A SYSTEMS ENGINEERING APPROACH TO THE ANALYSES OF WIRELESS POWER TRANSMISSION SYSTEMS

A Thesis

by

ALAN MADDEN BROWN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 1993

Major Subject: Electrical Engineering

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Approved as to style and content by:

Kai Chang

Kai Chang
(Chair of Commitee)

Steven M. Wright

Steven M Wright
(Member)

Thomas R. Lalk

Thomas R Lalk
(Member)

A. D. Patton

A. D. Patton
(Member)

A. D. Patton

A D Patton
(Head of Department)

August 1993

ABSTRACT

A Systems Engineering Approach to the Analyses of Wireless Power
Transmission Systems (August 1993)
Alan Madden Brown, B S, Texas A&M University
Chair of Advisory Committee, Dr Kai Chang

The objective of this thesis is to develop and evaluate a systems engineering approach to the analyses of Wireless Power Transmission Systems Wireless Power Transmission (WPT) is a general term for a diverse set of technologies and applications, all which are centered upon the transmission of power from one point to another via electromagnetic waves Past studies of WPT systems and applications have generally assumed a technological solution prior the analyses, usually skewed by the preference of the analysts

This thesis presents the history and current status of WPT technology, summarizes the key systems issues and potential applications of WPT technology, and presents a general overview of systems engineering. A general analysis approach for WPT systems is developed and applied to a specific example. The results of this analysis indicate that the systems engineering approach is a valuable analytical tool to study and evaluate WPT systems

DEDICATION

I dedicate this thesis to my father, Dr Dennison R Brown, and to the memory of my mother, the late Janet Madden Brown

I believe that my Mother's greatest anguish was the threat of unfulfilled potential Her belief in my abilities and her conviction that I could always "fly higher" has served as a daily inspiration. Her untimely death has made me realize that our tomorrows are few, and we must all work hard today to make our dreams come true I strongly believe that my success as a father, as a husband, as a professional, are gratifying to her now, and I will continue to strive to fulfill her ambition for me

My father has always served as my complete role model. Growing up, the question of "Who's your hero?" was easily and quickly answered to those that asked His love, patience, understanding, guidance, and sense of humor have provided me with the foundations of which I base my life Until now, I have lived in his shadow, hoping to one day continue his legacy as a teacher It is with this culmination of graduate study that I have found that my professional calling is not as an academic However, I will always strive to "fill his shoes" as a father, so that my son and daughter might find such easy answers to the question of "Who's your hero?" To this day, and forever, my answer will remain the same "My Dad"

ACKNOWLEDGMENTS

I would like to acknowledge the Center for Space at Texas A&M for their support in this endeavor. Dr. A. D Patton, as Director, has provided great leadership with regard to WPT programs at the Center. Drs Little and Lalk have also been helpful with the overall philosophy behind thesis And to those in the Center who wish to remain nameless, they are recognized for their contributions to my evolution as an engineer Mrs. Perry and Mrs. Wilson are also appreciated for their encouragement Mr. Ken Krock's advice and help was invaluable during this entire process Mr. Bradford Schupp's support is acknoweldged as well

I would like to thank my professor, Dr Kai Chang, for his support throughout my undergraduate and graduate career His confidence in my abilities allowed me to return to school to obtain this degree. Jim McCleary was especially helpful with regard to the "magic of Goubau." A special thanks is due to James McSpadden for his unending contributions to the success of the METS program and all the other WPT Programs at the Center.

Lastly, I would like to offer my sincere thanks to my family for their love and patience during this process. Clarence and Marilyn Whitesell have "been there for us" above and beyond the call of duty. My two children, Ryan and Anna, have grown up without their father present on weekends and evenings, and much love is owed to them both. Above all, my wife, Karon, has bravely weathered all of my crazy schemes, including this one, and I hope to spend the rest of my life repaying her for love and support

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CHAPTER I

INTRODUCTION

Wireless Power Transmission (WPT) is a general term for a diverse set of technologies and applications, all which are centered upon the transmission of power from one point to another via electromagnetic waves. Although the transmission of electromagnetic energy over long distances has been utilized in communication systems, the transmission of usable power (i.e., the valuable commodity is the energy itself, not the information that is modulated onto it) This concept itself is not new, as both Heinrich Hertz and Nikola Tesla investigated it nearly 100 years ago [1] , [2]. However, technology was not sufficiently advanced until the 1960's, when William C. Brown, of Raytheon, demonstrated the feasibility of the concept [3] , [4]. Previously developed radar technology was married with the then-new technology of solid state electronics, and thus, a new paradigm was introduced.

Since that time, various applications of WPT technology have been proposed and studied, and limited technology development has occurred [5] - [11] The majority of this work was performed from the perspective of a particular application or technology, and limited work has been performed which utilizes the systems engineering approach for such analyses. Systems engineering, broadly defined, is "the effective application of scientific and engineering efforts to transform an operational need into a defined system configuration through the top-down iterative process of requirements definition, functional analysis, synthesis, optimization, design, test, and

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The journal model for this thesis is *IEEE Transactions on Microwave Theory and Techniques.*

evaluation" [12] Emphasis is placed on using a top-down approach, ensuring that the components of the system effectively work together to achieve the mission at hand. Generally speaking, a systems engineering approach will expend more effort during the initial identification of system requirements, so as to better evaluate the system's effectiveness

Essentially, WPT involves the conversion of available electrical energy (Solar, Nuclear, Hydro, etc.) into an electromagnetic wave (microwaves, millimeter waves, laser), transmitting the energy via an antenna or set of optics, and receiving this energy at a remote point, and converting it back into a usable format (DC, 60 Hz, etc.). The ability to accomplish this efficiently is dependent upon the device efficiency used in the transmitting and receiving equipment, and the ability to focus the electromagnetic beam onto the receiver Higher frequencies can be focused into a tighter beam, but generally suffer from lower device efficiencies The converse is true for the lower frequencies Thus, tradeoffs must be performed at the system level to find the technology best suited for the application

1.1 Objective

The objective of the research effort and the development of the thesis is as follows

To develop and evaluate a systems engineering approach for the analysis of WPT systems.

A set of requirements were identified whose fulfillment must precede the development of the above approach·

1) Summarize the history of WPT technology and the associated programs Determine the status of current programs.

2) Gain an understanding of the methodologies and processes used in a systems engineering approach to complex problems and systems.

3) Obtain a systems - level understanding of the key parameters of WPT systems, i e , the interrelationships between them and how they affect the system design, etc This shall include the non-technological considerations, such as health and safety, regulatory, and cost.

4) Comprehend the nature of the technologies to be used in such systems, their development status, and possible future trends for development

5) Develop a compendium of the various proposed applications of WPT technology

6) Develop the general approach for the systems engineering approach to the analysis of WPT systems Evaluate the approach through its applications to specific examples

1.2 Organization of Thesis

Consideration of the requirements resulted in the following organization. Following this introduction, the history / status of current programs will be presented. Next, a systems engineering overview will be discussed to provide the necessary context for the application of a systems engineering approach. A WPT Systems Primer will follow, which will explain the key parameters, and the interrelationships. A general block diagram of a WPT system will be presented to aid in this discussion. A summary of applicable WPT Technology will follow, which will present an overview of the technologies, subsystems, and devices that can be implemented in a WPT system A compendium of WPT applications will also be presented to provide a brief "snapshot" of the applications of interest at this time. The general approach for the analysis of WPT systems will then be presented, followed by an a specific example of its application. Finally, the findings and conclusions of this effort will be presented

CHAPTER II

HISTORY / STATUS OF CURRENT WPT PROGRAMS

2.1 History

The development of the technology for Wireless Power Transmission began in the early 1960 's. William C Brown, of the Raytheon Company, demonstrated a microwave (2 45 GHz) powered helicopter, developed under contract to the Air Force in 1964. The platform was powered aloft for a period of 10 hours, tethered to an altitude of 50 feet [3] Raytheon later demonstrated a flight control system for a similar helicopter This system allowed the helicopter to a automatically position itself over the center of the microwave (2 45 GHz) beam and control its roll, pitch, and yaw attitudes with sensors that derived phase, polarization, and amplitude information from the beam itself The publicity from the these two developments generated great interest in adapting these technologies to various other applications

With the introduction of the Solar Power Satellite (SPS) concept by Dr. Peter Glaser of the Arthur D little Company in 1968, WPT technology development was greatly accelerated [13] In this concept, the sun's energy is captured in geo-synchronous orbit, converted into microwave power, and then beamed to Earth where it is converted back into usable electrical power Dr Glaser's concept was extensively studied by NASA and the Department of Energy through the 1970's, ending in the 1980 The SPS program was not continued, largely due to the high cost and risk associated with building such a large structure in space

As part of these studies, two technology demonstrations were funded in 1974 and 1975 In 1974, Quality Assurance representatives from NASA 's Jet Propulsion Laboratory (JPL) certified a Raytheon-built microwave (2.45 GHz) WPT system to operate at a dc to dc efficiency of 54 ± 1 percent [3] The evaluation and subsequent qualification of these results by JPL's Quality Assurance Department was significant as it validated earlier efficiency analyses previously believed by the scientific community to be unachievable.

In 1975, Raytheon and JPL teamed together to further demonstrate the viability of this technology. At the Venus Site of JPL 's Goldstone Facility, 30 kW of DC power was obtained from a 288 square foot rectenna, with a 84% RF to DC conversion efficiency [3]. The transmitting antenna was remotely located from the rectenna by the distance of 1 mile (1.54 km) The NASA transmitter operated at a frequency of 2 38 GHz, and the rectenna was designed for optimum performance at this frequency. This experiment demonstrated the capability for scaling of these technologies to significant power levels and significant distances. In addition, the reliable operation of the rectenna in the harsh desert environment testified to the robustness of the system.

Following the demise of the SPS program, other applications of WPT technology were studied by various companies and government agencies Building on Brown's earlier concept of a microwave powered helicopter, others began to analyze a similar concept, known as a High Altitude Long Endurance (HALE) aircraft. Such an aircraft could be kept aloft for long periods of time, powered by a microwave beam. The Department of Energy funded the study of a such a platform, whose mission would be the monitoring of the levels of Carbon Dioxide in the upper atmosphere [14] Conventional propulsion systems for high altitude aircraft would affect the instrumentation for determining such levels Although the study determined that such a concept was viable, no follow-on studies were funded

The Canadian Government began to fund feasibility studies of using such a platform for a variety of applications , most notably for a communications relay platform Flying at 21,000 meters, this platform could provide coverage over a circle 500 km in diameter Such a service would be extremely valuable for the northern regions of Canada, which do not have access to the geo-synchronous communication satellites, due to line of sight restrictions

The Canadian Stationary High Altitude Relay Platform (SHARP) program was begun to address such a need A one-eighth scale prototype, solely powered by a microwave (2 45 GHz) beam, was flown in September 1987 for 20 minutes at altitudes up to 150 m [15] Further flights remained aloft for periods up to an hour. The airplane's wingspan was 4 5 meters, and power was transmitted to the aircraft using a 4 5 m parabolic antenna, transmitting 10 kW of energy A 12 meter wingspan version of the aircraft has been built and flight-tested using a gasoline powered engine, but funding restrictions have limited the development of a microwave WPT system needed to power such an aircraft

Recently, researchers in Japan have developed small, focused, "cheap" WPT demonstrations to develop technology and gain support from their funding agencies Central to these efforts was the development of a high efficiency, solid state transmitter, operating at 2 41 GHz Traditionally in the

United States, microwave tubes have been recommended as the building block for microwave and millimeter wave systems The two demonstration projects were developed to demonstrate and evaluate the performance of the Solid State Transmitter. The first was a small, microwave -powered aircraft, MIcrowave Lifted Aircraft eXperiment (MILAX) flown in August of 1992 [16] Although smaller in size and altitude than the Canadian SHARP program, this aircraft was powered while flying over a small car, with the transmitter mounted on the car's top This effort was supported by the Japanese Government's Ministry of International Trade and Industry, (MITI) and received monetary and in-kind support from several of the leading industries (Subaru, Nissan, Fujitsu, Toshiba)

Following MILAX, the Microwave Energy Transmission in Space (METS) experiment was flown on a small sounding rocket The purpose of this experiment was to examine the effects of a 2 41 GHz microwave beam's interaction with the ionosphere, but an end-to-end demonstration of wireless power transmission in the space environment was also included This experiment was essentially a follow-on to a 1983 sounding rocket experiment, Microwave Ionosphere Nonlinear Interaction eXperiment (MINIX), whereby the ionosphere's interaction to the microwave beam was first tested However, this was the first ever demonstration of WPT in space. The solid state transmitter was installed on the mother section of the rocket's payload, and two rectennas and instrumentation packages were mounted on the daughter section One rectenna was built by Japanese researchers, the other by a team of U S. engineers, including representatives from the International Space University, Raytheon, and Texas A&M University.

