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Use of nuclear power sources in outer space

Technical processes and technical standards relevant to nuclear power sources in space: the position of the United Kingdom of Great Britain and Northern Ireland

Working paper submitted by the United Kingdom of Great Britain and Northern Ireland

I. Introduction

1. In previous documents submitted to the Committee on the Peaceful Uses of Outer Space (A/AC.105/593/Add.3) or to its Scientific and Technical Subcommittee (A/AC.105/C.1/L.192 and A/AC.105/C.1/L.203), the United Kingdom of Great Britain and Northern Ireland has discussed the use of nuclear power sources in space (A/AC.105/C.1/L.192), the justification for the risks from space nuclear power sources (A/AC.105/593/Add.3) and the interpretation and development of the safety principles for nuclear power sources in space (A/AC.105/C.1/L.203). In the working paper on the interpretation and development of the safety principles for nuclear power sources in space, it was argued that the use of probabilistic risk assessment provided a common basis for bringing together the international consensus on radiological protection and nuclear safety; it avoided the need for separate consideration of radioisotope and reactor systems, as well as accommodating new developments in nuclear propulsion; and it enabled the safety of all applications of nuclear technology to be evaluated against a common standard with no exclusions of any kind (A/AC.105/C.1/L.203, p. 6). It was noted that, while the risk-based approach was not a panacea for the achievement of high standards of nuclear safety, with the addition of principles related to safety culture and the control of pollution of outer space, such an approach could be seen to provide a comprehensive and effective safety regime (A/AC.105/C.1/L.203, p. 7)

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2. Document A/AC.105/593/Add.3 dealt with the requirement for justification of risks, which is fundamental to the radiological protection principles promulgated by the International Commission on Radiological Protection (ICRP)[1] and is assumed in the International Atomic Energy Agency (IAEA) considerations of nuclear safety.[2] While much of document A/AC.105/593/Add.3 remains valid, the whole question of justification will need to be revisited when the review of the safety principles for nuclear power sources in space takes place, in the light of significant recent developments in national and international thinking.

3. Recognizing these, and a number of significant inputs from other delegations, the Working Group on the Use of Nuclear Power Sources in Outer Space at its fifteenth session, held in February 1998, recommended that a work plan (proposed by the Russian Federation, the United Kingdom and the United States of America), should be adopted by the Scientific and Technical Subcommittee. That was agreed and, as a result, Member States and international organizations were invited to submit information on the following topics, to be considered in 2000 and 2001 (A/AC.105/697 and Corr.1, annex III):

(a) Identification of terrestrial processes and technical standards that may be relevant to nuclear power sources, including factors that distinguish nuclear power sources in outer space from terrestrial nuclear applications;

(b) Review of national and international processes, proposals and standards and national working papers relevant to the launch and peaceful use of nuclear power sources in outer space.

4. The present paper gives the position of the United Kingdom on the above-mentioned topics.

II. Processes and standards relevant to nuclear power sources

5. There are basically six classes of terrestrial processes that are relevant to nuclear power sources in space. These are:

(a) Nuclear power stations;

(b) Research reactors;

(c) Nuclear-powered vessels, particularly submarines;

(d) Transport of nuclear material;

(e) Fuel fabrication and reprocessing facilities;

(f) Industrial and medical radiography using radioactive sources.

6. Of these, the main areas with relevance to nuclear power sources in space are the first four.

A. Nuclear power stations

7. There are clear similarities between nuclear power stations and nuclear power sources in space in respect of:

(a) The technical complexities and advanced science and engineering involved in each;

(b) The reliance that each has to put in the high integrity of automatic protection systems;

(c) The difficulties that each faces in dealing with problems that occur when the plants are in operation;

(d) The unique safety (and public perception) issues that arise from the need to handle significant quantities of radioactive material;

(e) The fact that many potential accidents that might occur at either type of plant are likely to involve countries other than the "owner or originator" of the plant;

(f) The problems that each faces in dealing safely with the wastes that it creates;

(g) The vital importance of creating and maintaining an excellent "safety culture" among the staff involved in either of these processes.

