For participants only
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Committee on the Peaceful Uses of Outer Space
Scientific and Technical Subcommittee
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Vienna, 20 February-3 March 2006
Item 9 of the provisional agenda*
Use of nuclear power sources in outer space

Joint United Nations/International Atomic Energy Agency technical workshop on the objectives, scope and general attributes of a potential technical safety standard for nuclear power sources in outer space (Vienna, 20-22 February 2006)

Status of and needs regarding nuclear safety in outer space: a designer's point of view

Working paper submitted by France

Note by the Secretariat

1. In accordance with paragraph 16 of General Assembly resolution 60/99 of 8 December 2005, the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space will organize, jointly with the International Atomic Energy Agency, a technical workshop on the objectives, scope and general attributes of a potential technical safety standard for nuclear power sources in outer space, to be held in Vienna from 20 to 22 February 2006.

2. The working paper contained in the annex to the present document was prepared for the joint technical workshop in accordance with the indicative schedule of work for the workshop, as agreed by the Working Group on the Use of Nuclear Power Sources in Outer Space during the intersessional meeting held in Vienna from 13 to 15 June 2005 (A/AC.105/L.260).

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* A/AC.105/C.1/L.283.

Annex

Status of and needs regarding nuclear safety in outer space: a designer's point of view

Working paper submitted by France

I. Status and context

1. It is likely that in the near future new initiatives will make use of various nuclear power and propulsion systems. In the case of substantial use of nuclear energy for civil applications in outer space, it is important to note that many countries would be concerned by potential radiological hazards. Indeed, past experience has proved unfortunately that many countries are concerned by the cross-border effects of accidents involving spacecraft with nuclear systems on board. The SNAP-9A incident (dispersion of 1 kilogram (kg) of ^{238}plutonium (Pu) - 17 kilo curies (kCi)), the Cosmos 954 reactor in 1978 (north Canada, pollution of 50,000 square kilometres, >4,000 debris—85 kCi of total inventory—50 Ci recovered) and the Cosmos 1402 reactor in 1983 (Indian Ocean), can be mentioned as examples. Moreover, the potential risk still exists, for example, the recent Cassini/Huygens mission, the success of which was facilitated by the use of three radioisotope thermoelectric generators (RTG) containing 28.5 kg of ^{238}Pu -0.5 MCi.

2. In addition, it should be stressed that, given the global number of nuclear power systems (NPS) that have been launched so far, the resulting probability of an accident with such an NPS is in the range of 10^{-4} per year and per system. Though this value does not apply to a large number of systems, it can be compared with the 10^{-6} currently allowed as a maximum value for core damage frequency per reactor/year of a terrestrial power plant. This underscores the importance of the need for and justifies the implementation of a comprehensive and thorough nuclear safety programme for outer space.

3. Given the above considerations, all nuclear systems in space must necessarily be designed with safety in mind. In actual fact, safety aspects (analyses and testing) have always represented an important part of past projects and programmes (e.g. SP100, Topaz and Nerva). However, such safety analyses have been carried out on the basis of safety goals established by each of the space nuclear programmes without any international framework. While most decisions are made at the national level as regards terrestrial nuclear applications, international interests should be explicitly represented in the case of nuclear space applications.

4. The Committee on the Peaceful Uses of Outer Space proposed a preliminary general approach in a first resolution adopted by the General Assembly in 1992. Even if some important points can be highlighted, such as the banning of the use of the plutonium isotope ^{239}Pu in a space reactor, it is recognized that the first resolution did not tackle all the aspects involved (such as nuclear propulsion) and does not have real legal binding force. Moreover, no international quantitative safety criteria for the use of nuclear power in space have been identified, but the

Committee has instead made recommendations on how safety goals should be formulated to deal with this important topic.

5. The comprehensive safety programmes developed for past projects seem to form a safety policy and a safety approach and constitute a sort of general space nuclear safety culture. As with terrestrial power plants, the fundamental safety philosophy is to reduce risk to levels as low as is reasonably achievable.[a, b] Based on the defence-in-depth principle (the notion of lines of defence, multiple barriers and so on), safety goals are defined so as to guarantee public health and protection of the environment. Safety objectives must contribute to a complete reduction of the risk (frequency x consequences) to zero, if practicable, by technical and economical means.