Other applications of WPT technology have been studied as well. The PowerSat concept has also been extensively studied, whereby an orbiting central power station could provide power to a constellation of users, via WPT technology. Such a system is not viable at microwave frequencies, due to the large aperture sizes needed for efficient power transfer, but laser systems have been advocated Such a laser-based system would take advantage of the ability of a laser to focus its beam to a very small spot over long distances. Coomes, et al have studied such a system for the Department of Defense's Space Defense Initiative Organization (SDIO) [5] However, no significant WPT technology demonstrations have occurred at the optical frequencies.

2.2 Status of Current Programs

The following presents a brief summary of current activities in WPT technology The majority of this information was presented at the *1st Annual Wireless Power Transmission Conference (WPT'93)*, held on February 23 - 25, 1993 *WPT'93* (entitled "Wireless Power Transmission: The Commercial Potential") was structured to provide a forum for participants to present and discuss applications and markets for wireless power technology, relevant societal and business considerations, and environmental issues, as well as the status of and future direction for technology development [7].

The Electricite De France (EDF), the nationally owned electric utility, has sponsored several studies concerning WPT technology and applications [7], [11], [18] A Terrestrial, point to point demonstration is being developed for deployment on the French-owned Reunion Island, off the coast of Madagascar

[17]. Furthermore, a proposed space demonstration of WPT is being studied by EUROSPACE [11]

Historically, the Soviet Union was given credit for funding a large development program, with a Solar Power Satellite (SPS) being the eventual goal A 1987 London Times Article presented evidence of such a program, with quotes from Soviet officials indicating that the massive Soviet rocket booster, Energia, was named for such an eventual program. However, the collapse of the Soviet Union has revealed a much smaller development program, with limited technology development [19]

Japan now has several programs with regard to the development of WPT technology, and the eventual deployment of a Solar Power Satellite System As mentioned earlier, researchers in Japan have been quite active in microwave technology development, and other government agencies have funded detailed feasibility studies of Solar Power Satellites and other applications of WPT technology [16].

The United States has several programs under consideration, although few are being funded at levels needed for technology development A terrestrial point to point demonstration has been advocated for placement in Alaska [17] A millimeter wave WPT-powered HALE is under development by a California based company, using ARCO Power Technologies Inc 's 35 GHz rectenna [20] A laser WPT system is being studied by NASA for providing supplemental power to aging Communications Satellites and to Orbital Transfer Vehicles [21] - [24] The Electromagnetic and Microwave Laboratory (EML) at Texas A&M University, in conjunction with the Center for Space Power, has been developing advanced rectenna designs at 2.45, 10, and 35 GHz, as well as computer-based systems analysis tools [25] ,[26] , [27]

CHAPTER III

SYSTEMS ENGINEERING OVERVIEW

3.1 Introduction

The purpose of this section is to define, in the context of this thesis, what is meant by systems engineering Since its development in the 1940's, the discipline of systems engineering has grown to represent a variety of approaches for system development, problem solving, program management, etc As such, it is necessary to understand its historical development , the various interpretations of what systems engineering is, and how it will be used in this thesis

3.2 History

Historically, through the industrial revolution, system performance (of any system) generally was the result of whatever could be achieved by the assembly of available components Additionally, the traditional fields of study in science and technology were becoming increasingly fragmented into areas of specialization By World War II, a new approach had evolved; system performance requirements were established in advance to satisfy a defined need, and new specialized advanced technology system elements were invented, designed, and integrated on schedule so that the system would attain the required performance on the promised delivery date [28]. The various phases of component design and system development were carried out so that the required system performance would be attained

This new interdisciplinary approach to technology, known as the systems approach, requires a holistic, as opposed to an atomistic view of problems. It delineates the problem or need first, and then brings the technological resources to bear to solve the problem. It is a way of applying technology to solve large problems and to accomplish major missions, rather than to generate technological answers looking for questions The systems approach is an interdisciplinary method by which the talents and skills of professionals from many different fields can be applied to solve problems well beyond the capabilities of any one of them [29].

The origin of the systems approach can be traced to the 1930's, as the Radio Corporation of American (RCA) recognized the need for a systems approach in the development of a television broadcasting service It was found that the Bell Telephone Laboratories Inc. was probably the first organization to use the term systems engineering, circa 1940 [30]. The development of a formal academic discipline, now known as cybernetics, that used the systems approach evolved from the work of Norbert Weinter [29] Early work during World War II on automatic anti-aircraft gun directors demonstrated the value of feedback in the design of complex systems Cybernetic theory is based on the premise that all goal seeking behavior is controlled by the feedback of corrective information regarding deviation from a desired state

An even broader unifying concept than cybernetics took shape during the 1940's It was the idea that basic principles common to all systems could be found which went beyond the concept of control and self regulation. A unifying principle for science and a common ground for interdisciplinary relationships needed for the study of complex system was being sought Ludwig von Bertalanffy used the phrase general system theory to describe this endeavor [12] General systems theory is concerned with developing a systems framework for describing general relationships in the natural and the man-made world The science of systems or their formation is called systemology

During the 1940's, many scientists and engineers were recruited in the efforts to understand a host of common processes in military operations The team effort was called operations research. Simply defined, operations research means the application of quantitative methods of engineering analysis for development of new methods to solve operational problems

After the war, this interdisciplinary field began to take on the attributes of a discipline and a profession The Department of Defense, in particular, formalized the approach in the development and acquisition large, complex, military systems. NASA successfully applied the approach in the development of the Apollo program. Today, a body of systematic knowledge exists for military and is now finding application in commercial operations

3.3 Definitions

As mentioned previously, there have been many system engineering references written in the last 50 years, each with a particular set of definitions with regard to terms such as systems, systems analysis, systems engineering The following presents a collection of these definitions

1. System [29].

"A system is a collection of functional units which may include both man and machines, which interact with each other and with the environment to perform purposeful behavior.

Collection.
The collective behavior of a number of units or components Characteristically these components will behave the same way in different systems. However, the interaction between units or components may significantly affect their behavior.

Functional
In systems engineering, the emphasis is on the functional behavior of the several components, and not on what may be inside the black box. The systems engineer is concerned with the inputs and outputs and the transfer characteristics between input and output In general, the emphasis is on the function or the end to be attained rather than the means by which they are attained.

Interact
In systems engineering, the emphasis is on the interface between functional units or components and the way such units or components interact with each other, with recognition given to the fact that in combination they may perform differently than they do separately Functional units interact with a) each other b) the environment and other units of the system

Environment
Environment is defined as everything which affects the system but is beyond the control, of the designer of the subsystem

Purposeful behavior.
To provide purposeful behavior is the reason for designing and building the system in the first place "

2 System Analysis [31].

"This term is most meaningfully employed to describe the class of studies which are concerned with determining where all facets of a complex system can or will contribute to the achievement of intended operational purpose with desired economy of design and support The purpose of system analysis is to ensure that the big picture is clearly understood, that a clear cut relationship is established between the need and the design and that achievement is related to purpose An essential feature of system analysis is the accomplishment of trade-off studies to establish competitiveness in selection of system elements for alternative system design approaches, and point up possible weaknesses in the design approaches under consideration Also, in the process,

> it is important to establish the sensitivity of each system parameter, both internally in terms of the interplay of system elements, and externally as they relate to the intended use environment"

3. **System Engineering** [12]·

> "Broadly defined, system engineering is the effective application of scientific and engineering efforts to transform an operational need into a defined system configuration through the top down iterative process of requirements definition, functional analysis, synthesis, optimization, design, test and evaluation The system engineering process, in its evolving of functional detail and design requirements, has as its goal the achievement of the proper balance between operational, economic, and logistics factors"

4 **Systems Engineering** [32]

> "The application of scientific and engineering efforts to 1) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation 2) integrate related technical parameters and ensure compatibility of all physical functional and program interfaces in a manner that optimizes the total system definition and design; and 3) integrate reliability, maintainability, safety, survivability, human and other such factors into the total engineering effort to meet cost, schedule and technical performance objectives"

The author of this thesis agrees with and accepts the following summary of the key aspects of the systems engineering approach as presented in [12]·

> "Basically, system engineering is good engineering with certain designated areas of emphasis
>
> 1 A top down approach is required, viewing the system as a whole Although engineering activities in the past have very adequately covered the design of various system components, the necessary purview and understanding of how these components effectively fit together has not always been present

> 2 A life cycle orientation is required, addressing all phases to include system design and development, production and or construction, distribution, operation, sustaining maintenance and support, and retirements and phase out Emphasis in the past has been placed primarily on system design activities with little if any consideration toward their impact on production operations and logistics support
>
> 3 A better and more complete effort is required relative to the initial identification of system requirements, relating these requirements to specified design goals, the development of appropriate design criteria, and the follow on analysis efforts to ensure the effectiveness of early decision making in the design process
>
> 4 An interdisciplinary effort or team approach is required through the system design and development process to ensure that all design objectives are met in an effective manner This necessitates a complete understanding of the many different design disciplines and interrelationships, particularly for large projects "

3 4 Overview

The definitions from previous section provide insight into the purposes and processes of systems engineering However, these definitions still represent a vast array of approaches and applications, from problem solving to program management This section will present systems engineering in the context of a problem-solving approach and as chronological sequence

3.4 1 Problem-Solving Approach

In the broadest sense, systems engineering is a problem solving approach The philosopher John Dewey (1938) published a description of a problem-solving process, which was further refined by physical scientists into the more specific form, known as the scientific method Hall [30] further

1) Problem Definition is the identification and understanding of that set of factors which will define the system and its environment Since a problem is an expression of an unsatisfied need, the job is to find what the need really is

2) Seeking objectives is the logical end of problem definition. The objectives will guide the search for alternatives, simplify the types of analyses required of the alternatives, and provide the criteria for selection of the optimum system.

3) Systems synthesis entails compiling or inventing alternative systems which can satisfy the objectives. Each alternative must be worked out in enough detail to permit its subsequent evaluation with respect to the objectives, and to permit a decision as to its relative merits for possible development

4) Systems analysis means deducing the key aspects of the entire list of hypothetical systems. The deductions relate to system performance, cost, time, reliability, flexibility, market, etc

5) Selecting the best system involves evaluating the analyses and comparing these evaluations with the objectives, criteria, and constraints to select the smallest possible subset of alternative systems which merit further study

6) Communicating results is the final step It will draw one of three conclusions

1. That specific development will solve the problem
2. That exploratory development in the laboratory is needed on particular alternative before a sound conclusion can be reached
3. That no further work is justified at this time

These steps represent a generic approach for problem solving The adaptation of this technique with regard to the development of large, complex systems represents what most consider the systems engineering process to be· the chronological chain of events by which such systems come into being Thus, the systems engineering approach is essentially the iterative application of the above steps in a larger context that is also based in this problem solving approach

3.4 2 Chronological View of Systems Engineering

The development of large complex systems requires a systematic approach through each phase of design This approach will help to ensure that the fielded system will have been optimally designed for the given criteria and constraints Figure 1 presents a detailed look at the major steps of system design and development This process has been formalized by the Department of Defense into a series of Program Phases [33]. Each phase contains engineering and management tasks, requires various design reviews, and documentation to allow continuous insight into the development process

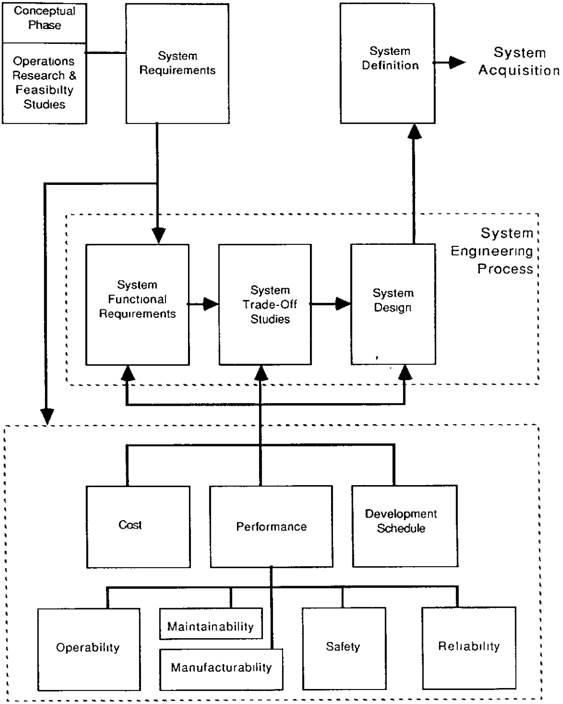

Figure 1 System Design and Development Process

3 5 Thesis Approach

Having defined the systems engineering process in its various contexts, it remains to be defined with regard to this thesis This thesis will assume that, through operations research and technical feasibility studies, the essential need for a Wireless Power Transmission system will have been established In other words, this thesis will not compare WPT with other competitive technological solutions for a specific need. Other published references have performed these analyses, usually to validate the assumptions made with regard to the technology that the author was looking to market A general system design methodology is shown in Figure 2 This figure presents the essential steps of Hall's methodology presented earlier and defines, in greater detail than Figure 1, the system engineering process for system analysis The application of this methodology to the specific application of Wireless Power Transmission will be presented in Chapter VIII An example of this methodology will be performed to demonstrate its use Another example of a systems engineering approach to WPT will be presented in Chapter IX

