Proceedings of ICAPP 2007
Nice, France, May 13-18, 2007
Paper 7325

ESA's Approach to Nuclear Power Sources for Space Applications

Leopold Summerer, Bruno Gardini, Giacinto Gianfiglio
ESA - ESTEC
Keplerlaan 1, NL-2201AZ Noordwijk, The Netherlands,
Leopold.Summerer@esa.int, +31-71-565-6227

Abstract - *Nuclear power sources for space (NPS) are, according to current physics knowledge, the only power source option for some classes of space missions. Europe has successfully used nuclear power sources for space exploration missions (e.g. Huygens lander on Titan, Ulysses spacecraft). While some small-scale study and development efforts have been undertaken at national level during the past 40 years, these did not go beyond study and early prototyping level.*

In the light of further European integration and European ambitions in space, an independent working group involving European institutional stakeholders has discussed options and proposed coherent European positions concerning the safety, use and development of NPS technology in Europe.

This paper presents safety aspects and options as identified by this European Working Group and ongoing related ESA in this field.

I. INTRODUCTION

The absence of hydrocarbon power sources in space and the limitations of batteries have led, since the beginning of space exploration in the late 1950s and 60s, to the development of photovoltaic and nuclear power devices; these were identified as the only options with the potential to supply sufficient energy over an extended time period.

Both technologies were developed and used in parallel, partly due to the criticality of power supply to any space mission and partly due to their complementary nature.

For several years ESA has been performing system studies on applications of nuclear power sources in space, in the frame of the ESA General Studies Programme. These studies fulfil mainly a "technological survey" function. ESA and ESA Member States have already cooperated with NASA on scientific missions involving US radioisotope thermoelectric generators and radioisotope heater units (Ulysses, Cassini/Huygens, Galileo). However, NPS development, management and handling in these missions were fully under the control and responsibility of the US partners, following US safety and approval procedures. Moreover, all these missions were launched on US launchers from US territory.

Based on plans of the European space science community and of the Aurora Space Exploration Programme, nuclear power sources appear as essential and enabling key assets for a significant number of envisaged science and exploration missions, like deep space missions towards Jupiter and beyond and surface missions on Mars and the Moon. This has been clearly confirmed within studies in the framework of the Aurora Preparatory Exploration Programme and by the *European Working Group on Nuclear Power Sources for Space.*

I.A. Definitions

The term "space nuclear power sources" or "nuclear power sources for space" (NPS) usually comprises:

nuclear fission reactors: small fission reactors that are in principle similar to terrestrial reactors but with different retained design options especially for reactor cores, cooling, moderation and control systems;

radioactive power sources (RPS): generally relatively small and currently only passive devices using the natural decay heat of radioisotopes either for thermal control (*radioisotope heater units (RHUs)*) or converted into electricity (*radioisotope thermo-electric generators (RTGs)*).

I.B. Power level range of nuclear power sources

Fig. 2 shows the approximate power level range of different nuclear power sources (from small RHUs emitting mW_{th} to nuclear thermal propulsion reactors in the GW_{th} range) and the comparison with terrestrial nuclear power sources (surface and submarine reactors).

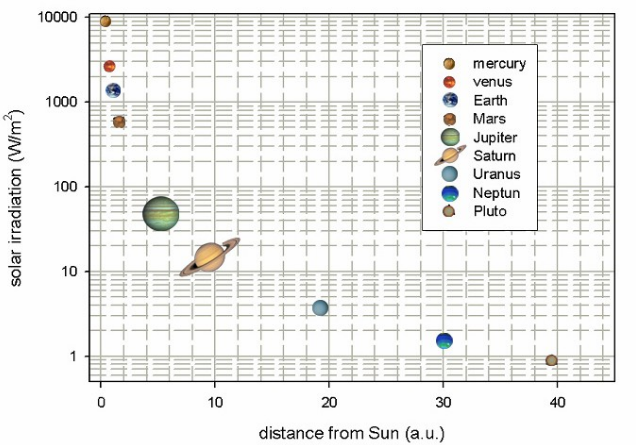

FIG. 1: Semi-logarithmic graph showing the decrease of solar intensity with the square of the distance to the sun, resulting in a 60% decrease at Mars orbit and more than 95% decrease at Jupiter orbit compared to its intensity at Earth distance.