II. Nuclear applications in space and the natural environment

6. First of all, it is noteworthy that all power plant-related safety goals have been defined on the basis of the natural and artificial (medical) radioactive background endured by the human body. It should also be stressed that the natural environment in space remains very hostile in terms of radiation (the Van Allen belt, galactic cosmic rays, solar particle events and so on). This means that, far from the Earth, safety objectives should be adapted to the absence of people and to the different natural background. This also raises the question of which cut-off doses or minimum release should be used in the estimation of accident risks, but also which dose limits should be applied under normal operating conditions. This concerns:

(a) The radioactive release of nuclear thermal propulsion (NTP) systems for which acceptable levels of fuel erosion and values of operating temperature shall be determined from safety objectives taking into account the direct impact on the performance of systems;

(b) The level of radioactivity in the primary circuit of a nuclear electric propulsion (NEP) system (retention of fission products in the fuel, operating temperature and so on);

(c) Acceptable doses for crews of spacecraft;

(d) The planetary applications for which a perimeter (or site limits) is to be defined with regard to the natural background where the reactor’s contribution becomes negligible.

7. However, one should keep in mind that, in addition to the situation far from the Earth, other important safety issues apply to entry (intended or accidental) of space nuclear systems into the Earth’s atmosphere. All these safety issues are linked to the type of nuclear system involved and are common to the particular situations that could arise in each of the mission phases, from pre-launch through ultimate disposal of the NPS. These topics are discussed below.

III. Specific safety features of nuclear power systems under normal operating conditions in outer space

8. As far as the normal operating conditions of a space reactor are concerned, the safety requirements can be summarized as follows:

(a) The reactor should be kept free of radioactive products until a safe operating orbit is achieved;

(b) Operating orbits should be determined in such a way that radioactive products can decay to negligible levels before possible entry into the atmosphere;

(c) The reactor should be maintained in space after use.

A. Clean reactor and start-up orbit

9. Even if strict reactor design prevents unauthorized start-up and operation, the first point mentioned above underlies on the one hand the launch of a spacecraft with a clean core and on the other permits operation only after successful attainment of safe orbit. Firstly, safe start-up orbits still have to be defined and will be a part of the safety objectives. Then, taking into account the previous recommendation of the Committee on the Peaceful Uses of Outer Space, only reactors based on fresh uranium fuel will be allowed. For this reason most fission reactors used in relation to space applications have been designed with enriched ^{235}U, especially highly enriched uranium (93 per cent) because of compactness and minimum mass requirements.

10. On the contrary, because space reactors are fuelled with a significant amount of highly enriched uranium, safeguard issues concerning nuclear reactors for use in space during their ground transportation and launch and following launch must be addressed. Such systems must remain under the control of stable Governments with a strong commitment to non-proliferation.

B. Operating orbits

11. In addition, once the cold and non-critical uranium core is in orbit, precautions must be taken concerning operating orbits when an Earth orbit return is scheduled—round-trip mission, Earth gravitational acceleration and so on—or simply the NEP systems that remain a long period in Earth orbit during their acceleration. These operating orbits should differ from the start-up orbit because of the higher radioactivity of the core and they must be defined among the safety requirements as appropriate in relation to the orbit lifetime and the reactor radioactive inventory (time of decay).

C. Final disposal

12. Finally, specific orbits must also be determined for the final disposal of a space reactor taking into account increased meteorite/debris hazards as a result of longer residence time. The question of alternative solutions, such as solar system

escape orbits and sending NPS to the Sun, will be investigated and could be proposed as safety recommendations as a result of the compromise between the reduced risks and the technical feasibility of a necessary additional energy reserve (to extend the lifetime of the reactor core).

D. Radiation induced by nuclear power systems

13. Commonly a shadow shield is incorporated into an NPS instead of a biological shield (as in terrestrial nuclear applications). Reactor-induced radiation can thus be reduced to a negligible contribution with regard to the natural environment, but nevertheless it is important to note that regulations on dose limits are needed for manned missions. Such dose limits will have considerable influence on the performance of the systems: the mass-to-thrust ratio for NTP systems or the mass-to-power ratio for NEP systems.