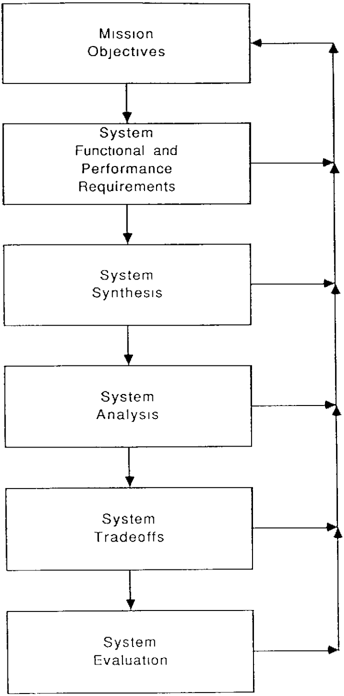

Figure 2 Systems Analyses Process Used in This Thesis

CHAPTER IV

WIRELESS POWER TRANSMISSION SYSTEMS PRIMER

4.1 Introduction

To properly analyze Wireless Power Transmission Systems, an understanding of the key parameters of WPT systems should be developed For a systems analysis, the emphasis is placed on the interrelationships between the key parameters and how they affect the system design, etc The generic mission of any WPT system is to deliver utility power to a remote user via electromagnetic beams Parameters that are subject to optimization are generally the system efficiency and the size/mass of the transmitting and receiving systems, and evaluated against applicable criteria. The relationships between these parameters has been studied in great detail, [27] , [34] , [35], and a systems-level description of these relationships can be developed Additionally, the design of a WPT system is subject to constraints, such as cost, schedule, technology availability, environmental constraints, etc The nature of these constraints will be explored to understand how they affect the design of the WPT system

4.2 System Block Diagram

A simplified block diagram of a generic WPT system is shown in Figure 3

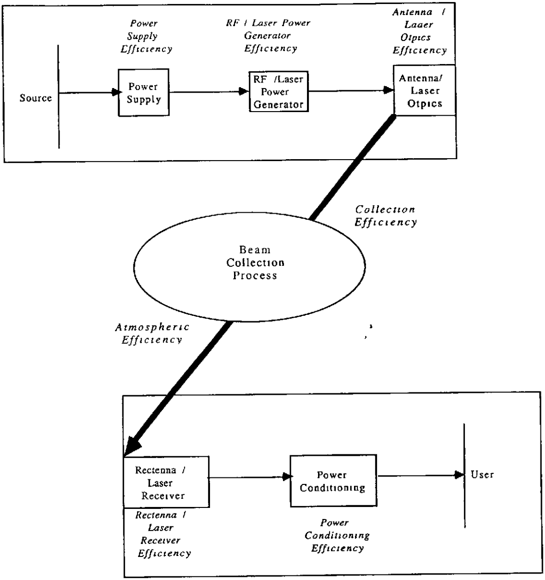

Figure 3 WPT System Block Diagram

Each block in the diagram represents a process which will have a given transfer function, for a specified set of inputs and outputs. Those entities symbolized by a square represent processes that are implemented via a particular technology. The transfer characteristics of these squares are determined by the technology chosen, and will impact the delivery of power to the end user by the inherent inefficiency of the technology The process symbolized by an oval is a function of the physical relationship of the preceding and proceeding subsystems

It can be seen from the block diagram that there are three primary processes to consider. The function of the transmitter subsystem is to transform the provided energy input into an electromagnetic beam whose characteristics will allow for the efficient transmission of power to the receiver The function of the receiver subsystem is to transform the impinging electromagnetic beam into the specified energy format needed at the output The beam collection process determines the amount of the transmitted beam that is collected by the receiving subsystem, and is determined by the relative sizes of the transmitting and receiving apertures, the wavelength of operation, and the distance separating the transmitter and receiver subsystems Additionally, any atmospheric attenuation of the propagating beam, which is a function of the wavelength of operation and power density, will be considered as part of this process Thus, the designs of the subsystems are strongly coupled through the collection process

4.3 Transmitter Subsystem

As noted previously, the function of the transmitter subsystem is to efficiently transform available electrical energy from an external source into an electromagnetic "beam" which has the proper characteristics needed for efficient transmission through the atmosphere. This conversion process can be implemented in many different ways, and will be highly dependent upon the desired frequency of operation. The first step in this conversion is to take the available energy, which may exist in various formats such as 60 Hz "wall plug power" and transform it into energy of the operational frequency. This can be accomplished using devices such as magnetrons, klystrons, traveling wave tube devices, free electron lasers; all which take advantage of an electron beam's ability to be modulated to a higher frequency. The efficiency of this process depends on the devices used. Additionally, solid state devices can be used to generate higher frequencies, but at much lower power levels, and generally with less efficiency. Small solid state sources can be combined to produce higher powers at microwave, millimeter wave, and laser frequencies, but this combination process will increase the system complexity

Once the energy has been converted to the proper frequency, then it can be transformed into a "beam" for transmission. For microwave and millimeter wave systems, this is accomplished via an antenna This antenna can take many forms, one of which is the familiar parabolic dish The parabolic dish takes advantage of its geometry to focus the energy into a well collimated beam which is needed for efficient power transmission Other systems can be employed to collimate this beam, and the decision on which system to use will be driven by the relationship of the microwave power converter with the antenna For example, if a single, high-power microwave source is used, then traditionally it will be married with a large, dish antenna, and beam steering will be accomplished by physically rotating the antenna Similarly, a large beam director can be used for the high power laser systems Due to the optical frequencies vulnerability to atmospheric effects, some type of adaptive optics must be employed to mitigate these effects These systems can range from large deformable mirrors to small segmented mirrors which are independently condoled

Advances made in military radar systems may be implemented to achieve a more robust transmitter system A phased array antenna is comprised of a large number of smaller radiators, which are controlled in such a way that each element's beam will constructively combine to produce a beam with the same characteristics as that of a large single dish antenna. This beam can then be steered electronically, by controlling the phase of each element's output. A phased array system can be used with a single, high power tube, by dividing the power output of the source into the different radiating elements, and then recombining the power via the control of the individual radiators However, of great interest may be the use of many, smaller power tubes which will feed the radiating elements directly, known as an active phased array. Control must be exercised over the power sources as well as the radiating elements to ensure that the transmitted beam will behave as expected With this configuration, the reliability of the transmitter site will be quite high as there will not be a single point of failure as there are in the single, high-power devices The configuration of the active phased array design will feature graceful degradation ability, as large number of subelements could fail before the performance of the overall system would not meet the specified performance

Thus, each subarray will contain a power generator, the phase control circuitry and the radiating element This concept can be extended from very small, very low power laser diodes to higher power solid state microwave sources to microwave tubes such as a 1 kW magnetron.

4.4 Receiver Subsystem

The role of the receiver subsystem is to efficiently transform the incoming electromagnetic energy into a format suitable for the application As such, the first step is the reception of the electromagnetic energy As with the microwave and millimeter wave transmitters, this is accomplished via an antenna system. The received electromagnetic energy is then converted to a DC power, via a rectification process. To make the rectenna as efficient as possible, the reception and rectification functions are combined into a single device, known as a rectenna (from rectifying antenna)

A rectenna traditionally uses a dipole - type antenna for the reception of the microwave beam The dipole-type antenna is used for its omni-directional features, i e the efficiency of its reception is not strongly dependent upon the angle of incidence of the incoming microwave beam. The rectification function is accomplished via a solid state diode Certain parameters of the diode's design can be optimized for efficiency, and both Silicon and Gallium Arsenide diodes could be used, subject to tradeoffs concerning cost, power handling, and efficiency Other functions are designed into the rectenna, such as DC filtering to purify the output voltage, and RF filtering to limit the amount of re-radiation from the diodes out through the dipoles

The receiver subsystem then is comprised of many such rectennas The spacing of each rectenna element is generally optimized for the minimum number of diodes needed to save costs The DC output of each rectenna element is then combined with the others to produce a high power output from the rectenna system This high power is then conditioned and properly formatted for its intended use via standard power conditioning equipment

For the optical frequencies, the receiving function is generally accomplished with a tuned photo voltaic cell The efficiency of a solar cell for monochromatic (laser) illumination is much higher than that for solar illumination This is primarily due to two factors: 1) the sun produces a wide-band spectrum, thus all of the solar photons cannot be used efficiently in a solar cell with a single bandgap Photons with energy less than the bandgap will not be absorbed, and for photons with energy greater than the bandgap, all of the excess (i.e. greater than the bandgap) energy will be lost. The fraction of the solar energy absorbed in the form of electron- hole pairs in single bandgap solar cell is at most 50% [36] For a monochromatic wavelength, however, all of the photon energy can be usefully absorbed 2) In general, a solar cell will only have high quantum efficiency over a limited range A laser can be tuned to a wavelength where the quantum efficiency is close to unity As a result, the efficiency of a solar cell under monochromatic illumination at a wavelength near the spectral response peak can be more than twice the solar efficiency.

4.5 Beam Collection Process

4.5.1 Beam Collection as a Function of System Configuration

The transfer function of the beam collection process is essentially the ratio of the RF or laser power at the receiver to the transmitted power Generally referred to as collection efficiency, many references present analytical approaches to the optimization of this parameter

The transmitting antenna will give rise to a diffraction pattern which is characterized by a main beam and associated sidelobes Such a diffraction pattern only occurs in the antennas "far field", which is determined by the antennas' size, and the characteristic wavelength for the operational frequency, as shown in Equation (4-1).

$$R = \frac{2D_t^2}{\cancel{2}\lambda} \tag{4-1}$$

where

R = minimum distance from an antenna to be considered as the far field

D_t = diameter of the transmitting antenna

λ = free space wavelength of operation

At distances less than R, known as the near field, the radiation pattern of the transmitting antenna become less defined, and changes greatly with distance. However, the phase distribution across the transmitting antenna can be adjusted to "focus" the transmitting antennas beam at a point within the near field, which will result in a diffraction pattern equivalent to the far field [27] This thesis will assume that any application that operates in the near field of its transmitting antenna will take advantage of a focusing phase distribution.

For WPT applications, the challenge to the system designer is to generally minimize the radiation pattern's sidelobes, which represent lost energy, and to define the size of the receiving aperture so that it optimally matches the main beam of the transmitting antenna. The characteristics of the diffraction pattern of the transmitting antenna are largely determined by its size, and the illumination function of the electromagnetic energy across the face of transmitting aperture

A uniform illumination of the transmitting antenna will result in a narrow main beam, but will suffer from high sidelobes The sidelobes can be effectively reduced by tapering the illumination function accordingly. The lower sidelobes come at the cost of the "spreading" the main beam, thus a larger receiving area will be required The trade-off , then, is between the lower sidelobes and the wider beamwidth, which is determined by the power density distribution (i e. the illumination function) across the transmitting antenna

Most often referred to in WPT-related publications is the work of Goubau [34] Goubau originally showed that collection efficiencies approaching 100% were theoretically possible, and this has subsequently been verified experimentally [35] In order to achieve such high collection efficiencies, one of a family of power density distributions for the transmitting antenna must be chosen This distribution will depend upon the desired collection efficiency and the system configuration, as shown graphically in Figures 4 and 5. Figure 4 presents a curve that shows the relationship of the collection efficiency as a function of the variable ,τ, which is defined as follows:

$$\tau = \frac{\sqrt{A_t A_r}}{\lambda R} = \frac{\pi}{4}\frac{D_t D_r}{\lambda R} \qquad (4\text{-}2)$$

where A_t = Area of the transmitting antenna
A_r = Area of the receiving antenna
D_t = Diameter of the transmitting antenna
D_r = Diameter of the receiving antenna
λ = Wavelength
R = Distance separating the two antennas

As can be seen from Figure 4, a direct correspondence exists between the parameter τ and collection efficiency. This curve may be modeled by the exponential relationship,

$$\eta_{\substack{collection\\ efficiency}} = 1 - e^{-\tau^2} \qquad (4\text{-}3)$$

Thus, if high collection efficiency is a system design driver, then the corresponding value of τ will determine the system configuration. The system designer, then, is left with the option of varying the diameters of the transmitting and receiving antennas, the wavelength of operation, or the distance between the antennas to achieve the specified value of τ. This value of τ will also determine the power density distribution function

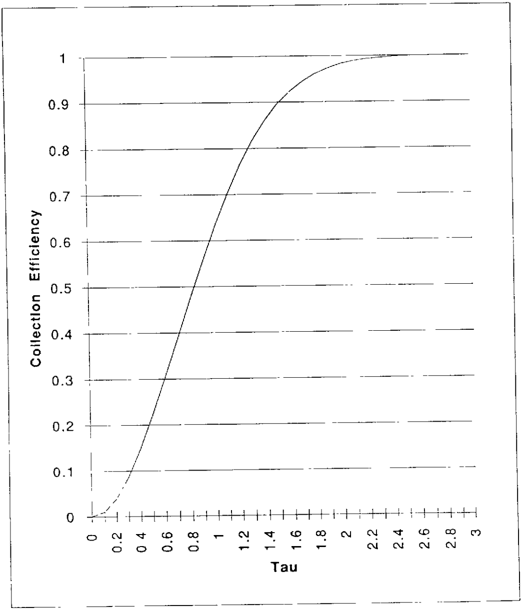

Figure 4 Collection Efficiency vs τ

Figure 5 depicts the transmitter power density distribution required to achieve the collection efficiency for the configuration of interest For efficiencies approaching 100%, these tapers approach a Gaussian distribution For such a Gaussian distribution, the taper across the transmitting aperture will manifest itself at the receiver aperture This distribution will essentially remain intact throughout the beam's pathway. In Figure 5, the x-axis is normalized to the radius of either the transmitting or receiving transmitter, and the y-axis represents the normalized power density. Thus, for a given collection efficiency, the corresponding value of τ will requires a specific power density distribution across the face of the transmitting antenna.