8. There are, however, some significant differences between nuclear power stations and nuclear power sources in space, including the following:

(a) The actual quantities of radioactive material involved—many tons in the case of nuclear power stations compared with a few tens of kilograms for most nuclear power source applications;

(b) Nuclear power stations are stationary devices, while nuclear power sources in space are mobile (which leads to the particularly significant considerations related to the launch of nuclear power sources into space and the possible re-entry at a later date);

(c) There are no radiation doses to the operators of most nuclear power sources when they are in space, unlike the situation with terrestrial nuclear stations;

(d) The problems associated with handling the wastes generated in the two cases are quite different in most respects;

(e) The types of possible accidents are quite different for the two types of plants;

(f) The public perception of the risks and benefits of space exploration and exploitation is different from the public perception of the risks and benefits of nuclear power.

B. Research reactors

9. Many of the above-mentioned similarities and differences exist between research reactors and nuclear power sources in space. However, there are additional similarities in the extent to which they are both often highly experimental in nature and could be operated in a "university" culture where safety may not be as highly systematized as in normal industrial situations. This could have important implications for any possible "read-across" from terrestrial standards to similar standards for nuclear power sources in space.

C. Nuclear-powered vessels

10. The majority of nuclear-powered ships around the world are nuclear submarines, although a few surface ships (including aircraft carriers) have been propelled by nuclear reactors (e.g. the *Otto Hahn*). The major similarities between such "plants" and nuclear power sources in space arise from the fact that they are both mobile and have to operate

reliably in hostile environments for long periods without the possibility of corrective maintenance. However, as all the above are likely to be pressurized water reactors, they are different and perhaps not relevant to the fast reactors most likely to be employed in space.

D. Transport of nuclear material

11. In the short term, it would seem that with radioisotope thermoelectric generators as the main issue and with reactors launched in a pre-critical condition transportation of radioactive material is a directly relevant terrestrial process.

III. Review of United Kingdom "standards" for terrestrial nuclear activities

12. Under United Kingdom legislation governing the safety of nuclear installations, civil nuclear sites are required to be licensed. Licences are granted by the Health and Safety Executive and administered by Her Majesty's Nuclear Installations Inspectorate. The licensing regime is established by the Inspectorate through powers under the Nuclear Installations Act to attach conditions to the site licence which are enforceable in a court of law. The Nuclear Installations Act is a relevant statutory provision of the Health and Safety at Work etc. Act (1974), which governs essentially all work activities in the United Kingdom. It is important to note that the Health and Safety at Work etc. Act is goal-setting by nature, with specific industrial sectors and activities being regulated by appropriate regulations made under the Act.

13. The nuclear regulatory regime has been successfully applied to a wide variety of nuclear installations within the United Kingdom over the past 40 years and has been shown to provide a powerful yet flexible system of control capable of being matched to the degree of nuclear hazard involved. The licensing regime covers a nuclear installation through its full life cycle, from design to decommissioning, and takes into account the need to regulate and control the management of radioactive waste.

14. In 1979, the Health and Safety Executive published the Nuclear Installations Inspectorate's safety assessment principles for nuclear reactors, followed shortly after by corresponding safety assessment principles for nuclear chemical plants. These separate documents were subsequently merged into a single set of principles. The safety assessment principles for reactors were subjected to detailed legal and technical scrutiny at the public inquiry into the proposal to build a pressurized water reactor at Sizewell in Suffolk, which ran for about three years in the early 1980s. The inspector in charge of the inquiry recommended that the Health and Safety Executive should publish a discussion document on its thinking about acceptable levels of risk. That document, *The Tolerability of Risk from Nuclear Power Stations*, was issued in 1988 and revised in 1992.[3] Revised safety assessment principles, taking into account the proposed risk "targets" in the tolerability of risk, were also published in 1992.[4]