I.C. General use of nuclear power sources in space

For interplanetary exploration beyond the Earth' distance from the Sun, solar power quickly reaches its limits (Figure 1), leaving radioisotope devices as the only possible power source for a whole range of missions: RPS were used on all past and current interplanetary spacecraft to Jupiter and beyond as well as on-board most planetary landers. [1, 3, 6, 8, 10, 11, 12, 13, 14, 18, 27, 28]

The first "nuclear battery" was presented to the public in 1959. The first US space mission involving an RTG was the *Transit 4a* spacecraft launched in 1961; 24 further missions into Earth orbit as well as into interplanetary space and to planetary surfaces followed.

While the US have focussed their effort right from the start of space activities on radioisotope power sources, the Soviet space nuclear programme has given priority to the development of space fission reactors, of which over 30 have been flown in the last 40 years. All of these have been used on experimental and defence related satellites in low Earth orbit. [16, 27]

I.D. European space science and exploration perspectives

Europe is expected to continue its knowledge-driven scientific discovery missions into the Solar System. For the timeframe 2015-2025, the European space science community will focus on studying the evolution of the Solar System, missions to the outer Solar System (Jovian satellites, Trans Neptunian Objects (TNO), boundaries of the heliosphere), and missions aimed at answering key questions related to the origin and evolution of life (e.g. old rock formations on Mars). [5]

ESA is currently engaged in the Aurora space exploration programme. Aurora is ESA's first step in human space exploration outside the low Earth orbits used for the Russian space station MIR and the International Space Station (ISS). Through this programme ESA is elaborating a long-term plan for human exploration of space, with Mars as its main objective and the Moon a very likely intermediate step. The approved programme consists of two main elements: the "core programme" and the "robotic missions". Among the tasks of the "core programme" is also the development of general enabling technologies for exploration. The first proposed mission of the "robotic missions" is the ExoMars mission, the first exobiology mission to planet Mars. [4]

Based on current physics knowledge, preliminary assessments and past experience, Europe will need to use radioisotope power sources for its missions to the outer Solar System. Europe might also need radioisotope heater units and possibly radioisotope thermoelectric generators for longer lasting lunar and Martian surface missions, among which the ExoMars mission would be the first candidate.

II. INSTITUIONAL EUROPEAN APPROACH

Not immediate need-driven, nor mission-specific, but based on the facts that

- Europe is likely to need nuclear power sources as essential elements for its planned space missions,
- Europe is currently fully dependent on its partners for their supply and launch, and
- activities involving nuclear power sources for space involve stake-holders outside the traditional space sector,

ESA has approached the European Commission in 2003 in order to reflect together with institutional stake-holders on the options for Europe in this area.

II.A. European Working Group on Nuclear Power Sources for Space

The *European Working Group on Nuclear Power Sources for Space* was established and mandated in spring 2004 to deliver a strategy level assessment of

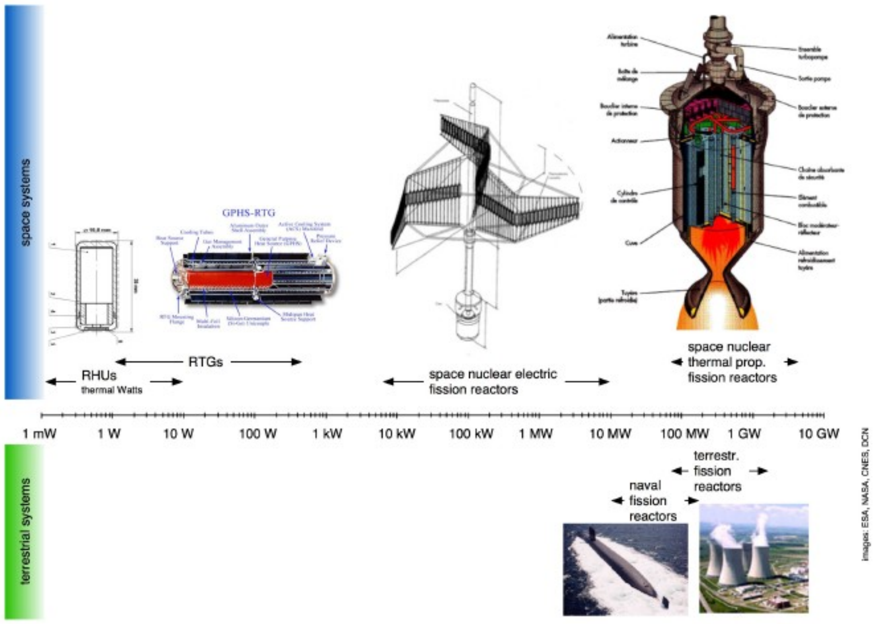

FIG. 2: Power range of nuclear power sources for space applications, and comparison with standard terrestrial nuclear power applications.

the European situation and options and make high-level recommendations within one year.