Recent works by McCleary [27] present analyses showing that other tapers may be chose by the system designer. The choice of taper will depend on the system requirements and constraints, such as sidelobe level, peak power density, power density distribution, etc. A set of computer programs have been developed by McCleary to facilitate the analyses of WPT systems with regard to the collection efficiency These programs provide the systems engineer with greatly increased flexibility with regard to the analysis of WPT systems

An examination of equation (4-2) and Figures 4 and 5 indicate that high aperture to aperture efficiencies can be obtained for relatively high values of τ Thus, for a given distance of transmission, the size of the transmitting and receiving antennas and the wavelength of operation can be optimized

As τ increases linearly with a decrease in the wavelength, there exists a strong motivation to move to higher frequencies (shorter wavelengths)

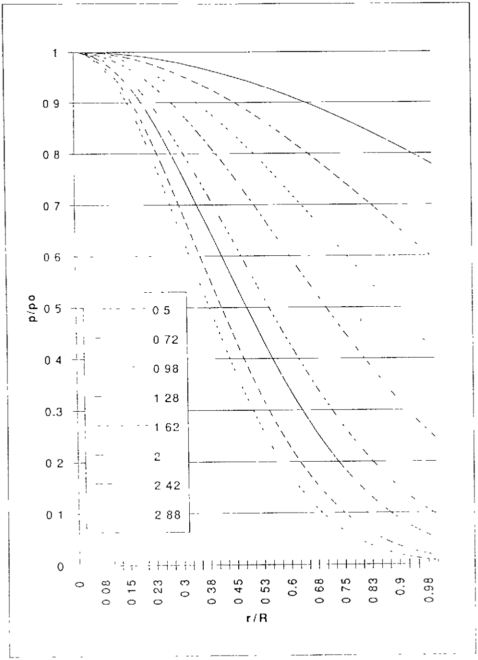

Figure 5 Power Density Distribution over Transmitting/Receiving Antennas for Various Values of τ

However, other constraints on system design are also a function of operational frequency, including availability and efficiency of the technology, and atmospheric degradation

It may also be observed that the sum of the antenna areas (for the transmitting and receiving antennas) for a given collection efficiency is a minimum if the transmitter and receiver apertures are of equal size However, it may be desirable to make one smaller than the other, dependent upon the constraints imposed by the application The larger the transmitting aperture is, the higher the directivity will be, and the resulting larger incident power density Obviously, the two apertures can be made large enough to approach the 100% collection efficiency, but the design then suffers the limitations imposed by such large apertures (i e cost, complexity, etc.). However, 95% efficiency requires a τ of 1.89, which increases each antenna diameter by 34% over that for 60% efficiency (τ=1), and increases their areas by 80% Therefore, size versus efficiency is clearly an important tradeoff.

4.5.2 Beam Collection Process as a Function of Power Density

Sizing of WPT systems based only on the collection-efficiency / aperture taper is only appropriate for first order analyses. A key parameter that is interrelated with the aperture taper is the power density of the electromagnetic beam at various positions within the systems boundary

The ability of an antenna to direct its radiated power in a particular direction is known its directivity The optimal directivity, D_o of an uniformly illuminated antenna of area A is given by·

$$D_o = \frac{4\pi A_t}{\lambda^2} \qquad (4\text{-}4)$$

where A_t = Area of the transmitting antenna

λ = Wavelength of operation

Thus, the power transmitted through the antenna's aperture will be directed in the direction of the main beam, and will be "magnified" in a particular direction by the amount of the directivity. Counteracting this effect is the exponential decay of the field strength with distance, i e the $\frac{1}{4\pi R^2}$ relationship that characterizes all far field electromagnetic radiation The resulting peak power density, then, will be given by the following relation

$$P_{\substack{density,\\ peak}} = \frac{P_t A_t}{\lambda^2 R^2} \qquad (4\text{-}5)$$

where P_t = Total transmitted power

A_t = Area of the transmitting antenna

λ = Wavelength of operation

R = Distance between transmitting and receiving antennas

Across the face of the receiver, the power density will follow the Goubau curve (or other taper used), and thus decay from its peak in the center of the receiver towards the edge Essentially, as the power density available for a rectenna element decreases (radially away from the center of the receiving antenna), the resulting power output will scale as well The average power density can be determined by integrating the power density distribution function over the area of the rectenna, giving the total power over the area, and dividing by the area of the receiver, as detailed in Equation (4-6)

$$P_{\substack{density,\\ average}} = \frac{\int P_{density}(\rho)\, dA_r}{A_r} \tag{4-6}$$

where $P_{density}(\rho)$ = Power density distribution across the rectenna area as a function of the radius, ρ

A_r = Area of the Rectenna

The transfer function of the receiver subsystem is directly influenced by the amount and distribution of the impinging power density Rectenna elements are generally designed for an optimal power density, and the conversion efficiency will decrease as the power density either increases or decreases away from the optimum Thus, if each rectenna element is identical, the conversion efficiency will vary with the power density distribution The system designer must examine the trade-off between designing rectenna elements for a optimal power density, dependent upon its position within the rectenna face, or make all of the elements the same Cost savings are generally available for standardizing as many components as possible.

4.5.3 Beam Collection Process as a Function of Atmospheric Attenuation

Atmospheric effects will affect the system design As seen in Figure 6, [37] higher frequencies suffer from higher atmospheric absorption rates, particularly during times of heavy rainfall A statistical approach can be taken to determine the amount of additional power that should be budgeted in order to provide service during these times

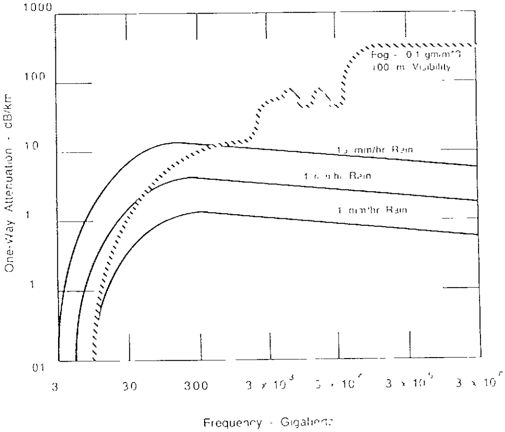

Figure 6 Atmospheric Attenuation vs Frequency of Operation

4 6 System Constraints

The following will discuss the nature of the constraints of the design and/or criteria in which the system will be evaluated.

4.6.1 Costs

As discussed above, the system design is greatly dependent upon the choice of operational frequency The technology to be used in the implementation, the size of the transmitting and receiving apertures, the atmospheric attenuation, etc., are all dependent upon the frequency selection Historically, many system designs have been based on technology already developed at a particular frequency Generally, the lower frequency systems enjoy higher device efficiencies, little atmospheric effects, and a more mature state of development, yet suffer from the necessity of building large apertures for acceptable collection efficiency Conversely, higher frequency system can achieve higher collection efficiency for a given aperture size, but suffer with regard to device efficiency, atmospheric effects, and technology maturity. These efficiencies will directly affect system cost as a function of prime power costs, and in the capital costs of large complex systems.

As systems engineering assumes a life-cycle cost approach in the economic analysis of systems, the general trade-off with regard to frequency selection will be between higher up-front capital investment with lower operational costs versus the opposite As mentioned above, the lower frequency systems generally require larger apertures, and thus a larger capital investment prior to initial operation capability. However, the higher system efficiency should result in lower operational costs than the higher frequency systems Thus, an intersection of these costs should occur, and the system design will depend on the expected operational lifetime The amount of return on investment and risk must also be taken into account

Note however that in some cases, the mass of the subsystems may be the determining factor for particular applications Higher frequency systems may be able to employ small apertures, vis the Goubau relation, but may be forced to be more massive to provide means for heat rejection, due to device inefficiency A lower frequency system will have a lower directivity, and thus, a lower peak power density. This may negatively effect the design of the rectenna system, yet may be beneficial with respect to safety limits.

Another trade-off to be considered is the mechanical tolerances for the surface of the transmitting antenna The higher frequency systems must maintain a stricter tolerance over a smaller area, as opposed to the lower frequency requiring less tolerance over a large area. If the tolerances are not met, then the main beam will be wider than predicted in analyses, and the rectenna will not be able to collect the energy originally predicted Tighter tolerances will require more exotic processing techniques and longer development times, resulting in larger costs

4.6.2 Environmental Constraints

Measures to ensure safe human exposure to microwaves associated with power transmission systems are similar to those employed with high power radar systems. Generally speaking, the interaction of microwaves and millimeter waves with biota are limited to thermal effects, and is considered a non-ionizing radiation. By non-ionizing radiation, no permanent change in the atomic structure of the material has been effected, which is the case for radiation effects associated with nuclear power systems With respect to thermal effects, the generally accepted exposure standards, ANSI C95 were revised in 1982 to ANSI C95 1 These allow an exposure of 5 mW/cm^2 averaged over 6 minutes. Thus a one second exposure would permit 1.8 W/cm^2 or 1800 W/m^2. However, the system designer should maximize efforts to reduce power density where biota may interact with the beam For the higher frequency systems, whereby the increased directivity will cause the power density to exceed these specifications, other precautions must be taken with regard to keep-out zones, etc Such additional provisions will add cost and complexity to the system

4.6.3 Regulatory Constraints

The frequency allocation issue could be one of the strongest system design drivers, as the frequency of operation selected for optimum performance may not be available. Historically, the majority of technology developed for power beaming systems has been at frequencies within the Industrial-Scientific-Medicine Bands, (2 45 GHz and 5 8 GHz) where specific allocation for WPT systems is not required, as long as interference with other systems outside the band is avoided However, the sanctity of these bands is being continually threatened as wireless communication systems continue to grow in popularity. The world's governing body for frequency allocation is the World Advisory Radio Council (WARC), which meets every 4 years to discuss which systems will be granted licenses The WPT community has failed to successfully lobby the WARC for spectrum allocation, and available spectrum space is becoming scarce Although system designs at 35 GHz have been proposed, it should be noted that no allocation has been given. The ability to gain permission will largely be a matter of investment, as the WARC and FCC are considering the auction of spectrum allocation to the highest bidder, providing the bidder follows up with actual hardware operating at that frequency.

CHAPTER V

WIRELESS POWER TRANSMISSION TECHNOLOGY SUMMARY

The systems engineering approach to the design and analysis of large complex systems requires a fundamental understanding of the technologies involved. Systems analysts/designers should obtain a comprehensive understanding of the nature of the technologies to be used in such systems, their development status, and possible future trends for development Although functionality is stressed in systems level analyses, failure to understand the key design and operational characteristics of these components can lead to improper system configurations.

The purpose of this chapter is to present information concerning the applicable technologies, delineated by the portion of the electromagnetic spectrum in which they operate, i.e microwave, millimeter wave, and optical (laser) regimes Within each regime, the technologies have been separated by the end of the system in which they will implemented· the transmitter subsystem or the receiver subsystem. An overview of the nature of operation, development status, and key characteristics are discussed for each component

As discussed in the WPT Systems chapter, the function of the transmitter subsystem is to transform the provided energy input into an electromagnetic beam whose characteristics will allow for the efficient transmission of power to the receiver The components that will be discussed will include the power source and the antenna (beam forming devices in the optical (laser) regime.)

