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RESULTS OF THE GRAND BASSIN CASE STUDY IN REUNION ISLAND :

OPERATIONAL DESIGN FOR A 10 KW MICROWAVE BEAM ENERGY TRANSPORTATION

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Abstract

The cooperative work of **an international task team** has resulted in suitable solutions for most of the technical problems in Grand Bassin Case Study, established in 1994 to evaluate the possibilities of providing electrical energy to a group of mountain homes by means of a microwave beam system similar to a SPS energy transportation system.

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This case study has brought the attention to the **environmental aspects** and public acceptance of such systems since the main challenge was to integrate the system in harmony with the general environment of the mountain canyon. Low cost of implementation and operation were also key constraints. It was found that the physical characteristics associated with the **122 mm wavelength** of the microwaves system were helpful in meeting the challenges. Although eventually important, the overall technical efficiency of the system was thought to be a secondary problem for the time being.

In the design case, the electrical energy is taken from the main utility grid to power an array of about 30 projecting elements laid in several rows on the side of the Grand Bassin Canyon to generate a 20-m diameter microwave beam of safe low power density. Depending on availability, the microwave generators may be either **phase locked magnetrons** or **conventional klystrons**. At a distance of 700 meters across the canyon, a receiving array combines a set of small mesh parabolic antennas with **cyclotron wave converters**, and surrounding arrays of **wire dipole rectennas**. A power conditioning unit converts DC to a usual 220 V - AC supply for the three tourist lodges at the bottom of the canyon. A radio-controlled **feedback circuit** is provided to adjust the microwave beam power to the variable needs of the end-users. The implementation cost of the system is expected to be similar to the cost of other more conventional ways to provide energy to the small village. The energy delivered could reach 10kW with a global efficiency expected to reach 20 %, making running costs more economical than

with other solutions such as photovoltaics. Legal and commercial problems have not been fully solved, and more studies will be needed to discuss **ownership and billing questions**.

The Grand Bassin Case Design study has already brought up many valuable considerations concerning the **end-to-end operation of a WPT link**. Close cooperation with the environmental organisations and with the potential users of the system has been instrumental in the acceptance of the project. It was shown that WPT could be **a solution to environmental problems**. Most of the local partners who worked with the scientific project team understood that the Grand Bassin "scale model" not only was a solution to the limited energy problem of a small isolated mountain village, but also one of the meaningful keys to the development of the future SPS systems that could provide **clean and sustainable energy** for mankind.

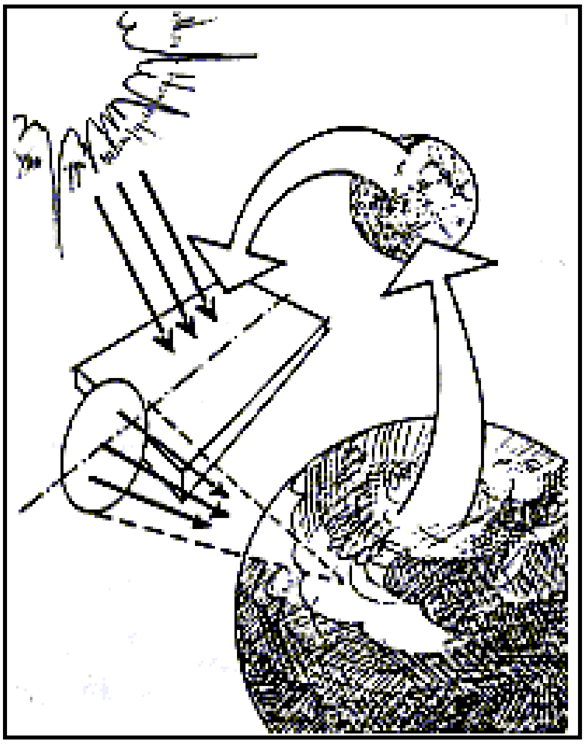
1 - introduction 1 : energy for the future

World oil and gas reserves are estimated to last some 50 years into the 21st century. Other fossil fuels (coal) are not expected to last over 2 or 3 centuries. It is not clear whether fission nuclear power will solve its radioactive pollution problems and in any case it seems that "cheap" nuclear fuel will not last much more than fossil energy sources.

The sustainable long term solution for Mankind is to turn to either fusion nuclear energy, which still has to be proved as a controlled source of energy, or to solar based renewable energies.

The most promising technology is the one of SPS systems [1] , with efficient collection of solar energy in outer space, and transportation to the surface of the Earth by means of microwave beams. The technical feasibility and economy of the concept have been demonstrated, especially with Moon based operations for the construction of the giant power satellites.