IV. Specific safety features of nuclear power systems under accident conditions in outer space

14. It has already been stated that safety issues are mission-phase-dependent and strongly linked to the type of nuclear system involved. Except for the case of launching, which should be dealt with separately, the different mission phases can be summarized as follows:

(a) Earth orbit, which corresponds either to the start-up phase or to the operating phase (as in round-trip missions or simple or multiple passes near the Earth). As regards the start-up phase, it is important to note that the short injection time in a NTP system (high-thrust) will reduce the risk of accidents with radioactive cores. On the contrary, low-thrust NEP systems require long transfer periods near the Earth with a radioactive core;

(b) Interplanetary situations, where unacceptable orbit accidents may become tolerable. This means, for example, that reduced margins for deep-space travel corresponding to different safety criteria than those in force near the Earth could be considered. Safety objectives might then differ during the lifetime of the reactor, which is a totally different approach than for a standard power plant;

(c) Planetary applications, where safety objectives will again differ from those of a terrestrial power plant because of the different number of people who could potentially be concerned in an accident situation and because of the absence of a biosphere. However, as for a power plant, standard measures should be taken into account with regard to the common accident of loss of coolant, fuel waste management-related issues and so on. In addition, the presence of RTGs on the Moon highlights that considering a planet as the ultimate storage for α radioactive terrestrial waste cannot now be precluded and will require specific regulation.

15. Finally, requirements concerning mission reliability may in some cases surpass safety goals. Indeed, the redundancy of certain components and the need to keep the NPS operational in order to ensure the success of the mission will also contribute to ensuring safety.

A. Accidents in Earth orbit

16. To protect against accidental re-entry hazards means precluding scenarios of radiologically hot re-entry after initial start-up. This can be done if adequate stable operational orbits and flight trajectory decrease the likelihood of such situations. Moreover, keeping a system manoeuvrable even in accident conditions will also contribute to reducing risks. Again it is worth noting that such a degraded operating mode could be an important objective in terms of mission reliability. To keep an NEP or NTP system “manoeuvrable” means ensuring a minimum thrust in the event of core damage (plugged fuel element, reactivity control device out of order and so on). It also means having some backup components (turbopump, divided radiator and so on) in the event of malfunction of a conversion system.

17. Unlike terrestrial power plants, no containment/confinement is possible in a space reactor. This means, firstly, that the integrity of the reactor must be maintained as well as possible during an accident and, secondly, that the reactor should be designed to remain safe even in the event of an accident. As an example, reactivity must remain under control in any situation and decay heat removal of the core in the event of loss of coolant should be manageable. Reactivity control includes:

(a) A negative void coefficient to avoid prompt criticality in the event of loss of coolant;

(b) An overall power coefficient negative to self-limit the fission reaction under all circumstances involving temperatures changes (so that the reactor cannot become prompt critical);

(c) A sufficient Doppler broadening that can limit fuel temperature rise and avoids core melt in the event of hypothetical accident (reactivity insertion accident). It is noteworthy that some space reactors are small, fast reactors and that a fast neutron spectrum often leads to very low Doppler coefficients, but that, on the other hand, the use of uranium fuel offers an important margin with regard to prompt criticality (ß ~650 per cent mille (pcm));[c]

(d) An estimation of the impact on the fission reaction chain of natural space radiation (e.g. perturbation due to solar p+ flux during a solar particle event).

18. As regards overcoming loss of coolant accidents and decay heat removal, NTP and NEP systems differ in their level of core power density:

(a) NTP systems with high power density often incorporate more pressurized coolant tanks and/or additional active safety devices than terrestrial power plants. Unlike NEP systems, decay heat removal in NTP systems also requires specific precautions with regard to the resulting residual thrust;

(b) For low power density NEP systems, passive heat removal remains possible, in which case, only conductive and radiative heat transfer phenomena can be expected, as in the high-temperature reactor concepts that have already operated in the past.

