而对于深空探测任务的大功率能源需求，空间核反应堆电源则是现实的必然选择。

在开发过程中，空间核反应堆电源一般需进行地面发电试验。地面试验阶段的空间核反应堆电源与一般的临界装置和研究堆类似，必须遵守面向临界装置和研究性反应堆的现行法规标准。但空间核反应堆电源的工作环境与陆上反应堆不同，对体积和质量有较多限制，诸多系统无法采用冗余性和多样性设计，而为尽量模拟其真实的工作环境和条件，地面试验样机也不宜做大的改动，因此相对于一般的临界装置和研究堆具有许多独特的属性，其中涉及的安全问题值得探讨。

2、现行法规标准

中国现行的与研究堆相关的法规标准主要分为以下四个层次。

国家法律：《中华人民共和国放射性污染防治法》；

行政法规：《中华人民共和国民用核设施安全监督管理条例》

部门规章：《民用核设施安全监督管理条例实施细则之二——核设施的安全监督》、《民用核设施安全监督管理条例实施细则之三——研究堆安全许可证件的申请和颁发规定》、《研究堆设计安全规定》、《研

究堆运行安全规定》、《研究堆操纵人员培训考核与资格审查管理办法》、《核设施放射卫生防护管理规定》等。

核安全导则：《研究堆运行管理》、《临界装置运行及实验管理》、《研究堆的应用和修改》、《研究堆和临界装置退役》等。

除此以外，中国国家核安全局还发布了与研究堆相关的一些技术文件作为参考性文件。这些共同构成了中国现有的研究堆核安全法规体系。该法规标准体系基本涵盖了国际原子能机构推荐使用的研究堆安全标准的所有内容，可作为空间核反应堆电源地面试验装置研发的支撑和保障。

3、反应性

由于工作于宇宙空间，对于热中子谱的空间核反应堆电源宜采用固态的慢化剂材料，如氢化锆、石墨等。当工作温度改变时，固态慢化剂的密度变化不明显，很容易导致慢化剂反应性温度系数为正值，并且可能使全堆的功率系数为正值。TOPAZ-II空间核反应堆电源就属于这种情况。

从安全角度讲，正反应性系数不利于反应堆的稳定运行，偏离运行状态后难以自我恢复。但对于空间核反应堆电源而言，正反应性温度系数不完全是缺点。对于具有正反应性温度系数的空间核反应堆电源，冷态时的剩余反应性小于初始运行状态。对于工作于空间的核反应堆，一个重要设计基准事故是在发射阶段由于运载火箭故障导致反应堆重返地面时的临界安全事故（此时反应堆处于冷态）。在堆芯寿期和反应性控制要求相同的情况下（即初始运行状态的剩余反应性相同），由于具有正反应性温度系数的空间核反应堆电源的冷态剩余反应性较小，更容易避免出现上述设计基准事故。

对于具有正反应性温度系数反应堆的另一个优点是各套反应性控制系统均可作为独立的停堆系统，并且更容易满足有效性、动作速度和停堆裕度方面的规定限值和条件，从而满足法规标准中对反应堆停堆系统设计的要求。

为便于对各种反应堆瞬态提供防护，法规标准一般要求在设计中需包含固有安全特性，其中一个实例是借助材料及堆芯几何形状的选择使之具有瞬发负反应性温度系数。对于空间核反应堆电源，采用固态铀作为燃料，可保证燃料反应性温度系数为负值，即具有瞬发负反应性系数，满足法规标准要求。

4、控制系统

对工作于宇宙的空间核反应堆电源的控制均需遥控完成，并存在一定时间的延迟，因此其控制系统应是高度自动化的。在地面试验阶段，为满足安全要求并提高安全裕度，除自身的控制系统外，还需要试验台架的控制系统参与对反应堆的控制，并具有更高的权限。

在地面试验阶段初期，采用台架控制系统来完成反应堆的启动、运行和停闭等操作，待完全掌握了反应堆特性和运行流程后，可转入由自身控制系统来操作运行，以完全模拟真实的工作状态。但在这一过程中，台架的保护系统始终处于工作状态，并保有手动停堆功能。

为检验空间核反应堆电源自身保护系统的工作能力，可对自身保护系统和台架保护系统设置不同的安全系统整定值。在不影响安全的前提下，首先触发自身保护系统，完成停堆等动作。如果自身保护系统不能动作或动作结果不满足要求，则进一步触发台架保护系统，确保反应堆处于安全状态。

5、堆芯冷却

在地面试验时，为模拟宇宙空间的工作环境，电源系统需整体放入真空室中。在运行时，除转换为电能的堆芯热量将经由冷却剂系统带入辐射器，辐射到真空室内壁，再由真空室外的冷却水套排入最终热阱。

与堆芯整体浸入冷却剂的研究堆相比，空间核反应堆电源的地面样机不具备自然循环的能力，自身的热容量也较小。但空间核反应堆电源的热功率

较小，即使冷却剂完全丧失，仍能通过辐射方式散发堆芯余热，保证温度不超过安全限值。为提高失流和失冷事故下的排热能力，可向真空室内充入氦气，增强堆芯向真空室的热传递。

真空室外的冷却水套是将堆芯热量排入最终热阱的关键。当冷却水套失流或冷却水丧失时，可喷淋真空室外壁，防止热量在真空室的累积，提高热量导出能力。

6、放射性包容

对于一般的反应堆，包容放射性物质的屏障有燃料基体、燃料包壳、一回路热传输系统等。对于某些空间核反应堆电源，包容放射性物质的屏障则要少一些。仍以TOPAZ-II为例，该电源系统采用热离子热电转换方式。在运行过程中，如果裂变气体不断累积，将使包壳肿胀，从而使发射极与接收极之间短路，最终导致电源系统失效。因此，TOPAZ-II电源系统需要将裂变气体从元件端部释放出来。在这种情况下，燃料包壳和一回路热传输系统将不能发挥包容放射性物质的作用。

在地面试验时，电源整体置于真空室内，释放出的裂变气体由密封收集器收集，而后排入过滤通风系统。如果收集系统发生破裂，裂变气体将排入真空室内，由抽真空系统排入过滤通风系统。在发生概率极低的燃料熔化超设计事故下，真空室和真空室外的生物屏蔽层将起到包容熔融物的作用。

在地面试验时，容纳空间核反应堆电源地面样机的真空室还将放置在密封厂房内。密封厂房的设计需满足法规标准的要求，构成封隔放射性物质的最后一道屏障，防止或减轻放射性物质向环境的无计划释放。

7、结束语

空间核反应堆电源在深空探测任务中有着不可替代的作用。虽然其相对于陆上反应堆有许多独特的属性，但在地面试验时可通过增加相应的系统和设施可基本满足现行法规标准的要求，安全性能够得到保证。

在对空间核反应堆电源地面试验情况进行安全分析时，建议采用确定论辅以概率论的分析方法，确保各类事故的发生概率处于合理可行尽量低的水平。建议针对空间核反应堆电源制定专用法规标准，对其特殊性做出专门规定，明确安全要求，以确保安全目标的顺利实现。呼吁世界各国加强对空间核反应堆电源安全技术的研究与合作，共同提升安全技术水平，以更好更安全地利用空间核反应堆电源。