1. *Methodology*

The EC-chaired working group comprised 31 members from seven European countries (including new EU Member States), including all large European countries involved in space and nuclear energy activities, in addition to the European Commission and ESA. Members were mainly from institutions in the space and nuclear energy sector in Europe.

Space and nuclear industry as well as academia were consulted during the elaboration of the report and provided written and oral input in the form of technical presentations. The working group held eight meetings and operated on a consensus basis. The final report was adopted by consensus by all members. Its findings and recommendations constitute the basis for the ongoing ESA activities in this field.

III. RELEVANT EUROPEAN COMPETENCE

Europe does not start from zero when engaging in space nuclear power source activities: Europe has developed and maintained a well-functioning institutional and industrial nuclear base, made early prototypes and in-depth studies on NPS for space already in the 1960s and gained experience on their integration and use during the *Ulysses* and *Cassini/Huygens* missions.

III.A. *Well-functioning European industrial and institutional nuclear base*

A number of Member States of the European Union and ESA have developed world-renowned expertise in nuclear power systems in general. Terrestrial nuclear power plants deliver 35% of the European electricity need. Europe has developed and partly implemented the full nuclear fuel cycle and successfully operated a large variety of different nuclear installations and nuclear power plant. [9]

III.B. *Early European work on NPS for space*

In parallel to the US and Russian efforts for the development of nuclear power sources for space, Europe has started research and development efforts for both radioisotope power systems and nuclear fission reactors. These have resulted in early prototypes of radioisotope thermo-electric generators, including nuclear fuelled testing during the 1960s and advanced studies on space fission systems in the late 1960s/early 1970s and late 1980s/1990s. [16, 17, 19]

III.C. *RPS application experience in space*

European industry and agencies gained some experience with the application of radioisotope power sources in space during the two co-operative space missions with the US: *Ulysses* and *Cassini/Huygens*. For both missions, however, the radioisotope power sources were provided and taken care of by the US partners and both missions were launched from US territory and on US launchers following US launch approval processes. [1, 10]

According to US and Russian experience and backed up by European studies, nuclear power sources for space require development times of the order of at least a decade. The European Working Group on Nuclear Power Sources for Space therefore recommends eventual development decisions to be taken as far in advance as possible, while keeping design choices relatively flexible and recognising that likely application scenarios may well change.

IV. PROPOSED EUROPEAN APPROACH TO NUCLEAR SAFETY IN SPACE MISSIONS

Since about 50 years, western Europe has accumulated a very high degree of expertise in operating nuclear installations in a safe and reliable manner. During that time, European nuclear institutions and industry have developed and implemented very high safety standards, that have led to excellent nuclear safety records.

The use of nuclear power sources for space missions needs to follow similar high safety standards and establish within the concerned parts of space industry and space agencies the same strong nuclear safety culture that is governing the nuclear industry.

Safety needs to be and is of primary importance for all activities involving nuclear power sources. Following the IAEA general nuclear safety objectives, a defence-in-depth strategy needs to be followed to protect individuals, society and the environment by establishing and maintaining effective defences against radiological hazards.

The prevention of the exposure of humans and the biosphere to harmful levels of ionising radiation is also treated by the International Commission on Radiological Protection (ICRP) and dealt with by the EC Directive 96/29/Euratom. [2]

Besides safety, security as well as non-proliferation aspects need to be considered.

IV.A. *Approach to radiation hazard*

Radioisotope sources and nuclear fission reactors for space present different types and levels of hazard. The radiation hazard is related to the possibility of release of radioactive material. In fission reactors for space, radioactive material is gradually produced only after its activation. Radioisotope power sources, in contrast, are based on isotopes generally produced in and extracted from terrestrial fission reactors.