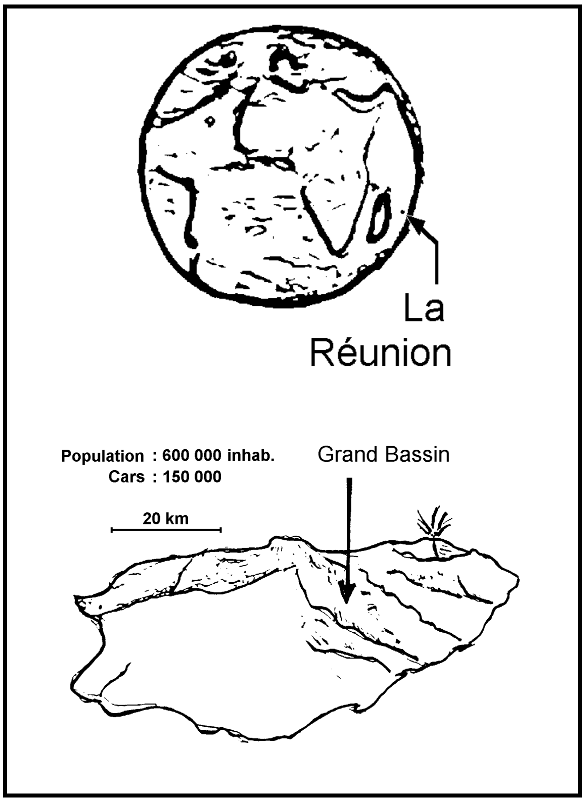
Wireless Power Transportation (WPT) by means of microwave beams has been fully demonstrated by many experiments. At the SPS'91 Symposium in Paris [2], the first initiatives were taken towards the implementation of operational transportation of energy from point to point at the surface of the Earth as a step towards more complex systems eventually leading to the construction of SPS systems. MITI of Japan has expressed views towards the implementation of SPS systems for the major cities of Japan in 2040.



Energy from the Sun, collected in space with Moon based SPS construction and transportation by microwave beams

2 - the history of the case

Several potential sites for operational WPT were selected in La Réunion as early as 1991. Preliminary investigations were made at the University of La Réunion in connection with SPS and WPT researchers in the USA and in Russia. Significant progress was made in 1994 with contacts with the SPS-2000 Task Team and ISAS in Japan. Subsequently, a international workshop was held in La Réunion in December 1994 with several international experts [3]. The case study approach was favoured as a method to make headway. Four cases were presented for study [4],[5]. The Grand Bassin case was selected as the most promising case.

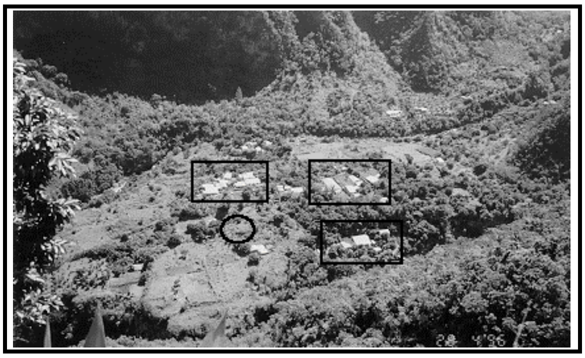


La Réunion, a remote region of Europe,
a large volcano island in the Indian Ocean
with world class canyon scenery

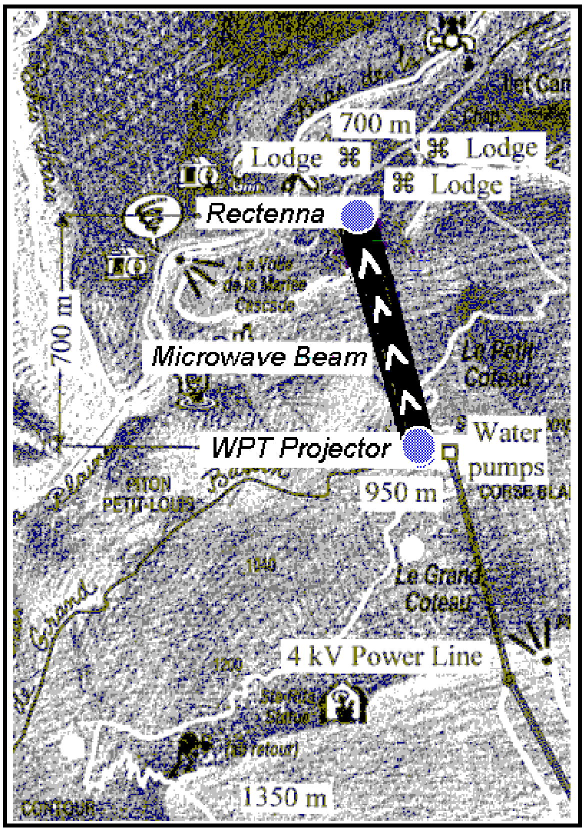
The technical question in Grand Bassin is to provide electricity to a group of three independent mountain lodges at the bottom of a 700 m deep canyon in a protected environment. Access is only by foot (one hour for good mountain hikers) or by helicopter.