B. Other potential accident scenarios

19. Appropriate safety criteria and requirements should be formulated to ensure that the meteorite hazard is specifically addressed in the design and operation of space NPS. Indeed, meteorites could be responsible for loss of coolant accidents or for partial damage of a conversion cycle (the turbo-pump, or especially the radiator for NEP, etc.). These scenarios must be classified on a scale of events in which their consequences and probability are related to meteorite mass and size. It should be stressed that planetary applications are also concerned.[d]

V. Key safety issues during the launch of nuclear power systems

20. First of all, it is important to bear in mind that radioisotope systems (RTG) and reactor-based systems (NTP and NEP) will not have the same initial radioactive inventory. A few curies will normally be encountered in a uranium reactor, whereas pure $^{238}PuO_2$ fuel leads to a few hundred kilo curies for an RTG-based mission. The table below shows some examples of standard inventories for a typical spacecraft with RTG and reactor and some examples of accidents, with both types of NPS (in curies):

Mission with a radioisotope thermoelectric generator (Cassini)	*Mission with a reactor*	*Accident with a radioisotope thermoelectric generator SNAP-9*	*Accident with COSMOS 954*	*Chernobyl*
~500 kCi	A few Ci	17 kCi	85 kCi (potential) 50 Ci (recovered)	>MCi

21. However, the absence of initial radioactivity in a reactor-based NPS is counterbalanced by the criticality risk. Indeed, if the integrity of the RTG can be envisaged in the event of an Earth atmosphere entry, specific safety criteria and requirements should be formulated to ensure that the reactor remains in an inoperable condition if launch accidents occur (to preclude inadvertent criticality). Two approaches can be mentioned:

(a) As now in operation on launchers, a command destruct action of the NPS can be implemented to avoid errant flight trajectories and to preclude any risk of core criticality. Such a destruction/dispersion option could be applied to a uranium-based reactor that, on the one hand, had a very low radioactivity level and, on the other, could not become critical if destruction systems could ensure the dispersion of the core fuel elements themselves. Backup and passive devices could ensure the separation of fuel elements and avoid critical configurations. However, considering that space reactors contain essentially highly enriched uranium, this option might be unacceptable with regard to the proliferation aspects;[e]

(b) The control of core reactivity must be ensured in any case of core flooding or compaction. Many potential solutions exist, such as specific absorbing safety systems, fuel loading in orbit and core poisoning, but these have a considerable impact on the performance of global systems.

VI. Other specific safety features for nuclear power systems in outer space

22. Some specific safety characteristics inherent in the use of nuclear systems in space must also be underscored:

(a) Some transport and technological operations may be executed in the presence of a reactor already loaded with nuclear fuel;

(b) The reactor will have to operate in dual media (Earth and space) with no site boundary. This makes definition of safety criteria more complex. In particular, the limits of radioactive product release during ground tests of prototypes of an NTP system come out as a limit to the thrust level of a unit engine;