A. The tolerability of risk

15. The key features of the tolerability of risk philosophy are illustrated in the figure. The narrowing of the triangle from top to bottom represents the reduction in risk. Towards the top of the figure, there is a boundary between the (just) tolerable and the intolerable region. A plant would not be licensed if the risk were in the intolerable region. Below that, the plant is, in principle, licensable, but the as low as reasonably practicable (ALARP) requirement of United Kingdom law requires the risk to be pushed down to as low a level as is reasonably practicable. At the lower end of the triangle, the risk is broadly acceptable and so HM Nuclear Installations Inspectorate would not expect to push for further improvement, though the law still requires the licensee to provide such improvement if reasonably practicable. The more general matter of risk assessment in environmental protection which is applicable to the area of nuclear power sources can be found in a report by the United Kingdom Parliamentary Office of Science and Technology entitled *Safety in Numbers?: Risk Assessment in Environmental Protection.*[5]

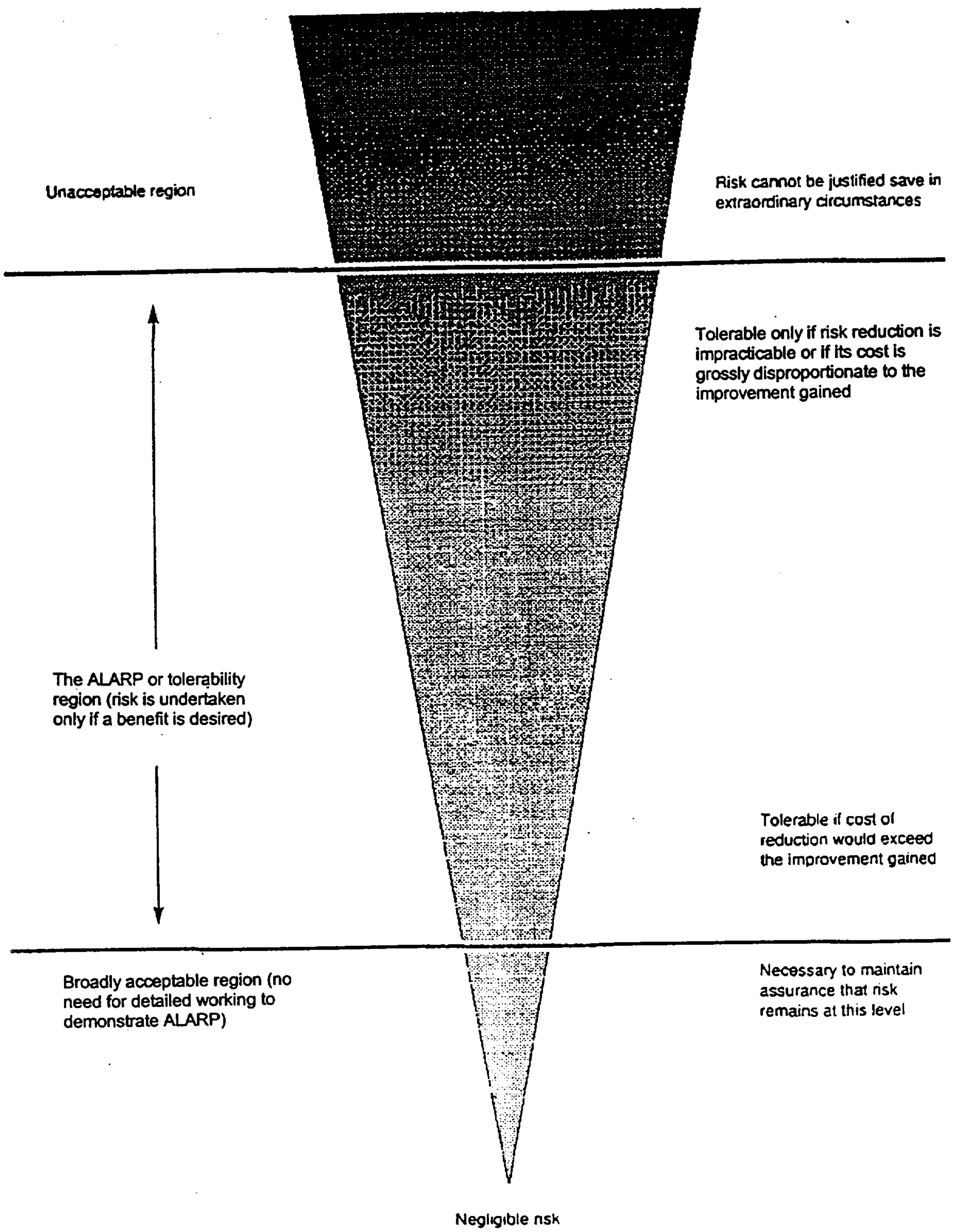
B. Safety assessment principles of Her Majesty's Nuclear Installations Inspectorate