The lodges are currently equipped with photovoltaic panels which provide enough energy for communications (radio telephones), for radio and television sets or basic light. But more power is needed, especially for household equipment such as washing machines and deep freeze storage. Several solutions are under consideration, such as diesel generators or the extension of a power line, aerial or buried. WPT is both the most challenging and the most interesting solution so far.

From the beginning of the case study, it was clear that Grand Bassin is a very favourable site for WPT, especially since a 4 kV power line is already installed from the top of the cliff to half-way down the slope. It is used to feed the electrical pumps that lift water from a large pipe running along the cliff from a source located several kilometres upstream. From the site of the pumps to the potential site for the energy receiving system, the straight line distance is only 700 m.



Three lodges (boxes) with capacity for 40 tourists
between two rivers at the bottom of Grand Bassin
The circle indicates the potential site for
the microwave beam reception systems
(see general layout map below)



3 - the environmental challenge

Like many other sites in La Réunion, Grand Bassin features world class scenery for tourists and hikers [6]. Great care is taken to protect the originality of the environment. It would be hardly thinkable to see power lines across the canyon. However, the site is not totally "clean" from that point of view since a cable car is used to shuttle equipment and farm products between the "world" at the top of the cliff and the small village at the bottom of the canyon. The cable runs mostly close to the mountain and does not really cross the valley, but the local and regional authorities are reluctant to see further installations of cables that might deface the canyon. The solution of aerial power lines, which clearly would be the most simple and least expensive one, is not favoured. Some other possible solutions are the extension of photovoltaics, a diesel generator, a buried power line along the access path, or wireless power transportation by a microwave beam.

The Grand Bassin unique scenery should not be defaced by aerial lines running across the canyon.

The challenge of the case study was that the proposed WPT system should integrate as well as possible with the environment. Low cost was the next consideration. Since the system should be operational and no longer a laboratory experiment, it should compete for construction and operation costs with the other possible solutions. Efficiency was the least constraining consideration, behind the guarantee of proper continuous operation. It was though that after the prime objective of running an operational system would be achieved, further research could then focus on improving operating characteristics and efficiency, with a great potential for technical development.

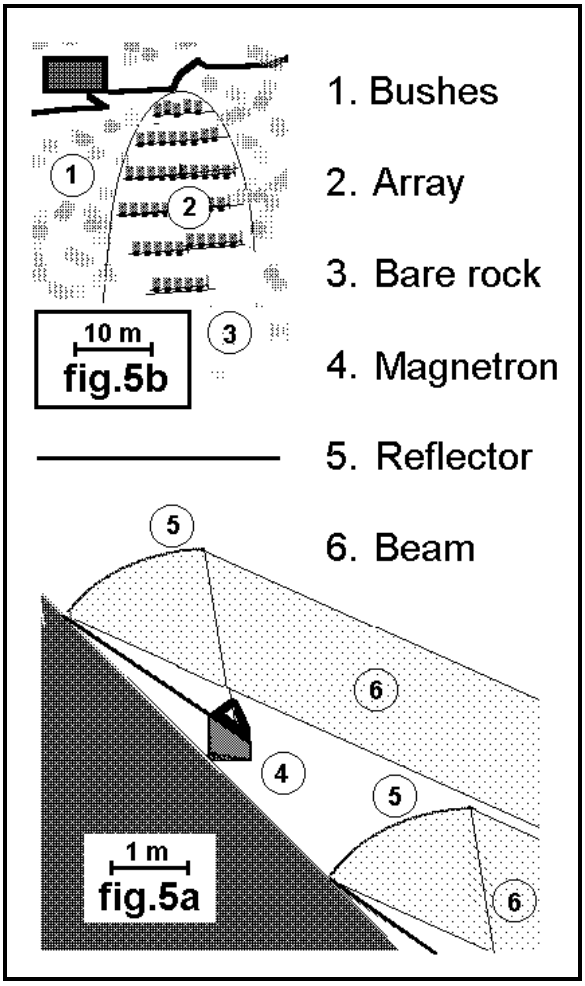
It appeared during the study that WPT would be a favoured solution with regard to the environmental and economical problems. Diesel generators would be likely the most simple to install but the most expensive in terms of running costs. The significant extension of solar panels would have difficulties meeting the constrains for visual integration with the environment. The WPT solution would compare with a buried line in installation costs. Although the power losses of a WPT system would be somewhat greater than for the buried line, such a system should be considered, because of its great potential for the future.