Radiation hazards specific to the use of nuclear power sources for space missions can be divided into three categories:

Launch hazards: The accidental release of radioisotopes during accidental launch conditions is prevented in the case of reactors by launching a cold, non-critical Uranium core (almost no radioactive fission products present), and in the case of radioisotope devices by adding protection layers that are able to withstand all foreseeable accidental conditions. Reactors are furthermore designed to prevent the possibility of accidental criticality. Radiation hazards caused by possible additional neutron sources or the dispersal of fuel debris require to be managed by the abovementioned defences.

In-space hazards: In space, humans and spacecraft are exposed to higher natural levels of radiation than on Earth, taken into account as an operational constraint. Radioisotope sources do not present any significant additional hazard in space. Shielding and distancing protects humans and materials from additional radiation from fission reactors.

Re-entry hazards: Radioisotope sources are enveloped with several protecting layers that are able to withstand all foreseeable accidental reentry conditions. Nuclear reactors are either operated in or put into a safe orbit in the case of a malfunction or at end of life.

IV.B. *Prevention and mitigation of accidents*

Along with the gradual increase of international safety, radiation and environmental protection standards over the last 50 years, safety requirements for the use of nuclear power sources in space have changed over time.

During the 1960s, a period of multiple atmospheric nuclear bomb test explosions, radioisotope sources were designed to break up in the upper atmosphere in case of re-entry and dilute to then-acceptable levels. Now safety measures prevent the release of radioisotopes under any foreseeable accidental conditions. During all past accidents with radioactive power sources, the prevention and mitigation measures worked as foreseen.

Following the accidental re-entry of an active Soviet nuclear fission reactor in 1978 (*Cosmos-954*, [7]), prevention and mitigation measures were implemented for all space nuclear power sources and agreed upon at international level in the United Nations General Assembly Resolution 47/68 in 1992. [25]

The operation of nuclear power sources in Earth orbit also needs to consider the interaction with orbital space debris. In particular for a spacecraft with a nuclear power source on board, it is necessary to increase the orbit up to a "sufficiently high" Low Earth Orbit consistent with the UN Principles Relevant for the Use of Nuclear Power Sources in Outer Space. [25] In its report the *European Working Group* recommends considering both the nuclear and the orbital debris conditions when defining the sufficiently high orbit for spacecraft with NPS.

V. ONGOING ESA ACTIVITIES

In order to put ESA in a position to be able to *decide* about the use of radioisotope power sources in general and radioisotope heater units specifically, several preparatory activities have been identified as necessary.

V.A. Regulatory Framework

Following a general practice for activities involving radioisotopes above a certain activity level, the UN NPS Recommendations [25] and the example of US and Russian practice since 40 years, Europe needs to establish a comprehensive nuclear safety framework for the use and launch of nuclear power sources for space. Only with such a framework in place, Europe would be able to decide on a potential use of nuclear power sources for its space missions.

In the case of the US and Russian processes, this cycle starts at the very early stages in a project, as soon as the potential need for nuclear power sources is identified and covers all aspects until the launch, use and final disposal in space and involves in addition to NASA several other governmental entities.

The establishment of a European safety framework for the use of nuclear power sources for space needs to be seen within the frame of the ongoing work within the "Working Group on the Use of Nuclear Power Sources (NPS) in Outer Space" of the Scientific and Technical Subcommittee of the UN Committee on the Peaceful Uses of Outer Space (COPUOS). [20, 21]

Given that space activities in general and those involving nuclear power sources in particular are of inherently global nature with potential global consequences, it seems to be of general interest to ensure that these activities are conducted with similarly high minimum safety standards wherever they are conducted. This is especially true since the number of states able to use nuclear power sources in space is likely to increase. European member states and ESA* are therefore working towards the adoption of high and possibly binding international safety standards.

Space activities, and especially space activities involving nuclear power sources, are considered in international law as ultra-hazardous activities. [15] Given the special liabilities and responsibilities of states in space activities [22, 23, 24, 25, 26], the approval chain for the launch of nuclear power sources in the US and Russia also involve political entities taking the political responsibility for the launch. In the US, the *Office of Scientific and Technical Policy* as part of the *Executive Office* of the US president is taking this political responsibility.

Within the drafting of the European space nuclear safety framework, this aspects are addressed with an emphasis on achieving one integrated efficient process that allows the appropriate involvement of all relevant entities.