The potential application of active phased array transmitters blurs the distinction between the power source and antenna functions, thus this technology will be discussed separately Power sources may be generally discussed as one of two types Electron beam devices (tubes) and solid-state devices Information concerning ancillary equipment, such as power conditioning and cooling components, are not discussed, but will be factored into the systems analyses

The function of the receiver subsystem is to transform the impinging electromagnetic beam into the specified energy format needed at the output As above, ancillary equipment is not discussed but will be factored into the system analysis

5.1 Microwave / Millimeter Wave Systems

Microwaves Systems operate at wavelengths less than 30 cm (corresponding to frequencies in excess of 10^9 Hz) but greater than 0 03 mm (10^{13} Hz) Millimeter waves are a subset of microwaves in the 10 - 0 03 mm range Microwaves are bounded on the long wavelength side by radio waves and on the short wavelength side by infrared waves Historically, the majority of technology developed for WPT systems has been at microwave frequencies, more specifically at 2 45 GHz This frequency is located at the middle of an Industrial-Scientific-Medicine Band, and is thus allocated to developmental programs such as WPT Spectrum allocation is a significant issue when discussing WPT systems, and could ultimately weigh very heavy in system-level tradeoffs when deciding what the frequency operation will be

Additionally, 2.45 GHz was chosen as the operational frequency for earlier systems as atmospheric attenuation is minimized at frequencies up to 3 GHz. At frequencies higher than this, significant power reserves must be included in the power budget to allow for periods of high attenuation, such as rain storms, snow etc. The early systems, such as the microwave powered helicopter and the Solar Power Satellite chose 2.45 GHz for these reasons. The technology available at 2.45 GHz has been extensively studied, and is quite mature. Much of the development costs have been spent, and this will be factored into the systems analyses.

5.1.1 Transmitter Subsystems

The following will discuss the various options available to the WPT system designer for implementation with regard to power sources and antennas.

5.1.1.1 Power Sources

Figure 7 shows the power output vs. frequency for both solid state and tube devices in the microwave and millimeter wave regimes [38]. Microwave tubes will be discussed first.

5.1.1.1.1 Tubes

All microwave tubes depend on the interaction between an electron stream and an electric field supported by a microwave circuit that results in a basic amplifying mechanism. Microwave tubes can be divided into two classes

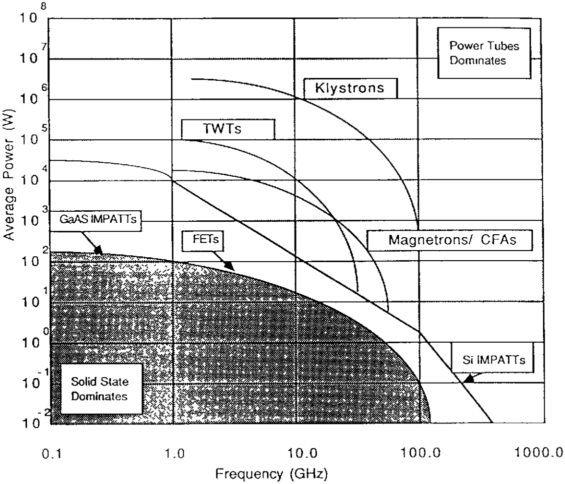

Figure 7 Microwave Tubes and Solid State Devices Power Output

crossed field and linear beam devices In a crossed field tube, electron flow occurs in a space with perpendicular magnetic and electric fields. In the linear beam tubes, the two fields are parallel and the electron flow forms a beam traversing the length of the tube

5.1.1 1.1.1 Magnetrons and Cross - Field Tubes

Microwave devices were preceded, in the early decades of this century, by gridded, or triode, tubes that operated by modulating the density of an electron beam But, as the frequency increased, distances between the cathode grid and anode shrank, because it was necessary to keep electron transit time well below that of one RF cycle of the signal Those tubes failed in the microwave range because they became so small it was impossible to build them and they could no longer handle any appreciable power. Magnetrons, the first true microwave devices, are high-power, self excited oscillators for converting pulsed DC input power to pulsed RF power output.

A magnetron consists of a cylindrical central electrode (cathode) ringed by a second cylindrical electrode (anode), with a gap (interaction space) in between. Evenly distributed around the inter circumference of the anode are resonant cavities opening into the interaction space. As the cathode emits electrons, an externally mounted permanent magnetic produces a strong magnetic field normal to the axis of the electrode. A strong dc voltage is applied between the cathode and the anode The electrons accelerate toward the anode, but the strong magnetic field produces a strong force, causing them to follow a curved path past the openings of the cavities The frequency of the subsequent electric field is determined by the size of these cavities A probe inserted into one or more of the activities transfers the microwave energy into an output channel for transmission [39]

The crossed field amplifier (CFA) is a logical extension of the magnetron, which generally acts as an oscillator In a CFA, the circuit on the anode has an input and an output, and the internal structure is modified to minimize feedback [40]

Often studied as the building block for wireless power transmitters is a modified microwave oven magnetron These magnetrons have been mass produced, and thus are available for less than $20 per unit The design has been optimized for long life, and a minor modification can configure the magnetron into a high gain reflection amplifier(as opposed to a CFA) At output powers up to 1 kW, these devices can be phased together as part of a phased array system to provide the needed high power at the receiver. Conversion efficiencies can be up to 60% to 70%, thus a passive waste heat removal system can be employed, further simplifying the system design The magnetron can also be operated in a low noise configuration by turning off the filament heater current [41]. The microwave oven magnetron has also been the subject of a development effort of a space-based , radiation cooled microwave source [42] Higher power magnetrons used in industrial heating applications are also available, and deliver up to 5 kW of power.

5 1.1.1.1.2 Linear Beam Devices

The klystron and the Traveling Wave Tube (TWT) are both linear beam power amplifiers Both use a slow wave structure to achieve microwave power amplification Essentially, an electron beam is passed through a structure that alternatively accelerates and decelerates the electrons so that they form "bunches". The periodicity of these bunches is determined by the physical structure of the devices, which in turn, determine the output frequency of the resulting amplified signal. The multicavity klystron, invented at Stanford University by R. H Varian, modulates the velocity of an electron beam via a set of cavities [38]. The TWT generally uses a helix structure where the interaction with the electron beam is continuous over the path of the beam There are klystrons that are commercially available that can deliver power levels up to 30 kW. Varian also makes CW Superpower Linear Beam Amplifiers that can deliver 450 kW of RF power at 50% efficiency [43]. At such high power levels, active cooling systems must be employed. TWT oscillators and amplifiers have been extensively developed and utilized in defense and space programs, and are quite mature

5.1.1.1.1.3 Gyrotrons

The recent development of cyclotron resonant masers, known as gyrotrons, has allowed millimeter wave power systems to become viable for WPT systems. Gyrotrons operate on the basis of the interaction between an electron beam and microwave fields where coupling is achieved by the cyclotron resonance condition Unlike the linear beam tubes, only electron energy transverse to the magnetic field axis can be used in a gyro device. Thus, the electron beam has both a radial and axial component, and the applied dc magnetic field will bunch the radial portion of the electron beam as it travels the length of the tube This type of coupling allows the beam and microwave circuit dimensions to be large compared to a wavelength Hence, the gyrotron avoids the power density problems encountered in conventional klystron and traveling wave tubes at millimeter wavelengths [43]

The Varian company has been developing these devices since 1975, primarily for the Department of Energy's programs in controlled thermonuclear fusion. The gyrotron is used for electron cyclotron resonant heating(ECRH) of plasmas for controlling the fusion reactions Varian indicates that the data taken from the operational environments indicate the tube-life and reliability should be as long as any microwave power tube Further development work is under way to increase efficiencies and power output at many different frequencies, including the two windows of interest 35 and 94 GHz Existing Gyrotron oscillators can produce RF power levels above 100 kW CW at 100 GHz. The efficiency of the devices operating in the fundamental cyclotron mode are inherently in the range of 30%, but with efficiency enhancements, it may extend above 50% [44]. The Varian Company produces a 200 kW CW Gyrotron at 35 GHz, operating at 35 % efficiency (Model # VGA-8003) [43]

5.1.1.1.1.4 Magnicon

A new microwave source which could have the potential for operation at high frequency, high average power and high efficiency is the magnicon. This source has been developed in the Soviet Union as a source to power accelerators The interaction of the beam with the electric field is similar to the gyrotron, but uses a low power RF signal to deflect the beam so that it enters an output cavity properly phased so that all electrons have the same interaction with the wave at that point Design parameters are a power of about 200 kW with an efficiency of about 80 to 90% However, these parameters represent theoretical values, and much further research is needed before this device can be considered for implementation [45]

5.1.1.1.2 Solid State Sources

For WPT systems, solid state sources are only viable when coherently combined to produce the output power required The technology required could constructively combine these small sources into a single, well behaved beam is well understood and has been developed for radar and communication systems. These systems, known as phased array antennas, use special techniques to control the phase of the individual devices to combine their outputs. Such techniques introduce cost and complexity into the system, and thus must be carefully considered. It is also possible to use these techniques on higher power modules, such as the microwave oven magnetron, with much fewer active sources to control.

Solid-state microwave systems are continually increasing output power levels, while decreasing costs Silicon BJTs (Bipolar Junction Transistors) are capable of handling the highest power below 5 GHz Gallium Arsenide Metal-Semiconductor field effect transistors (GaAs MESFETs) are traditionally chosen for applications using frequencies in the 5 - 30 GHz spectrum As GaAs FET devices reach maturity, attention has turned to the development of GaAs monolithic microwave integrated circuits (MMICs). There are several advantages in using monolithic technology for power amplifiers. MMIC amplifiers have size and weight advantages over hybrid amplifiers with comparable performance. When utilized in high volume lots, MMICs can deliver significant advantages in cost and reliability. Monolithic amplifiers are well suited for operation at millimeter wave frequencies, where on-chip impedance matching is desirable.

At frequencies above 30 GHz, IMPATT (IMPact Avalanche and Transit Time) and Gunn devices dominate most of the applications, but the development of higher power density devices, such as the Heterojunction bipolar transistors (HBTs) and High Electron mobility transistors (HEMTs) will allow them to compete in future system designs. The advantages of HEMTs over GaAs MESFETs for power applications are high power gain and high efficiency Those advantages are due to a high current cut off frequency resulting from the HEMT's higher sheet carrier density and higher electron velocity, which can also lead to greater output power The output power of IMPATT devices is limited by the maximum current density and device area. Current density is limited by thermal and the peak breakdown field in the drift region Device area is increased to increase output power; however, device impedance falls linearly and the circuit loss increases [46]

5.1.1.2 Microwave/ Millimeter-wave Antennas

The choice of antenna, or beam launching device, is dependent on the type of RF source that is chosen As discussed in Chapter IV, for efficient transmission of electromagnetic energy over large distances, the size of the antenna's aperture will be dependent on frequency, but in general, will have to be quite large. Large antenna structures have been built for applications such as radio astronomy, primarily as spherical or parabolic reflector- type antennas. Such reflector-antennas are generally considered for transmitting antennas in conjunction with a single, high power tube, in which the contiguous area of the reflector will be illuminated by a feed horn. In considering such a reflector type antenna, considerations must be given to the surface tolerance of the reflecting surface, so that the resulting beam is well behaved. Additionally, the feed structure will impose a blockage which will constitute a loss factor in the efficiency of the antenna. These reflector type systems have the advantages of being quite mature However, due to the large area required, single reflector systems are mainly considered for millimeter wave systems

For those applications that would utilize microwave sources, phased arrays of many parabolic dishes or flat, slotted waveguide array panels, have been proposed due to the large transmitting antenna area needed to maximize the system efficiency. Phased array systems utilize an arrangement of smaller radiators which are controlled in such a way to produce a coherent, well behaved beam. The individual sources can be varied and include microwave tubes married with smaller parabolic dishes, as the Canadian SHARP Program has proposed [15]. Additionally, Dickinson and Brown have proposed a sub-array consisting of an aluminum slotted waveguide antenna combined with a microwave oven magnetrons as a low-cost radiator [47] The components that build up these arrays are technically mature and have been well characterized Furthermore, the control techniques needed to properly phase the outputs of each subarray have been developed for other programs and are quite mature as well.

Phased array systems with distributed sources are inherently more complex, due to the need for distributed phase control systems, but benefit from the characteristic graceful degradation due to the large number of sources. Thus, the reliability of a phased array system could be significantly greater than a single "spigot" design However, at large scan angles away from broadside, the array's projected aperture becomes foreshortened, and effectively, an additional loss must be considered Thus, the operational requirements of the application will have to be carefully considered when selecting a solution A phased array concept can be implemented at millimeter wave frequencies by using Traveling Wave Tube Amplifiers (TWTAs) or solid state sources However, proper phasing of these sources is highly complex

5.1.2 Microwave / Millimeter-wave Receivers

Receivers for WPT systems operating in the Microwave and Millimeter-wave regions have been termed "rectennas", coined from the two terms "rectifying" and "antenna". A rectenna is essentially composed of an antenna, a filter, and a diode rectifier to convert the incident field into the desired DC component Several variations have been designed for different applications, and the design chosen for each will be determined by the various functional requirements imposed on the design.