4 - the projection system

The microwave projection systems should use an array of phased separate projecting units for two basic reasons : the most immediate reason is that it is easier to integrate many small units in the landscape than a single large one; the long range reason is that there are limits to the size of single units but none to the global size of multi-element systems. Since the system is intended to be used as a testbed for the development of larger systems, the array option was selected.

Since cost was another major factor, the MDA Magnetron Device Amplifiers [7] designed by Dr. Bill Brown have been favoured. However they are still in an early development stage and for the reference Grand Bassin design, readily available 2 kW klystrons [8] have been considered at a cost of about 100 kF per unit (20 000 $)., i.e. a total cost of 2.5 MF (5 M$). To cut cost, the final choice was to use for the time a single 50 kW klystron at a cost of 400 kF (80 000 $) and to distribute the power through wave guides to 32 separate projecting elements in order to shape the microwave beam.

The average slope of the mountain where the projecting array is to be installed is 45°, and the beam should be projected at an angle of about 20° with respect to the ground. In order to achieve a compact beam with a slightly elliptical section, the array should cover a land area about 20 m in width and some 60 m along the slope. Unit positioning has to be achieved with a precision of less than 1 cm.



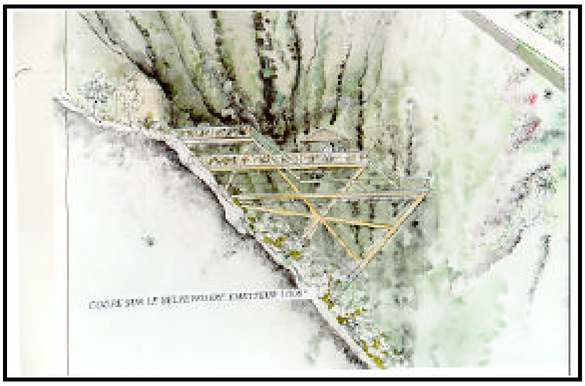
The 32 unit reflectors array
forms an elongated ellipse on the slope,
down from the water pumps where
power grid connection is to be made

Architectural research has been made to design specific reflectors [9] for landscape integration, and a "magnetal" shape has been found, where the reflectors should look like bushes or small trees on the slope. A 1.2 by 1.5 m simplified prototype has been built and demonstrated, consisting in a parabolic wire Fresnel system. The single demonstration unit was demonstrated successfully for officials in July 1996 in Plaine des Cafres, the city where Grand Bassin is located. Operational unit reflectors should be significantly larger with sizes of approximately 2 by 3 m. The Fresnel stepped layout, which can be fully two-dimensional, contributes significantly to depart from the conventional parabola shapes. With a polarised generation of the microwaves, a one-dimension spread of conducting wires with a 2 cm spacing can efficiently reflect the 2.45 GHz microwaves without impairing visibility.

The artist concept of a "magnetal" reflector.
The curve shaped reflectors can merge easily be staged to merge with bushes surrounding the array

On the picture taken during the Plaine des Cafres demonstration, the large see-through micro-wave Fresnel wire parabola reflector (to the right of the picture) is hardly visible against the landscape

An alternate solution has been proposed for a more compact circular array by hiding it under the structures of a lookout architectural building where the tourists could stop half way down to the bottom of the canyon to admire the unique panorama offered by the surrounding environment. However such an option would be specific and not portable to other sites in the perspective of the development of WPT applications.



An architectural lookout could hide the projecting array under its supporting structure as an alternate solution to landscape integration

5 - the reception system

It has been proposed to use both rectenna and CWC Cyclotron Wave Converters for the receiving array in order to test and evaluate both technologies under operational conditions. Both systems have been demonstrated in laboratory experiments.

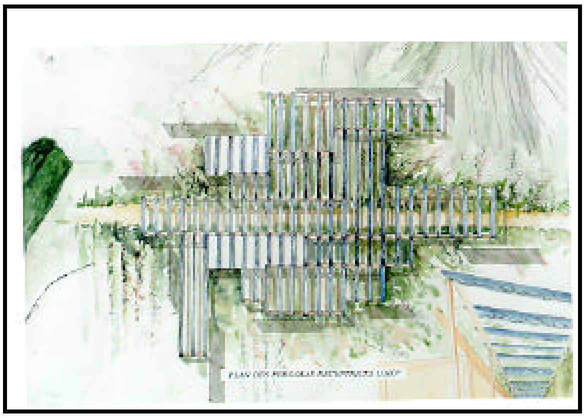
The combination array should be approximately 12 m in diameter. It would be set up on top of constructions resembling the pergola structures used for growing vines. For aesthetic purposes, it is easy to depart from the classical parabola designs by extending the structures beyond the reception area, as has been proposed by architecture researchers.