16. The safety assessment principles of HM Nuclear Installations Inspectorate begin with five fundamental principles that deal with the requirement that the statutory dose limits should not be exceeded and, furthermore, that doses and risks should be made as low as reasonably practicable. The statutory limits in the United Kingdom are based on ICRP recommendations that are incorporated into the European Community's Basic Safety Standards Directive (see section IV below). The concept of "reasonable practicability" is the central feature of health and safety legislation in the United Kingdom: in essence, radiation doses in normal operation and the risks from accidents should be made as low as is reasonably practicable (ALARP). ALARP is the United Kingdom version of the as low as reasonably achievable (ALARA) principle.

17. In the application of the tolerability of risk concept in the safety assessment principles, the boundary between the tolerable and intolerable regions is translated into basic safety limits and the broadly acceptable level into basic safety objectives. For normal operation the basic safety limits for worker and public doses are consistent with ICRP recommendations.

18. The principles applicable to accident conditions embrace the concept of design basis accidents, again in line with international thinking, such as that of IAEA. Principles are also included that relate to severe accidents; again, these are in line with international thinking. However, for probabilistic safety analysis, the safety assessment principles translate the tolerability of risk limit for individual risk into a basic safety limit frequency-consequence diagram, known as a staircase, and the broadly acceptable tolerability of risk level into a parallel basic safety objective staircase two decades lower in frequency. This diagram follows the generally accepted premise that the larger the potential consequences of an accident, the smaller its frequency should be. However, in constructing it the Nuclear Installations Inspectorate linked the consequent steps to the different actions that would be necessary for accidents of different severity. They also introduced principles on the frequency of core damage and large radioactive releases, the latter intended to represent societal (social) risk.

Levels of risk and the as low as reasonably practicable (ALARP) principle



19. Because of their numerical nature, it is easy to assume that the probabilistic principles are the sole arbiter in Nuclear Installations Inspectorate's judgements on plant licensability. This is by no means true; in fact those principles are only a small fraction of the safety assessment principles. The engineering principle comprise about 75 per cent of all of the principles. If a plant satisfies the engineering principles, the probabilistic principles should provide a check that in general would be expected to confirm the plant's acceptability or, possibly, to highlight aspects of the design where shortcomings exist. These numerical checks may be regarded as representing the finishing touches to the assessment process, though that should not undervalue the importance of incorporating the probabilistic approach in the early stages of designing the plant.

C. Engineering principles

20. The engineering safety assessment principles start with about 20 key principles embracing three broad groups: the first covers the need for a sound concept; the second, the engineering requirements that are fundamental to a safe plant; and the third, those principles which have a significant influence on the cost of the plant. Among these key principles are well-known principles dealing with defence in depth, inherently safe or fail-safe design, diversity, redundancy, segregation and layout.