An important design characteristic of rectenna systems is the level of incident power density which the rectenna can efficiently convert to DC The higher the power density at the rectenna, the smaller the receiver can be to achieve the needed power output However, the size of the transmitting antenna is directly influenced by the required power density at the receiver In addition, to ensure long life, the amount of power and resulting waste heat that each diode is to handle should be constrained Additionally, the choice of the rectifying elements will dictate the efficiency of the device, but also the cost Radiation from harmonics developed in the rectification process must also be considered when determining the type of rectenna to be used

5.1.2.1 S-Band (2.45 GHz) Rectennas

As with the sources, the majority of the development work has been done at 2.45 GHz , including the Goldstone experiment, the efficiency demonstration, and the SHARP-5 flight Peak conversion efficiencies of 85% have been achieved, with the incident power density varying, depending on the application The original rectenna was a close-spaced thermionic rectifier which Brown used to first demonstrate the feasibility of microwave power transmission However it proved to be an unreliable and short-lived device Semiconductor power rectifiers were soon introduced, and used in the first microwave powered helicopter, in 1964 [3] Improvements in the device and circuitry designs have occurred since then, resulting in three essential configurations· three plane bar type, two plane bar type, and 2 plane printed circuit [35]

The three plane bar type rectenna configuration was used in the successful demonstration at the Goldstone facility of the Jet Propulsion Laboratory An 82% RF to DC conversion efficiency was achieved at this demonstration [3] The 2 plane bar type rectenna construction uses the foreplane to carry out nearly all the functions The ratio of power output to area of the rectenna is 800 W/m^2 . The latest form of the traditional rectenna design is based on a thin and flexible substrate where the circuit is photo etched on both sides of the substrate. Such a light substrate results in a favorable power to weight ratio of 2.5 kW/kg, and it can operate at power densities up to $600 W/m^2$.

5.1.2.2 C-Band (5.8 GHz) Rectennas

For the development of the SHARP prototype, a 2 45 GHz rectenna system was used However, it differed from early devices, which generally consisted of arrays of linear dipoles, and each dipole had its own rectifying circuit (diode and filters) For the SHARP concept, relative motion of the rectenna with respect to the transmitted beam was a given, thus some means of negating the polarization mismatch was required. Alden, et al. developed a two foreplane, dual polarization rectenna, which eliminated the need for polarization tracking [48] It consists of two orthogonal linearly polarized rectenna arrays (foreplanes), each collecting power of its corresponding polarization. This rectenna has proven to be highly efficient, however, it has certain drawbacks in its power handling capability, manufacturability, and accessibility for testing and repair. The power handling capability of the two-plane system is limited by the requirement of antenna spacing of at least half a wavelength in the x and y direction

To reduce transmitter aperture size, the next phase of the SHARP development program has increased its operating frequency to 5.8 GHz. While re-designing the rectenna for the higher frequency, a single foreplane rectenna was developed to overcome the drawbacks indicated above. The two foreplanes have been integrated into a single planar array of linearly polarized dipoles It is noted that in the array, collinear dipoles are contiguous with no gap between adjacent dipole elements. This construction allows the reduction of the antenna dimension to values small compared to a wavelength without the large increase in antenna reactance normally found with separately spaced dipoles with small dimension

Contiguous dipoles and the removal of the quarter wavelength transmission line between the output filter and the next antenna allows the dimension of each rectenna unit to be reduced to a small fraction of a wavelength This high packing density allows for an increase in power handling. Conversely, similar power handling capabilities to previous systems may be achieved with the use of lower power, lower cost diodes.

Rectennas using the separate dipole single plane design have been built at 5.8 GHz using multiple, low cost, low power HP2835 diodes. Output DC power densities up to 800 W/m^2 have been achieved, a factor of 8 over traditional designs [48]

5.1.2.3 Ka-Band (35 GHz)

In 1987, ARCO Power Technologies Incorporated (APTI) undertook an effort to develop a working rectenna and to design a power beaming system in the Ka band The first 35 GHz rectenna was working at 50% efficiency level in June of 1988 An updated design has been published, with claims of 70% to 80% conversion efficiencies at power densities of up to 8 kW/m^2 [49] The most salient feature of this rectenna is the increased power reception due to an enhanced resonant structure without any significant increase in total weight

This design also incorporates a solution to the problem of thermal management The network was realized in such a way that the placement of the diode allows the use of the outer layer as an effective radiator This would permit operation at high power densities (approaching 1 W/cm^2) This configuration represents an order of magnitude increase in system power densities at the lower frequencies

The losses in the rectenna are the power re-radiated due to the mismatch with the antenna, the loss in the network and transmission lines, and the loss in the diode For a 70% efficient microstip rectenna, the largest loss will probably be the re-radiated power due to mismatch which may be as much as 20% Diode loss will comprise from 5% to 10% [37]

A patent was issued to APTI for the design of power beaming systems, although the patent does not discuss the resonant structure that nearly doubled the RF - DC efficiency APTI has indicated that they are pursuing an additional patent on that improvement Further research efforts at 94 GHz and 300 GHz are ongoing, but early test results indicate very low efficiencies

5.2 Laser Devices

Beamed power systems utilizing the very short wavelength associated with laser devices maintain the advantage of being able to transmit power over very long distances Beam diffraction is very small over large distances, thus transmitting and receiving aperture may be made very small However, atmospheric effects are significant at these smaller wavelengths and must be factored into the design tradeoffs.

Technology advancements over the past several years, mainly sponsored by the Strategic Defense Initiative, have produced a state of the art that is near capability for directing high laser power from the surface of the Earth to lunar distance and beyond If the source of power is on the Earth, high efficiency in conversion from electric power to laser power is not economically important and laser efficiencies currently achievable are adequate to realize advantageous systems Key elements of this emerging laser technology include

1. Continuous operation with infrared or visible light generated by a free-electron laser, at hundreds of kW up to a few megawatts Lasers to be considered must operate in the wavelength range centered around the visible spectrum in which the atmosphere is nearly transparent. The minimum wavelength is about 350 nm, limited by atmospheric absorption by ozone The maximum wavelength to be considered is 1000 nm , unless new photo voltaic receivers responsive to long wavelength light are to be developed [23].

2 Adaptive optics capable of forming a highly collimated beam and responding rapidly enough to compensate for atmospheric turbulence, making it possible to direct a near-diffraction-limited beam through the atmosphere into space with acceptable beam degradation Flight experiments have demonstrated this capability at modest apertures of roughly one meter. Laboratory tests and analyses now in progress are developing technical alternatives suitable for apertures up to ten meters, with many thousands of adjustable elements, as needed for turbulence compensation in apertures of this size

3 Photo voltaic arrays capable of converting laser light to electricity at greater than 50% efficiency. This has been demonstrated on a laboratory scale at low power with continuous laser light Planned experiments will develop means of matching photo voltaic response to laser pulse formats so that high-power systems can be operated at high efficiency

5.2.1 Laser Sources

The following describes the laser power sources available to the system designer.

5.2.1.1 Free Electron Lasers

Free Electron Laser (FEL) technology has rapidly matured in the last 10 years The FEL is conceptually quite simple, consisting only of an electron beam, a periodic pump field, and the radiation field. The electron beam passes through the pump field (usually a wiggler field, caused by a series configuration of opposite pole magnets) and begins to oscillate. The electrons are bunched together as they pass through the magnet array, and the electrons emit synchrotron radiation at the same wavelength. FELs feature high-power capabilities and high efficiency. As there is no physical lasing medium that must support the radiation field, problems of heating or breakdown which plague conventional solid or gaseous lasers are absent. In theory, 20% to 50% of the electron beam energy could be convertible into light, but current laboratory system efficiencies are much lower

There are three critical components in any free-electron laser the source of the magnetic field, the electron accelerator and the optical cavity Different types of accelerators can be used. Radio frequency linear accelerators, best suited to the Compton regimes, use a traveling wave from a pulsed RF source to accelerate electrons to high energies, but with limited currents. Both Rocketdyne and Boeing have developed RF FELs in support of SDIO's directed energy programs [50]

Higher beam currents are possible with an induction accelerator, but the beam is less concentrated, and produces longer wavelengths. Science Research Laboratory is developing an induction free electron laser The highest peak power achieved with an induction linac driven free electron laser reportedly exceeded 10 GW at a wavelength of 1 cm, and the highest average power possible is anticipated to be greater than 10 MW at the wavelength design value of 1 micrometer. Efficiency is expected to be less than or equal to 50% SRL has built a number of .5 meter accelerator modules for the FEL [21].

5.2.1.2 Chemical Lasers

Chemical lasers, which only operate for a few minutes before using up large quantities of the necessary reactants are the state of the art in high power lasers These lasers can be very efficient in terms of power produced per pound of laser for short times in which the weight of the reactants is less than or equal to the dry weight of the device However, when total efficiency including the cost of producing the reactants is taken into account, the cost of long term operation becomes prohibitive compared to the cost of megawatts of electrical power to run an FEL

The highest power lasers currently available use carbon dioxide as the lasing medium However, the characteristic wavelength, 10600 nm, is too long for a photo voltaic receiver The best high power CW lasers are Neodymium doped Yttrium - Aluminum Garnet (Nd:YAG) lasers. Its wavelength of 1064 nm is theoretically near the optimum energy for conversion by a silicon solar cell [51]

5.2.1.3 Nuclear Pumped Lasers

Sandia National Laboratories in Albuquerque, NM has been researching a Fission Activated Laser CONcepts (FALCON) laser that uses the abundant energy of fission fragments to pump the laser [52] A general design for a reactor laser system includes a nuclear gain generator, a lasant flow system, an optical extraction system, a heat exchange and a system for controlling both the laser beam and the overall device. The gain generator consists of an array of laser channels containing fissile material. Neutrons impinging on this region cause fission and subsequent excitation of the laser medium Coupling many of these channels forms a module that can have a substantial laser output.

With a NPL, the direct neutron coupling of the reactor with the laser eliminates the need for a thermal electrical conversion cycle, significantly increasing the overall system efficiency. For land based units where weight is not a factor, a thermal conversion system can be retained to produce commercial electrical power simultaneously with the NPL power beaming operation. Thus, the overall plant efficiency is increased significantly by using what would otherwise be waste heat as the input to the electrical generation portion of the unit. Second, the income from electricity sales would significantly improve the economics of the facility [53]

5.2.1.4 Laser Diode Arrays

A 1988 NASA study investigated four electrically pumped, space- based laser systems, all scaled to 1 MW laser output, that could provide power to a spacecraft [54] . The four laser systems studied were krypton fluoride, copper vapor, laser diode array (LDA), and a carbon dioxide laser Although the LDA appeared to be the most efficient electrically pumped candidate, there are major technical uncertainties with regard to phase matching, cooling, and making electrical connections to the approximately one million laser diodes required to produce a 1 MW laser beam The high power GaAs diode laser operate at about 795 - 820 nm, which is nearly optimal for existing silicon solar cells. Shorter wavelength GaAlAs lasers can be manufactured which would be preferred for GaAs solar cells [51].

An array consisting of a very large number of individual lasers could yield the required power. Monolithic arrays of diode lasers have recently demonstrated power densities as high as 80 W/cm^2 and CW power level of 1 kW. The problem of beam collimation from a large number of individual diode beams has yet to be solved Available high power diode lasers have total energy efficiencies of 40%; a 70% efficiency has been obtained in the laboratory Efficiencies as high as 84% are theoretically possible [5].

5.2.2 Photo voltaic Receivers

Although other methods of converting impinging laser illumination into electricity have been studied, solar cells are generally considered to be the standard for use in wireless power transmission applications Issues involved with the use of these in WPT systems:

1. Operating wavelength The choice of semiconductor material will depend on the wavelength of operation chosen

2 Effects of laser pulsing Free electron lasers operate in a pulsed mode with high peak powers. The high peak current output can decrease the solar cell output due to series resistance and inductance; the high frequency components in the pulse results in LC interactions with the cell and the circuit

3. Effects of high intensity and high temperature operation For some applications, it is useful to operate the photo voltaic receiver at high laser intensities [48].

Existing solar cells have peak response to monochromatic illumination at about 850 nm (for GaAs cells) and about 950 nm (for Si cells) For wavelengths shorter than the peak, the efficiency will decrease roughly linearly with wavelength For longer wavelengths, the efficiency will drop rapidly to zero Thus, it is important to select a wavelength near the optimum value. Near the optimum wavelength, the response of a solar cell to monochromatic illumination is much higher than the efficiency produced by the broad solar spectrum. As discussed below, high efficiency GaAs cells can produce over 50% efficiency under laser illumination, and conventional Si cells over 40% [48].