One of the advantages of the system is that it would allow the growing of vegetables under the structure, since sunlight would be able to go through either the rectenna panel or the mesh wire parabolas for the CWC's.

A small traditional building could be used to house the power conditioning equipment, and provide shelter for the technicians and researchers who will have the responsibility to monitor the operation of the system or make tests on new advanced designs for future systems.

This environmental architecture research should be considered as a laboratory, in the perspective of larger developments for environmental technology integration in the 21st century.

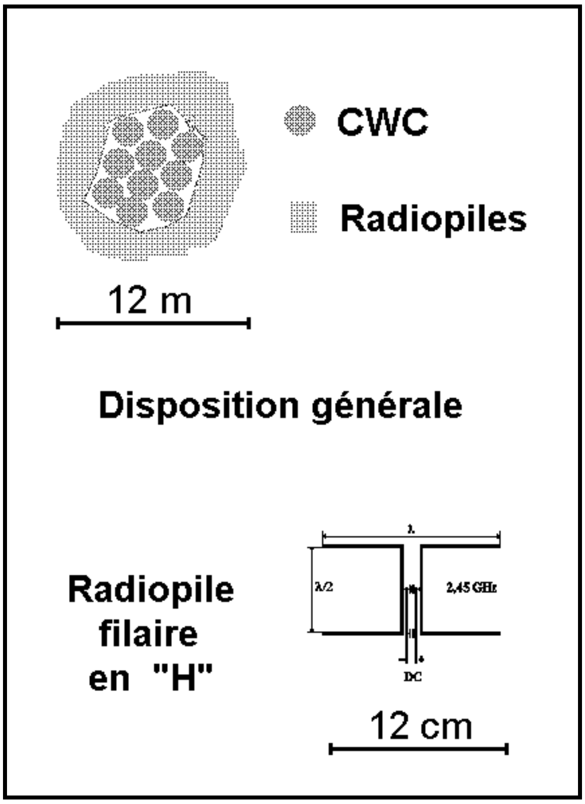
Vines are grown on top of pergola structures Similar constructions could be used to sustain the microwave receiving devices



By extending the supporting structures beyond the micro-wave beam footprint, it is possible to make them inconspicuous into the surrounding landscape.

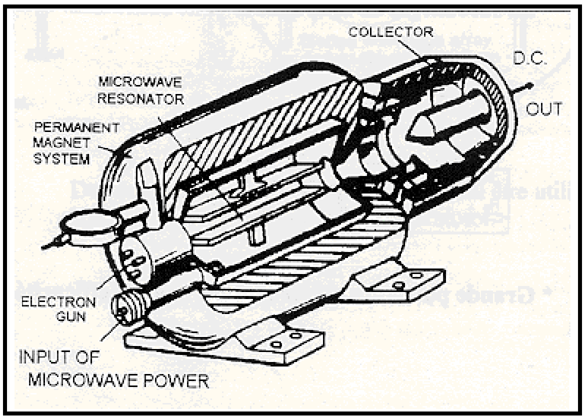
"H" type wire rectenna have been developed at ISAS in Japan and at the University of La Réunion [10], and have proved to be effective for the collection of microwave energy. Advanced designs are in development [11] at the University of La Réunion. The main question is the availability of inexpensive Schottky diodes for gigahertz range rectification. 1SS97 NEC diodes or equivalent would be used. Because of the limited voltage and power characteristics of the unit diode (35 Volt and 150 mA) it may be necessary to use 16 individual diodes for each rectenna element. A total number of 100 000 diodes would be necessary. This is the present situation in 1996. Due to the quantity, it may be possible in the future to create more specifically appropriate components in cooperation with the manufacturers .

A protection system with limiting diodes has to be implemented to avoid excessive voltage and to protect the rectifying diodes against overload or accidental damage.



Rectennas ("radiopiles") may combine with "reverse cyclotrons" to convert microwaves back to electricity

CWC's need parabola reflectors to concentrate the low energy density of the microwave beam towards the rectifying device, which may be located directly at the focus of the parabola, or below the parabola itself, with goose-neck feeders. An array of 6 or 7 wire-mesh parabolas similar to the equipment used for space reflectors can be used, in order to let the light through. Several 3 m diameter parabolas arranged in a flower pattern are less conspicuous than a single large dish, and can be easily integrated with the landscape.



CWC Cyclotron Wave Converters
The electron beam is accelerated by the energy of the microwave beam and produces high DC voltage on the collector

Behind the rectennas which produce low voltage DC, and the CWC which produce high voltage DC current, it is necessary to install a power conditioning unit, with some storage capability, to provide a stable 220 V standard household AC supply.

6 - operation of the integrated system

The original power would be taken either from the existing 4 kV power line, or from an additional line which would follow the same already equipped path which is used for the energy supply to the water pumps.