21. There are then over 200 more detailed principles, dealing in quite general terms with the design and engineering features that are necessary to ensure a safe plant. Many of these would have no relevance to nuclear power sources in space, although some, like safety management and human factors, may have some useful "read-across". Human factor considerations cover a wide range of requirements and, in particular, human factors interface with many facets of the engineering design. There is a human factor section within the engineering principles, therefore, and human factor contributions to other sections, including probabilistic safety analysis and life cycle requirements. This emphasizes the importance of analysing the functions of personnel at all stages in the lives of nuclear plants.

D. Summary

22. The tolerability of risk philosophy and Nuclear Installations Inspectorate's safety assessment principles are not intended to be prescriptive. Rather, their approach is to set top-level safety goals that should be achieved by licensed nuclear installations in the United Kingdom and then to leave it up to the licensees to demonstrate how they have met those goals. This essentially non-prescriptive approach is markedly different from certain other nuclear regulatory bodies, particularly the United States Nuclear Regulatory Commission, which specify in considerable detail the source terms, analytical tools, modelling assumptions etc. that the licensee must use. Such a prescriptive regulatory system has the merit of consistency and reproducibility, though it tends to be resource-intensive and can inhibit innovation on the part of the licensees. Non-prescriptive approaches, such as that adopted by the Nuclear Installations Inspectorate, put the onus very much on the licensees to develop their own safety solutions. The Nuclear Installations Inspectorate encourages, and indeed expects, each licensee to develop its own safety criteria for the particular types of nuclear plants that it wishes to operate. Such criteria have been developed by the nuclear power station operators, by the United Kingdom Atomic

Energy Authority, by the operators of the fuel reprocessing plants at Sellafield (BNFL) and by the Ministry of Defence, for instance.

23. The challenge for both the licensee and the Nuclear Installations Inspectorate is to ensure that, while their safety criteria are separate and distinct, there is no failure of understanding or communication between them—and that they achieve the same level of safety if properly applied. In a non-prescriptive regulatory regime there is plenty of scope for misunderstandings to develop between the licensee and the regulator over such things as:

(a) What exactly is the "safety case"?;

(b) What assumptions and protocols should be used when carrying out cost-benefit analyses to help demonstrate that the ALARP principle has been met?;

(c) How the risk profile of a plant might be expected to change as a function of time.

24. Such areas of potential misunderstanding need to be discussed and resolved if the regulator and, through him, Parliament and the public are to be reassured that an adequate level of safety is being achieved.

IV. Recent international developments that have influenced standards of the United Kingdom

A. 1990 recommendations of the International Commission on Radiological Protection

25. The recommendations of ICRP form the basis of radiological protection worldwide and represent the starting point for United Kingdom legislation on radiation protection. Within the European Union, ICRP recommendations are translated into legally binding requirements, mainly in the Basic Safety Standards Directive. As a member of the European Union, the United Kingdom is subject to the provisions of the Treaty Establishing the European Atomic Energy Community (EURATOM) and has to implement the Directive. When ICRP issued its updated recommendations[1] in 1990, the European Commission started work on producing a revised Directive that was adopted by the member States of the European Union in December 1995, with a four-year implementation period. The majority of the requirements of the Directive have been implemented by revised Ionising Radiations Regulations, made under the Health and Safety at Work etc. Act, which came into force on 1 January 2000.

26. Probably the most important implications of the new recommendations, for terrestrial nuclear operations in the United Kingdom, arise from:

(a) The increased emphasis on "justification" of such activities;

(b) The requirements for hazard and risk assessment;

(c) The new dose limits, i.e., for classified workers, either a straight limit of 20 mSv per annum or a five-year limit of 100 mSv, with no more than 50 mSv in any single year;

(d) The more explicit requirements associated with exposure to natural radiation.

27. It is considered that these will also have important implications for any potential rewriting of the safety principles for nuclear power sources in space. In addition the possibility of exposure of the public due to a launch failure or a re-entry event will continue to be a significant issue.