There are three basic approaches to making photo voltaic arrays for use in space. The conventional approach is to use a flat plate array, consisting of individual cells electrically interconnected. An alternative is to use thin-film cells manufactured directly on a thin flexible substrate and monolithically interconnected in place This has the potential for lower costs and lighter weight, but has not yet been demonstrated in space A third approach is to concentrate the incident light onto a small area cell. This approach allows the individual solar cells to be more expensive, and allows the cells to be well protected from radiation. However, thermal management of concentrator systems can be a major issue, especially for high incident power levels

The effect of pulsed illumination is a significant issue for system designers, as Free Electron Lasers (FELs) seem to be the most prominent candidate for near and mid-term applications. If the laser transmitter uses a pulsed format instead of CW, the efficiency drops drastically due to the extremely high peak current (1000 to 3000 peak to average ratio) and the concomitant response capability of PV cells Modifying the circuitry in an effort to smooth out pulsed effects, via a capacitor, can raise the efficiency of a GaAs to 44%, but only for the closely spaced pulses typical of a RF FEL Negligible effects of this circuitry modification are seen for induction FEL simulation, which characteristically have pulses widely spread. These lower efficiencies for FEL laser illuminations can be overcome by proper PV cell design. As high as 60% to 70% conversion efficiencies may be achievable [55]

5.2.3 Adaptive Optics Systems

Adaptive optics systems have been developed that may be able to compensate for atmospheric turbulence effects Essentially, a beacon signal is transmitted though the atmosphere, and the perturbed wavefront is sensed by the adaptive optics The optics then align themselves to produce the phase conjugate of the beacon signal so that the phase front of the high power wave is reconstructed by the turbulence, and thus propagates with minimal loss. The Phased Array Mirror Extendable Large Aperture (PAMELA) concept, a proprietary design by Kaman Corporation, is the conceptualized approach for the optical telescope used to project and correct the beam [20]

For the PAMELA application, each hexagonal segment would have three actuators for piston, tip, and tilt control plus edge sensors coupled to an on-board microchip that senses segment position relative to adjacent segments Each segment senses the edge mismatch and corrections are made with pistons Algorithm convergence performance to find the optimal tilt of the mirror segments with the smallest number of iterations is critical to development

Three atmospheric phenomena significant to laser propagation and adaptive optics are extinction, atmospheric turbulence and thermal blooming Turbulence is caused by random heating variations in the atmosphere. Thermal blooming results from the interaction between the beam and the medium, and extinction refers to the losses associated with propagating the beam through the atmosphere

The provision of a known source to characterize the atmospheric effects is critical to the success of systems such as PAMELA Friedman at Lawrence Livermore Laboratory has constructed a facility to demonstrate the feasibility of an adaptive optics, atmospheric compensation system using a sodium-layer laser guide star as a reference beacon. They have propagated over 1 kW of laser light at 589 nm to produce a fifth magnitude visible star in the sodium mesospheric layer at 100 km and have measured photon returns and distorted wave fronts [56]

5.3 WPT System Family Tree

Figure 8 presents a WPT "Family Tree" This family tree identifies the various subsystems and components that are available to the systems designer for use in WPT systems This figure will especially valuable to the systems designer during the systems synthesis stage when different system configurations must be developed for analysis and subsequent trade-offs and evaluation

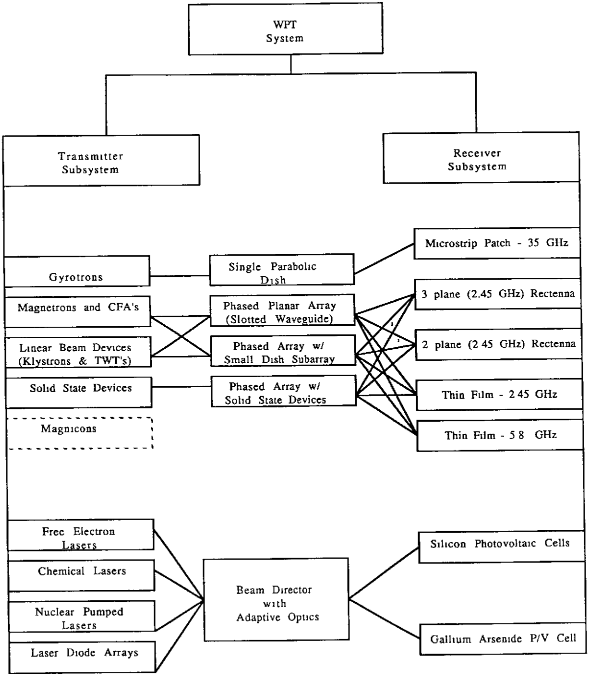

Figure 8 WPT System Family Tree

CHAPTER VI

WIRELESS POWER TRANSMISSION APPLICATION COMPENDIUM

In Chapter III, it was noted that systems engineering puts a great deal of emphasis on the analysis of the mission requirements The rationale for this emphasis is that a viable system design can be defined only when a firm understanding of the requirements that the system must fulfill is obtained Usually, these analyses will require a significant amount of up-front effort in a system design process, but the return on that investment will be provided by less, if any, re-design and/or re-work The following attempts to provide a brief overview of the proposed applications. A much more detailed analysis will be required before the various WPT candidate systems can be evaluated for a particular application.

6.1 Terrestrial Point to Point WPT Systems

The notion of being able to convey large blocks of usable power without the restriction of transmission lines is certainly attractive; unfortunately, WPT technology will not compete well with conventional technology System efficiencies and line of sight requirements essentially eliminate WPT systems, unless there is no other way of providing power to a user along a line of sight, who must also be willing to pay the additional costs incurred by the inherent inefficiencies However, a terrestrial WPT point to point pilot project is feasible in supplying the much needed data prior to the implementation of other programs such as the Power Relay Satellite and / or the Solar Power Satellite Such a pilot project could supply quantitative and qualitative data concerning the construction and operation of a WPT system used in the delivery of baseload energy. As the Goubau relationships have long been verified as true, smaller apertures can be built for lower cost. Projects have been proposed and studied extensively for operation in Alaska, Hawaii, Japan, and Reunion Island (France)

Trade studies were conducted by Raytheon concerning the best technology to be used for a 50 kW, 5 mile pilot project The resulting system design used a phased array concept, built of slotted waveguide panels with microwave oven magnetrons as the subarrays Antenna sizes were nominally 100 feet tall, and power densities were limited to the 23 mW/cm^2 limit System cost was approximated to be $20 to $25 million, including 3 years of operation [17].

6.2 Beam Powered HALE Aircraft

A variety of missions, including commercial and government-sponsored missions, can be envisioned for a platform that can stay aloft for long periods of time. In order for such a platform to stay aloft for long periods, the aerodynamic characteristics must be optimized for minimum fuel consumption, which requires operation at minimal airspeeds This can be accomplished by flying at very high lift coefficients and at altitudes where wind speed is as low as possible. Traditional power systems for high altitude aircraft are limited by on-board fuel storage capacities, and can only stay aloft for a relatively short duration In-flight refueling on a continuous basis would be cost prohibitive Thus, unique and novel solutions are required

Although aircraft powered solely by the photo voltaic conversion of solar energy have been demonstrated, the diurnal limitation would require massive amounts of on-board energy storage for continuous operation Nuclear powered aircraft are technically feasible, but safety and societal concerns eliminate their inclusion as a viable option at this time.

A platform that receives it propulsive and payload power from a remote source would be able to stay aloft for the long periods required. Time aloft would only be limited by the Mean Time Between Failures (MTBF) of the on-board components A WPT powered HALE aircraft could fulfill such requirements. Note that a more detailed analysis of this application is presented in Chapter VII.

6.3 Satellite Power Augmentation from Terrestrial Sources

Terrestrial-based WPT systems has been investigated in the past as a means of providing power to orbiting assets. However, WPT systems have generally not competed well with on-board power systems, due to the small number of users combined with the low power levels required. Studies conducted by the Strategic Defense Initiative Organization (SDIO) for orbital-based interceptor platforms concluded that earth based microwave and millimeter-wave systems were not viable solutions [5]. However, recent investigations may have found an application whereby laser transmitter could illuminate the existing photo voltaic arrays of geo-synchronous Communication Satellites [57] -[59].

The COMSAT corporation has expressed an interest in providing augmentation power to those COMSAT satellites that have outlived the original planned life span Such older assets are generally removed from the original GEO slot, through an orbital maneuver known as the COMSAT maneuver, to make way for newer systems with upgraded capabilities Such satellites may still produce revenue for the company, through the sale of transponder capacity to non-traditional customers, such as third world nations. However, existing battery systems used to supply power to the communications equipment may be weakened due to the large number of charge-discharge cycles experienced

Laser transmitters could illuminate the existing photo voltaic receiver while the satellite is in the shadow, thus overcoming the limitation of battery systems. If this application could be extended to the large number of existing GEO-synchronous satellites, then it is envisioned that this could become a commercial enterprise. Once in place, these systems could allow satellite bus designers new options concerning power systems, which may result in added capacity/unit and resulting lower cost / higher profits

Although the large laser systems needed to provide power to a constellation of GEO-synchronous satellites do not exist now, the technology does exist for demonstration of laser power beaming to a LEO asset. In fact, several laser sources may be made available, and it is unclear as to which source is correct for a demonstration project. A low-cost demonstration could be deployed within a 2 to 3 year time frame, with follow-on development of higher power laser systems, and optimized laser receivers.

6.4 Power Relay Satellite (PRS)

First proposed by Kraft Ehricke [60], the Power Relay Satellite could allow the development of renewable energy resources in remote locations by the transmission of the energy to a region with high energy demands Essentially, the PRS systems involves a terrestrial based transmitter subsystem and receiver subsystem and a space-based reflector to redirect the energy beam from the transmitter to the receiver Recent studies funded by the Electric Power Research Institute (EPRI) found the PRS application was competitive with systems such as HVDC Transmission Lines, Submarine Cables, Superconducting Transmission lines, and the long distance transportation of Hydrogen [61]. System operation could occur at 2 45 or 5.8 GHz. However, the amount of power to be transmitted must be quite large for the economics to prove favorable, thus large transmitting and receiving structures are required, as well a large space-based structure Projects such as the Point to Point Pilot Project or the Beamed Powered Aircraft will leave significant technological and societal legacies for the development of the transmitter and receiver subsystems. The construction of large space structures, such as Space Station Freedom, will provide much needed information about the design of the reflector. For efficient transfer of the power, the reflector will need to be over two kilometers in diameter, and further development work on such a system is warranted.

6 5 Orbital Transfer Vehicles

Transportation costs continue to be a significant obstacle to the commercial development of space Clearly, a more cost-effective means of delivering payloads from Low Earth Orbit (LEO) to higher orbits, such as Geo-Synchronous Orbits (GEO) is needed WPT technology may provide a means to power an Orbital Transfer Vehicle (OTV), which would derive its propulsive power from electric ion thrusters. This particular application has been analyzed for both microwave and laser systems [6], [23], [24] The microwave system suffers from large aperture sizes, but is not limited by atmospheric conditions Again, near term projects such as the Point to Point Pilot Project or the Beamed Power Aircraft will provide the needed legacies for the microwave OTV. The Satellite Power Augmentation from Terrestrial Sources Project will provide similar legacies for the Laser Powered OTV. Unfortunately, this does not appear as a near term market, as NASA, ESA, and commercial launch vehicle manufacturers continue to focus on conventional chemical propulsion technologies However, if the recommended pilot projects succeed, then a new paradigm may be introduced for interorbital transportation

6.6 PowerSats

As with the OTV application, the current paradigm for powering satellites is for each to have a self-contained, stand alone power system, i e. photo voltaic arrays, batteries, fuel cells, etc However, economies of scale could provide significant cost and weight savings if the power generation function were off-loaded to a single co-orbiting asset (coined as PowerSat). This application has been extensively studied by Coomes of Pacific Northwest Laboratories for SDIO and Hannigan of EUROSPACE for ESA, as well as earlier NASA studies. Traditional microwave frequencies will require apertures that are much too large for realistic operation Millimeter wave and laser systems are characterized by acceptable aperture sizes, but system inefficiencies require large sources and complex heat rejection schemes Additionally, pointing accuracy must be quite exact, and although this may be achievable with current technology, it is not inexpensive Thus, significant numbers of users requiring large amounts of power must be committed for the economies of scale to make the system's operation cost effective. Unfortunately, most satellite systems planned for the near term do not have such large power requirements

One might argue that if such a system were available, then the market might expand and new space systems may be designed to take advantage of the benefits. Such is the argument of WPT as an enabling technology, or for space development by technology push However, technology is not yet available for a viable PowerSat system WPT system will benefit from technological advancements of millimeter wave and laser components, as supported by other communities (communications, observation platforms, weapon systems. etc.)

Technology is available for a space demonstration, and Japan's recent flight of the Microwave Energy Transmission in Space (METS) in February, 1993 reveals the value of small focused demonstrations. Although microwave frequencies are not viable for space to space WPT systems, the technology is cost effective for demonstration purposes Additionally, needed data was taken on the interaction of the microwave beam with the ionosphere, understanding of which is required for the PRS, OTV, and SPS applications Follow-on demonstration projects could increase power levels and frequency, eventually moving towards those of an implemented system.