A specific power supply is necessary to feed the microwave generators. Water cooling can be easily arranged due to the availability of large quantities of water from the pipeline.

In order to maintain a safe energy density along the beam, the projecting area will be larger than the receiving one, with a slight focusing effect towards the receiving array.

After the receiving and power conditioning system, protected power lines would run on the ground to the three lodges, along the already existing water distribution network.

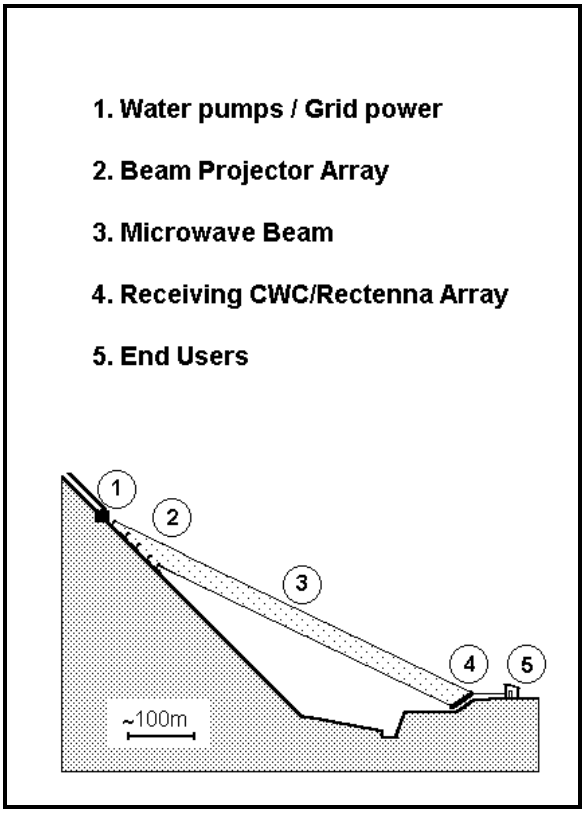


Diagram of the Grand Bassin WPT system
The length of the beam is approx. 700 m.
The operating mode is on/off at full power,
with storage battery regulation
on the receiving end.

The need for power will be modulated along the day. A small set of storage batteries will be used for temporary overruns of the demand, and when the microwave beam is temporary shut down. Since it is difficult to modulate the level of output of the devices used for microwave generation, the mode of operation on the projecting side will be on/off, remotely controlled as needed by a radio signal transmitted from the receiving end.

7 - cost and efficiency evaluation

The estimated cost for a first operational WPT link has dwindled by a factor of about 20 since the first estimates were given in 1991. This is due to a better choice for a first implementation, a downsizing of the power requirement, and mostly a significant reduction in the cost of GHz range rectifying diodes.

In the reference design, the equipment costs share about equally between the projection system and the receiving system. The construction costs are more important for the projection array because of the important slope of the mountain. The total cost of implementing a WPT system compares with the cost of burying a power line in this difficult working environment.

Projection	
Microwave generation	400 KF
Associated hardware	600 KF
Civil engineering	1 000 KF
Reception	
Rectennas	300 KF
CWC equipment	300 KF
Conditioning equipment	100 KF
Associated hardware	300 KF
Total estimated construction cost	**3 000 KF**
Engineering studies (10%)	**300 KF**
Engineering prototype (10%)	**300 KF**
Total estimated project cost	**3 600 KF**

A system cost comparable
to the cost of a buried power line

If the case study is to be followed by effective implementation, it will be necessary to conduct extended engineering studies, at a cost of about 10% of the total project cost, and to build a prototype to test the engineering solutions with real size projector and reception units. An engineering prototype with four phased projecting units, and a fully integrated system capable of transporting a power of about 1 kW over a distance of 100 m has been proposed as an intermediate step towards full implementation. The main question is a technical one because it is not the same thing to build demonstration equipment and to prepare for industrial construction.

In the laboratory, global efficiency better than 50% has been demonstrated, with efficiencies better than 80% for each of the three key aspects of WPT operation : electricity to microwave conversion, beam collection on the receiving site, and microwave to electricity conversion. In the case of Grand Bassin the first requirement is good integration into the environment and efficiency is a secondary requirement. This precludes the use of large highly efficient dish parabolas, but it should be reminded that the goal is general harmony, not the optimisation of a specific criterion at the expense of the art of good living.