B. Convention on Nuclear Safety

28. The idea of a nuclear safety convention arose out of the Chernobyl accident and was proposed formally at the International Conference on the Safety of Nuclear Power, held in Vienna from 2 to 6 September 1991. After nearly three years of development, the Convention on Nuclear Safety[6] was adopted by a Diplomatic Conference on 17 June 1994 and it entered into force in October 1996. By the first quarter of 1999, practically all States with nuclear power installations had become contracting parties to the Convention. Between 12 and 23 April 1999, the contracting parties met in Vienna to review the progress that they had made in fulfilling the Convention's objectives, which are:

(a) To achieve and maintain a high level of nuclear safety worldwide through the enhancement of national measures and international cooperation including, where appropriate, safety-related technical cooperation;

(b) To establish and maintain effective defences in nuclear installations against potential radiological hazards in order to protect individuals, society and the environment from harmful effects of ionizing radiation from such installations;

(c) To prevent accidents with radiological consequences and to mitigate such consequences should they occur.

29. The Convention has adopted a novel "incentive" approach to enhancing nuclear safety culture worldwide. It essentially involves the contracting parties producing regular national reports on their nuclear activities, which are then subjected to a peer review process by the other parties. Through the process of preparing their national reports, the contracting parties have created a valuable record of the current status of nuclear power worldwide. Furthermore, the first round of the Convention's review process has produced a "benchmark" regarding the status of nuclear safety in virtually all nations that utilize this energy source. This benchmark can be used to assess future progress in enhancing nuclear safety.

C. Technical basis for the Convention on Nuclear Safety

30. Between 1978 and the middle of the 1980s, IAEA published 5 codes of practice and about 60 safety guides, all based on national experience of the member States. A unique set of standards (Nuclear Safety Standards (NUSS) for nuclear power plants, Regulations for the Safe Transport of Radioactive Material, and Radioactive Waste Safety Standards (RADWASS)) was prepared under the IAEA programme and is being updated. The recommendations cover all major areas of regulatory body activities: legal framework, organization and staffing, review and assessment, inspection and enforcement, licensing, emergency preparedness, regulations and guides. The recommendations have played an important role in international harmonization.

31. The IAEA International Nuclear Safety Advisory Group (INSAG) has identified three fundamental management principles (safety culture, responsibility of the operating

organization, and regulatory control and verification), three defence in-depth principles (defence in depth, accident prevention and accident mitigation), six general technical principles (proven engineering practices, quality assurance, human factors, safety assessment and verification, radiation protection, and operating experience and safety research), 50 specific principles distributed in seven areas (siting, design, manufacturing and construction, commissioning, operation, accident management, and emergency preparedness).

32. In preparing the Safety Fundamentals, published in 1993, the IAEA Nuclear Safety Advisory Group (NUSSAG) went even further in condensing the principles derived from the three basic safety objectives and identified 25 basic safety principles, which have been taken up as the technical basis for the Convention on Nuclear Safety. It is recommended that any review of the principles for nuclear power sources in space should take careful note of the safety fundamentals and the approach adopted in the Convention on Nuclear Safety.

33. For nuclear power sources in space, the use of radioisotope thermoelectric generators and the launch of reactors in a pre-critical condition means that terrestrial regulations concerning the transportation of radioactive materials are directly relevant. Therefore, any review of the principles for nuclear power sources in space should also take account of the IAEA Regulations for the Safe Transport of Radioactive Material.[7]

V. Areas where nuclear power sources in space differ from terrestrial ones

34. The previous discussions have illustrated that there are many similarities between the safety issues faced by nuclear power sources in space and those confronting terrestrial nuclear plants, particularly nuclear power plants. In dealing with such issues, it would be expected that the concept of a safety case, based on a full probabilistic risk assessment, would apply to nuclear power sources in space in much the same way as for terrestrial nuclear activities; the safety culture aspects should be very similar; and the risk philosophy should also be the same. The concepts underlying the risk philosophy developed in the Health and Safety Executive's tolerability of risk document seem to have very wide applicability and have been taken up by international organizations, such as ICRP and IAEA. It is recommended that they should be looked at carefully in any revision of the principles for nuclear power sources in space. It should, however, be recognized that the actual numerical risk "targets" for nuclear power sources in space may differ from those for terrestrial nuclear activities—for a variety of reasons that will need to be explored and elaborated.