V.B. Technical and safety assessment of radioisotope heater units

It is important to that the development of radioisotope power sources within ESA Member States is currently not considered. Therefore all technical activities, and indeed the overall European approach to radioisotope power sources, is based on enabling Europe to make use of externally procured devices onboard European spacecraft. Following the recommendations of the *European Working Group on Nuclear Power Sources for Space*, the potential use of Russian devices is currently assessed within the Aurora space exploration programme. Based on the potential first needs identified within the Aurora programme, the focus is put on the assessment of radioisotope heater units.

While preliminary studies performed under the ESA General Studies Programme have substantially increased ESA's understanding of the technical details of radioisotope power systems, technical details of

* as an observer

some steps in the production process and details of the Russian qualification tests are essential in order to assess the safety associated with the use and launch of these devices. In early 2007, ESA has therefore started a thorough assessment of the technical and safety aspects of these devices, which is expected to deliver substantial information for a technically based decision on their potential use on European missions.

V.C. Integration aspects

Europe has only limited expertise and knowledge on the implementation of radioactive power sources in spacecraft and launchers. Since the presence of radioisotopes however impacts many aspects of the mission, starting from the spacecraft design up to the launcher trajectory and emergency measures, its is necessary to understand and assess these implications as early as possible for a project.

Given the restrictions applying to the transport of radioisotopes and the common practice of late integration of the radioisotope sources at the launch site (as practiced by US NPS launches of the last 20 years), special emphasis is put on launch-site integration aspects.

VI. CONCLUSIONS

Europe is in the process of defining its position towards nuclear power sources for space activities, a key enabling technology for European ambitions in space science and exploration and according to present knowledge the only power source option for several classes of missions (e.g. all missions to the outer Solar System). In the past, Europe has used US nuclear power sources on two collaborative missions on US launched spacecraft.

In the frame of the EC/ESA Framework Agreement, an EC-chaired institutional working working group on nuclear power sources for space analysed the European situation with respect to nuclear power sources, identified options for Europe and recommended a phased approach with clear action steps and milestones towards increased European independence in the field.

ESA member states and ESA are working within the UN COPUOS *Working Group on the Use of Nuclear Power Sources in Outer Space* towards the establishment of a strong *"international, technically-based safety framework for the use of nuclear power sources in outer space"*.

In order to enable Europe to independently launch and use nuclear power sources, a coherent European safety framework for nuclear power sources for space is currently drafted, including safety objectives, the repartition of tasks and responsibilities and and efficient, streamlined and transparent European nuclear launch approval process. In addition, the required technical knowledge about radioisotope heater units and the implications of their integration into European spacecraft and launchers are assessed.

NOMENTCLATURE

ACT ESA's Advanced Concepts Team

AEC Atomic Energy Commission, former US government commission created by the Atomic Energy Act of 1946 and charged with the development and control of the US atomic energy programme following World War II, dissolved in 1974, activities integrated into DoE

CNES Centre National d'Etudes Spatiales, French National Space Agency (France)

DLR Deutches Zentrum für Luft- und Raumfahrt (Germany)

DoE Department of Energy (US)

ESA European Space Agency

IAEA International Atomic Energy Agency

ICRP International Commission on Radiological Protection

IRCU International Commission on Radiation Units and Measurements

JPL Jet Propulsion Laboratory (US)

MER Mars Exploration Rover mission (US NASA)

NASA National Aeronautics and Space Administration (US)

NPS Nuclear Power Source, in this document synonymously used for *space* nuclear power sources

RPS Radioisotope Power System (sometimes used synonymously to RTG)

RTG Radioisotope Thermo-electric Generator.
The term "thermo-electric" should not be confounded with thermoelectricity, the Seebeck-effect based mechanism used in thermocouples, but designates only the thermal to electric conversion, which might be static or dynamic

RHU Radioistotope Heater Unit

[1] ESA, JPL. Ulysses Operations Index Page, 2005. http://ulysses-ops.jpl.esa.int/ (acc. Aug.05).

[2] European Commission. Laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation. *Official Journal of the European Communities*, L159, Volume 39(Council Directive 96/29/Euratom of 13 May 1996), 1996.

[3] European Space Agency. Esa science and technology: Ulysses, 2005. http://sci.esa.int/ulysses/ (acc. Aug.05).

[4] European Space Agency, Aurora Exploration Programme. ESA - Aurora Exploration Programme, 2005. http://www.esa.int/aurora (acc. Oct.05).

[5] European Space Agency, Science Programme. ESA's Cosmic Vision, 2005. http://www.esa.int/esaSC/SEMA7J2IU7E_index_0.html (acc. Oct.05).