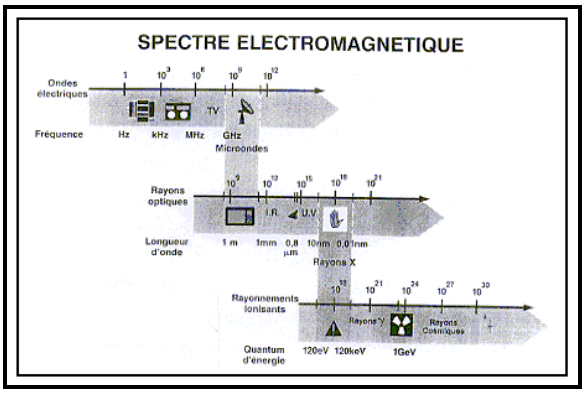
Grid Power		Projected Power		Received Power		End Power
	AC to MW conversion		Beam collection		MW to AC conversion	
	60%		60%		60%	
50 kW		30 kW		18 kW		11 kW

Global target efficiency of WPT is 22 %
In comparison, cost efficiency of photovoltaics is only 5%

In the case of Grand Bassin, the objective targets for efficiency have been set at 60% for each key step of the process, leading to a global efficiency of the system of about 20%. This is considered as acceptable for a running operation. The cost ratio between grid power and photovoltaic power is about a factor of 20 [12]. It results that as long as the WPT system efficiency will be better than 5%, it will deliver electricity at a better cost than current photovoltaic systems.

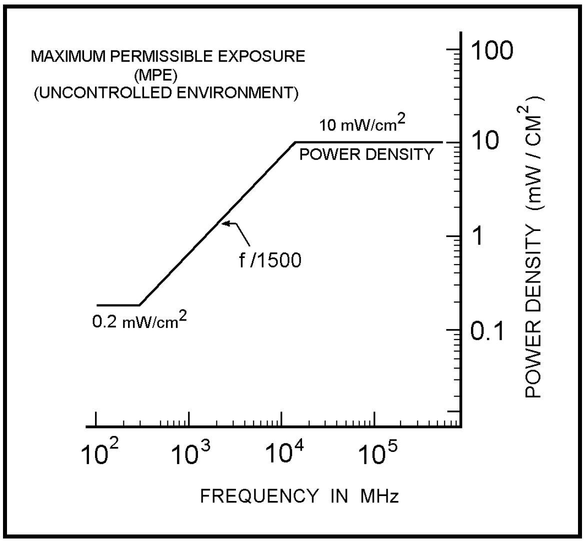
8 - safety and compatibility considerations

The first consideration is that 2.45 GHz microwaves, with a wavelength of 122 mm, have energy levels some one million times lower than the threshold where the radiation may cause ionisation in living cells [13]. Therefore the risk of cancer or genetic alteration is totally excluded, although popular fears may arise, due to the fact that most people have a very limited understanding of the nature of electromagnetic waves.



The three regions of the electromagnetic spectrum :
radio waves, optical rays and ionising radiation.
The 2.45 GHz microwaves do not cause cancer.
The only risk is the thermal risk.

The only real risk with microwaves is the thermal risk, and the popular image is that of roasted meat. Microwave ovens are good demonstrators that energy can be transported by microwaves, but WPT systems are not ovens, and the energy density can be kept within safe limits. The basic reference is the energy density of sunlight on the surface of the Earth at about 100 mW/cm². Full sun exposure is not comfortable and can lead to familiar sunburns. The risk begins at about 50 mW/cm² and safety standards for continuous exposure to microwaves have been set one order of magnitude below at 5 mW/cm², although some more recent US medical standards are set at lower levels [14]. It is essential to underline that any medical standard is only a local compromise between the dangers and the benefits of the use of microwaves. A maximum energy density of 25 mW/cm² has been considered as acceptable for WPT energy transportation beams since humans or animals are not expected to remain continuously in the beam. The only dangerous area in the whole system is the space between the source and the projecting reflector where access should be prevented by adequate protection means.



Microwave oven permissible energy leakage standard at 2.45 GHz is 5 mW/cm².
US medical standards for maximum permissible exposure is 1.6 mW/cm².

A specific risk of power radiation is electromagnetic interference with sensitive electronic equipment. The 2.45 GHz is located at the center of a frequency band allocated for Industrial, Scientific and Medical applications, and already some 50 million kitchen microwave ovens operate on that frequency around the world. In the case of the Grand Bassin projects the 25 mW/cm² power level is low enough so that it will not present a hazard for electronic equipment, and it will be perfectly possible for helicopters to fly through the beam without danger. And although the energy level within the beam is expected to be higher than the 5 mW/cm² standard, it is possible to define a virtual enclosure around the beam, outside of which the radiation level will fully comply with the regulations for electromagnetic compatibility.

9 - social issues

The first consideration is the aesthetic acceptability of the system. A great effort has been made towards new equipment designs that may integrate well with their natural environment. Beside the structural aspect, it can be noted that with the 122 mm wavelength, WPT systems do not compete with sunlight for frequency. Therefore, unlike photovoltaic systems, they can be painted to match surrounding colours. Also they can let sunlight through, and especially under the receiving area, this can be used for growing vegetables or other plants, allowing a dual use of scarce space. These aspects are key elements for the acceptability of the system.