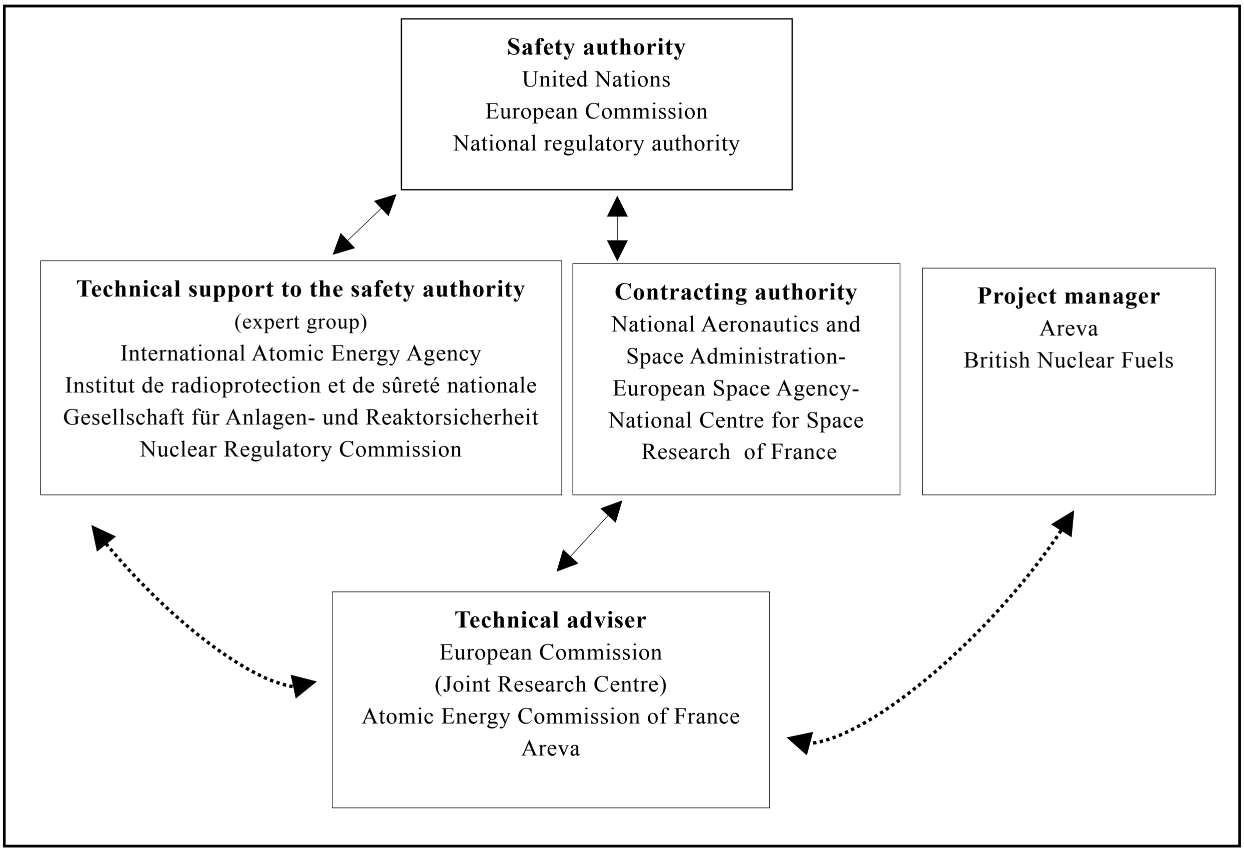
(c) The weightlessness factor in inter-planetary flights renders natural convection for decay heat removal (passive safety) difficult and consequently could act as a limit to the power density of the core of NEP systems;

(d) The delay of control signals in the event of considerable distance from the Earth may compound the difficulty of managing reactivity accidents. If this has been identified as a safety issue, some performance criteria should be laid down for the system’s telemetering control with regard to the control of the reactor.

VII. Legal framework for the definition of safety goals

23. Safety goals may help decide whether a space NPS is safe enough or not. Provision of recommendations and safety guidelines may thus assist a safety authority in making a decision, so it is important to identify in cases of use of NPS in space who makes the decisions (operator, regulator, designer, the public or a minister) and where the legal responsibility lies (with the contracting authority, for example).

24. While most decisions are made at the national level as regards terrestrial nuclear applications, international interests should be explicitly represented in the case of space applications because the countries involved should be more concerned with the cross-border effects of possible space NPS accidents. The figure below provides an example, based on terrestrial applications, of who might be the actors in a safety review and approval process for space applications:



Notes

[a] *Regulatory Practices and Safety Standards for Nuclear Power Plants: proceedings of an International Symposium on Regulatory Practices and Safety Standards for Nuclear Power Plants*, International Atomic Energy Agency, Proceedings Series (Vienna, IAEA, 1989).

[b] M. S. El-Genk, ed., *A Critical Review of Space Nuclear Power and Propulsion: 1984-1993* (New York, American Institute of Physics Press, 1994).

[c] S. Bernard and others, “Conceptual design of the MAPS NTP cargo shuttle based on a PBR”, paper prepared for the 13th Symposium on Space Nuclear Power and Propulsion, Albuquerque, New Mexico, 1996.

[d] European Space Agency, *Lunar Nuclear Power System (LunPS) Studies* (1998).

[e] E. Rigaut and X. Raepsaet, “First studies on the Optimized Propulsion Unit System OPUS within the current Nuclear Space Program in CEA”, paper presented to the Space Nuclear Conference, San Diego, California, 5-9 June 2005.