35. There are, however, a number of important differences between nuclear power sources in space and terrestrial ones that need to be taken into account, including:

(a) The justification for utilizing nuclear power sources in space is more complicated than for terrestrial nuclear activities, as discussed in document A/AC.105/593/Add.3;

(b) Nuclear power sources in space are incorporated into moving facilities, which gives rise to a range of design/operational issues and potential accident scenarios that are not usually covered by terrestrial nuclear standards (and in particular during the launch and possible re-entry period);

(c) Nuclear power sources in orbiting vehicles will overfly many countries repeatedly, raising issues of third-party liability, the provision of safety information to third parties and the handling of abnormalities or emergencies;

(d) Nuclear power sources in space often cannot be inspected in service;

(e) In-service repair and maintenance of nuclear power sources in space is difficult, if not impossible;

(f) The ultimate disposal of nuclear power sources in space presents unique problems (which may be delayed for many years in some cases);

(g) The diversity of potential applications of nuclear power sources in space and the range of possible users present real challenges to the maintenance of a proper "safety culture" over the long time periods involved.

36. None of these differences should, however, invalidate the use of a modern (framework) approach to setting principles for nuclear power sources—such as the one used in the Convention on Nuclear Safety and the IAEA Safety Fundamentals.

VI. Conclusions and recommendations

37. The United Kingdom's approach to setting safety criteria for terrestrial nuclear installations, based on the tolerability of risk philosophy as elaborated in the Nuclear Installations Inspectorate safety assessment principles, has shown itself to be powerful and rigorous in a wide variety of situations (while still leaving the operators the flexibility to devise their own safety solutions for their own particular plants). It is recommended that it should be studied further as background to any future review of the safety principles for nuclear power sources in space.

38. The 1990 recommendations of ICRP[1] incorporate several new concepts, especially concerning dose limits and the need for hazard and risk assessments, which impact on nuclear power sources in space and should be a fundamental part of any review of principles for nuclear power sources.

39. The nuclear "standards" developed under the auspices of IAEA, particularly the Safety Fundamentals for nuclear power plants, and the Convention on Nuclear Safety have had a major impact on the harmonization and transparency of safety levels for terrestrial nuclear power plants worldwide. It is recommended that they should be studied closely to see what lessons they may have for nuclear power sources in space.

40. While it is important to cover the full range of possible nuclear devices that may need to be used in space, some emphasis may need to be given to the most likely devices to be used in the short, medium and longer term in order to manage the issues and prioritize activities (e.g. in the short term the continued use of radioisotope thermoelectric generators and radioisotope heater units can be expected).

Notes

[1] "1990 Recommendations of the International Commission on Radiological Protection", ICRP publication 60, *Annals of the ICRP*, vol. 21, Nos. 1-3 (1991).

[2] *The Safety of Nuclear Installations*, Safety Series No. 110 (International Atomic Energy Agency, Vienna, 1993).

[3] *The Tolerability of Risk from Nuclear Power Stations* (Her Majesty's Stationery Office, 1992).

[4] *Safety Assessment Principles for Nuclear Plants* (Her Majesty's Stationery Office, 1999).

[5] United Kingdom of Great Britain and Northern Ireland, Parliamentary Office of Science and Technology, *Safety in Numbers?: Risk Assessment in Environmental Protection* (June 1996).

[6] International Atomic Energy Agency, "Convention on Nuclear Safety" (INFCIRC/449), annex.

[7] *Regulations for the Safe Transport of Radioactive Material*, Safety Standards Series No. ST-1 (International Atomic Energy Agency, Vienna, 1996).