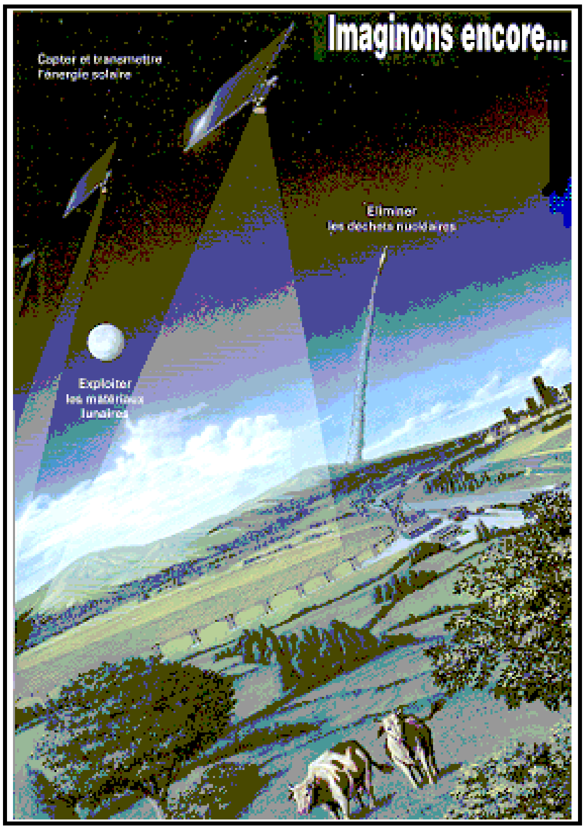
But some social problems may arise with ownership and billing considerations. Who will pay for the implementation of the system ? Who will take care to maintain it ? What will be the relations with EDF, the national French utility, with regard to the ownership of the transportation system ? How will the customers be billed ? Advance consideration should be given to these points to avoid unnecessary friction and seek the most appropriate ways by which the new technology of WPT can be integrated into existing social and economic structures.

10 - introduction 2 : the future of energy

With this outline, the Grand Bassin case study comes almost to its conclusion. More detailed day-long final presentations are expected to be given at the end of November 1996 during the SPS-IdR'96 workshop to be held in La Réunion.

But already the message is clear and the general conclusion of the case study is that Wireless Power Transportation for Grand Bassin is feasible, technically, financially, socially.

Progress goes by steps. The final report on the case study will be the successful end of a step. It may be, depending on the decisions that will be made by the different interested parties, the beginning of a new step, towards the effective implementation of a real operational system. If this next step is taken, at its completion, the beneficiaries will be the inhabitants of Grand Bassin, but also the Universities and the research centers, the Industry and the economic community, who will go that one more step into an integrated understanding of WPT and future SPS energy systems [15].



The Grand Bassin case study is an important step towards the understanding of future SPS systems for a sustainable energy supply to Planet Earth.

11 - acknowledgements

The completion of the Grand Bassin Case Study is a major step towards the practicality of WPT operation. It was made possible because the task team received all along strong encouragement from many supportive individuals : Peter Glaser, who challenged us first during SPS'91, Lucien Deschamps, of SEE, who brought together the initial teams, Patrick Hervé, now President of the University of La Réunion, who gave the regional impulse in La Réunion, Rémi Carle, Deputy General Director of Electricité de France, whose advice was instrumental in creating a center of expertise in La Réunion, Denis Clément, Regional Director for the Environment in La Réunion, who helped us select the Grand Bassin site, Professor Makoto Nagatomo, of ISAS, and his team, who helped us gather the basic technology, André Thien-Ah-Khoon, Representative to the French Parliament and Mayor of Le Tampon where Grand Bassin is located, who gave us operational support in many occasions. And also Georges Posé, of Sainte Rose, who provided the generator for the projection tests, and Bernard Charles, Secretary of the "Colonies de l'Espace", who made video tapes of the crucial experiments. We would like also to thank Jacques Breton, Chief of the Prospective and Evaluation Department of CNES, for his continuing support. We are also most grateful to many colleagues and friends from Japan, Russia, Ukraine, the United States, Germany, France and Italy, who gave us useful advice all along the years, and thus helped us make way into the future.

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LA RÉUNION - SPS-IdR'96

26 - 29 November 1996

INTERNATIONAL WORKSHOP

*** Final Presentations**
of Grand Bassin International Case Study
*** Field Visits to Grand Bassin**
and to other potential WPT sites
*** Discussion of Future Projects**
for International Cooperation

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