[6] R. O. Fimmel, W. Swindel, and E. Burgess. *Pioneer Odyssey*. Number SP-349/396. National Aeronautics and Space Administration, revised edition edition, 2004.

[7] E. Galloway. The USSR Cosmos 954 and the Canadian claim. *Akron Law Review*, (12-3):401–415, 1979.

[8] P. Haanappel. Nuclear power sources in outer space. *Proc. Intern. Inst. of Space Law*, (33):215ff, 1984.

[9] IEA/OECD. World Energy Outlook 2002. Technical report, International Energy Agency, 2002.

[10] Jet Propulsion Laboratory. Cassini program environmental impact statement supporting study. JPL Publication D-10178-4, Jet Propulsion Laboratory, 1993.

[11] Jet Propulsion Laboratory. Mars exploration rover mission, 2005. http://marsrovers.jpl.nasa.gov/home (acc. July 2005).

[12] Jet Propulsion Laboratory. NASA's Solar System Exploration: Galileo Legacy Site, 2005. http://galileo.jpl.nasa.gov/ (acc. 8 August 2005).

[13] Jet Propulsion Laboratory. Viking, September 2005. http://pds.jpl.nasa.gov/planets/welcome/viking.htm (acc. Sept.05).

[14] Jet Propulsion Laboratory. Voyager, 2005. http://voyager.jpl.nasa.gov (acc. July 2005).

[15] A. Kerrest. The liability convention and liability for space activities. In *Capacity building in space law*, The Hague, November 2002. United Nations/International Institute of Air and Space Law.

[16] H. Löb. *Kerntechnik bei Satelliten und Raketen*. Number 36 in Thiemig Taschenbücher. Verlag Karl Thiemig KG, 1970.

[17] H. McAndrews, A. Baker, C. Bidault, R. Bond, D. Browning, D. Fearn, P. Jameson, J.-P. Roux, D. Sweet, and M. Weston. Future power systems for space exploration. ESA-Report 14565/NL/WK, QinetiQ, 2003.

[18] NASA. 40+ years of Earth Science - The Nimbus Program, 2005. http://www.earth.nasa.gov/history/nimbus/nimbus.html (acc. Aug. 05).

[19] X. Raepsaet. Les réalisations ou études anciennes: ERATO, MAPS, SP100, Nerva. Presentation, September 2002. Séminaire sur la propulsion spatiale nucléaire.

[20] Scientific and Technical Subcommittee of the UN Committee on the Peaceful Uses of Outer Space. Multi-year work plan for developing an international technically based framework of goals and recommendations for the safety of nuclear power source (NPS) applications in outer space covering the period 2003-2006. Technical Report A/AC.105/804, annex III, United Nations - COPUOS, Vienna, Austria, 2003.

[21] Scientific and Technical Subcommittee of the UN Committee on the Peaceful Uses of Outer Space. Report of the working group on the use of nuclear power sources in outer space of the scientific and technical subcommittee on its intersessional meeting, held in vienna from 13 to 15 june 2005. Technical Report A/AC.105/L.260, United Nations - COPUOS, Vienna, Austria, 2005.

[22] United Nations. Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies. *United Nations General Assembly Resolution*, 2222 (XXI), entered into force October, 10 1967.

[23] United Nations. Convention on the International Liability for Damage Caused by Space Objects. *United Nations General Assembly Resolution*, 2777 (XXVI), entered into force September, 1 1972.

[24] United Nations. Convention on Registration of Objects Launched into Outer Space. *United Nations General Assembly Resolution*, 3235 (XXIX), entered into force September, 15 1976.

[25] United Nations. Principles Relevant to the Use of Nuclear Power Sources in Outer Space. *United Nations General Assembly Resolution*, 47/68, adopted December, 14 1992.

[26] United Nations. United Nation Treaties on Outer Space can be downloaded from the website of the UN Office for Outer Space Affairs, 2005. http://www.OOSA.unvienna.org/SpaceLaw/outerspt.htm (acc. Jul. 2005).

[27] US Department of Energy. *Atomic Power in Space - A History*. Number DOE/NE/32117-H1. US Department of Energy, 1987.

[28] US Department of Energy. Space nuclear power systems, 2005. http://www.ne.doe.gov/space/space-desc.html (acc. July 2005).