6.7 Solar Power Satellites / Lunar Power System (SPS/ LPS)

The SPS / LPS Systems could offer the ultimate return on investment for the world's space program. The worlds' energy requirement are ever increasing, and conversely, the world's available resources for producing such energy are finite, and thus are decreasing. Environmentally sound solutions are required to meet the future energy needs The essence of the SPS and the LPS applications are essentially the same, whereby the sun's energy is captured by an orbiting satellite (the moon in the case of the LPS), converted to microwave energy, and beamed to a collection site on the Earth [13], [62] The trade-off issues between these two applications are the costs and complexities involved with the construction of large apertures on Earth, and transporting them to a slot in geo-synchronous orbit, versus building the larger apertures on the moon's surface, using the lunar,regolith as the material for the construction

As concluded in the 1980 NASA / DoE studies, there are no known technological show-stoppers to the implementation of such systems. However, economic and societal issues could result in the failure of its implementation

CHAPTER VII

WIRELESS POWER TRANSMISSION SYSTEMS ANALYSES APPROACH

7.1 Approach Definition

The preceding chapters have presented the information needed to develop a WPT systems analyses approach Essentially, the systems issues discussed in Chapter IV will be integrated into the system analysis approach discussed in Chapter III and depicted in Figure 2 The diversity in the applications and the technologies require that the approach be kept general in nature The nature of the specifics that may come into play for a systems analysis will be exemplified in Chapter VIII, where this approach will be applied to the specific example of a HALE Aircraft

7.2 Mission Objectives

As was stated earlier, this thesis is assuming that previous trade studies may have been conducted to determine if WPT technology can compete with other systems for the same mission objectives. Thus, the set of mission objectives from the earlier analyses will be a legacy to this phase of the systems engineering process Refinement of the mission objectives should occur to factor in the influences that a WPT system may affect into the mission objectives A clear, concise communication of these objectives is paramount if a team of systems engineers and analysts will be used to perform the analyses

Everyone should perceive and understand the essence of the need, otherwise the system analyses will be skewed. Generally, for a WPT system, some portion of the system configuration will be determined directly from the mission objectives, i.e the separation distance, the available area for transmitting or receiving antennas

7.3 System Functional and Performance Requirements

From the mission objectives, the applicable functional and performance requirements should be specified This effort will require a significant amount of investment of time and resources, as these will define the criteria in which the system designs will be evaluated against This will require patience on behalf of the system designer/analysts, as the natural desire will be to "get on with it" However, a clear understanding of these requirements, however costly, will generally deliver return through the elimination of re-work caused by a lack of understanding of the requirements. Additionally, the constraints under which the system must be developed and operated will be defined in this session

For a WPT system, generally the power required from the receiver is specified, based on an accurate understanding of the needs of the particular application. Additionally, the environmental aspects of system operation will be determined, i e , temperature, humidity, etc. Programmatic requirements such as cost, development time will be specified as well.

7.4 System Synthesis

Systems synthesis entails compiling or inventing alternative systems which can satisfy the objectives Each alternative must be worked out in enough detail to permit its subsequent evaluation with respect to the objectives, and to permit a decision as to its relative merits for possible development For a WPT system, once the functional and performance requirements have been developed and documented, a set of candidate systems should be synthesized These candidates will generally be differentiated along the lines of operational frequency, and within the same frequency bands, along lines of a particular technology. Given the wide range of technology options discussed in Chapter V, the system designer must cull the possibilities into a representative sample As was discussed previously, the entire analysis process is iterative in nature Thus, the configuration of interest in iteration #1, could be significantly altered in its basic makeup by iteration #n, resulting from the analyses of it and the other systems The system designer must take care to develop configurations that are internally compatible with regard to availability, etc The WPT family tree, presented as Figure 8 in Chapter V will be a valuable aid.

7 5 Systems Analysis

The systems analysis phase will require a detailed examination of relationships of the configurations of interest For WPT systems, particularly for microwave and millimeter wave systems, a complete understanding of the beam collection process should be obtained, for both the size of the transmitting and receiving antennas, but the required power density distribution functions (tapers) required These analyses will be iterative in nature themselves. A link table should be established that describes the power levels and efficiencies of the various processes within the system An evaluation of the configuration should be made against the specified functional and performance requirements to ensure further investigations are warranted. It is conceivable that the analyses will reveal that the original specifications are unobtainable given the system criteria and/or constraints, in which case, the system designer will have to return to the second phase to refine these requirements

7.6 System Trade-offs

Once it has been established that each remaining configuration (some candidates may be eliminated in the analysis phase) can fulfill the specified functional and performance requirements, a trade-off analyses is performed The purpose of trade-off analyses is to determine the preferred solution to any given problem from the viewpoint of cost, schedule, and technical considerations. As a formal decision analysis method, trade studies can be used to solve any complex problem where there is more than one selection criteria and provide the documented decision rationale for review by a higher authority The trade-off analysis methodology provides a structured analytical framework for evaluating a set of alternative concepts and designs

For WPT systems, the trade-off criteria will generally have been determined in the second phase, along with the functional and performance requirements There are various ways to perform such tradeoffs, depending upon the complexity of the system and the evaluators performing the tradeoffs. A Multi-Attribute Utility Analysis (MUAT) will assign each configuration a rating for a particular criteria. It should be noted that the utility ratings among various configurations is not necessarily linear For example, if System A costs 5 times more as System B, it does not necessarily follow that System B's rating will be 5 times better than that of System A However, such non-linear analyses will lend itself to large evaluation groups, as opposed to the individual analysts. The system designer must determine the most applicable evaluation process

7.7 System Evaluation.

After the trade-off analyses are performed, the information is collected and analyzed with regard to the weight of each criteria In other words, each criteria is given a relative weighting with respect to each other so that the final score of each system can be determined. Sensitivity analyses can be performed to determine how much variance in the total score can be expected for a variance of a given input, across all of the system configurations. Such a sensitivity analyses could reveal areas that may require further and more detailed analysis, given the systems relative strong dependence As discussed earlier, the entire process is iterative in nature, and the results of such an analyses will be fed back into the beginning phase to re-examine the configurations for an alternate set of criteria and/or constraints.

7.8 WPT System Analyses Flow Chart

Figure 9 presents a general WPT System Analyses Flow Chart to identify the various phases involved with such an analyses The specifics of the application of this chart will be explained in the following chapter

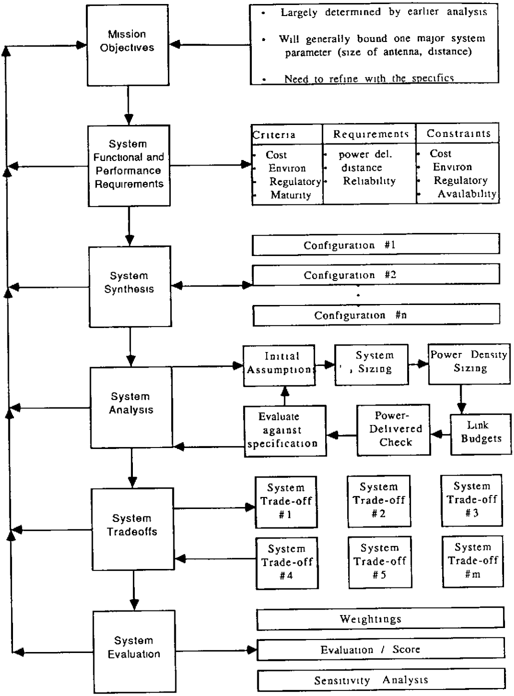

Figure 9 WPT System Analyses Flow Chart

CHAPTER VIII
WIRELESS POWER TRANSMISSION SYSTEMS ANALYSES
EXAMPLE - HALE AIRCRAFT

8.1 Mission Objectives

A variety of missions can be envisioned for a platform that can stay aloft for long periods of time Table 1 lists a selection of potential applications In order for such a platform to stay aloft for long periods, the aerodynamic characteristics must be optimized for minimum fuel consumption, which requires operation at minimal airspeeds This can be accomplished by flying at very high lift coefficients and at altitudes where wind speed is as low as possible. Figure 9 [63] represents a profile of wind speeds as a function of altitude

Figure 10 indicates that wind speeds are at a minimum at altitudes near 20 km Additionally, air densities are relatively low at this altitude. The platform configuration for a HALE (High Altitude Long Endurance) aircraft will be characterized by low power to mass ratios and low wing loadings Traditional power systems for high altitude aircraft are limited by on-board fuel storage capacities, and can only stay aloft for a relatively short duration In-flight refueling on a continuous basis would be cost prohibitive Thus, unique and novel solutions are required.

Table 1 Summary of Potential Applications of a HALE Aircraft

Military	Comunications Relay
	Ballistic Missile Early Warning
	Weather Monitoring
	Ocean Survelliance
	Battlefield Tactical Intelligence
	Nuclear Explosion Cloud Sampling
Scientific	Astronomical Observations
	Atmospheric Research
	Oceanagraphic Research
Civil	200 Mile Fishery Enforcement
	Border Patrol Surveillance
	Atmospheric Pollution Monitoring
	Resource Managment
	UHF TV Broadcasxts
	National TV Distribution
	Ice Suverying / Mapping of Waterways
	Emergency Response Communications
	Drug Interdiction

Although aircraft powered solely by the photo voltaic conversion of solar energy have been demonstrated, the diurnal limitation would require massive amounts of on-board energy storage for continuous operation Nuclear powered aircraft are technically feasible, but safety and societal concerns eliminate their inclusion as a viable option at this time

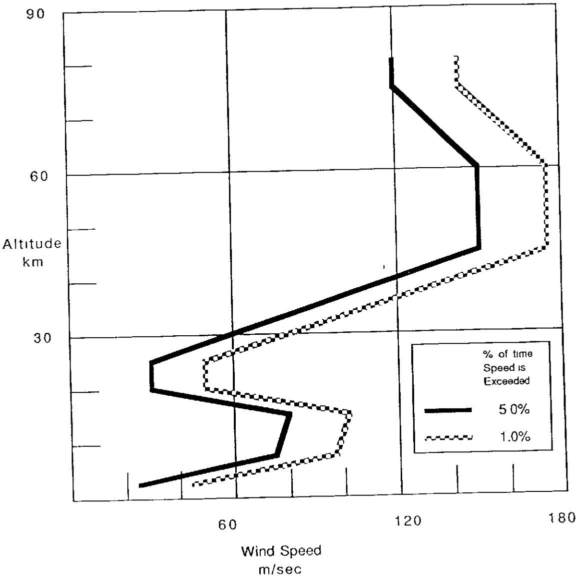

Figure 10 Wind Speed vs Altitude

A platform that receives its propulsive and payload power from a remote source would be able to stay aloft for the long periods required by naval task forces. Time aloft would only be limited by the Mean Time Between Failures (MTBF) of the on-board components Several studies have been performed in the last 15 years to determine the feasibility of a HALE aircraft who receives it power via the conversion of electromagnetic energy into energy usable by the propulsion and payload systems. The electromagnetic energy is delivered to the aircraft via an antenna beam, launched from a ground based transmitter Studies done by Sinko [64], Kuhner, et. al [65], Heyson [66], Morris [67], Turriziani [68], Brown [69], DeLaurier [70], Jull [71], Graves [72], Bouquet, et. al. [14], and Nguyen [63] indicate that such a concept is viable.

Thus, the mission objectives of such platform would be to provide one of the services in Table 1 for long durations (up to one year) The altitude of operation will be dependent upon mission specifics, such as required surface spot size for a communications platform

8.2 System Functional and Performance Requirements

In the design and analysis of a WPT powered HALE aircraft, the interaction of the platform's aerodynamic characteristics with the power beaming system design is such that neither system can be designed "in a vacuum" Close coordination is required, and systems tradeoffs must be performed in determining the optimum configuration

One of the major system sizing drivers is the interaction of the diameter of the focused power beam, or spot, relative to the receiver and platform geometries Power density is the greatest at the center of this spot and decreases roughly logarithmically toward the edges. Useful power is usually considered to exist between the center and a radius established at the points where power has decreased to one-half the value at the center of the spot This is known as the half power circle, and there is a corresponding ground antenna diameter to produce the required spot size.

There are a wide variety of platform shapes to carry the receiver A highly efficient aerodynamic shape will require less power than a less efficient shape, but will intercept less of the circular power spot As less power is intercepted, more power must be beamed up and more must be generated on the ground, requiring a larger transmitter and antenna. Alternately, a very low aspect ratio wing (i.e , the shape of a circle) matches the power circle geometry very well, but has extremely high drag and thus high power requirements. Therefore, these very high and very low aspect ratio platforms bound the system configuration, with the optimum system somewhere between these

Another consideration for aircraft design with respect to minimizing the power requirement is the turn radius of the aircraft. A small turn radius would produce a large roll angle, requiring a larger propulsive power, but limited in available power as the receiver is less visible to the oncoming beam. If a phased array transmitter / antenna system is used, then larger radii turns may have even less available power due to scan losses

The power system design is based primarily on the efficiencies of the various subsystems, and the transmission efficiencies that may depend on the physical size of the transmitting and receiving antennas

For this analysis, the performance requirements will be for a platform to fly at an altitude of 20 kilometers Flight durations from 9 days minimum to a 1 year maximum, which is essentially dependent upon the reliability of the transmitting and receiving subsystems Up to 10 kW of DC power should be allocated for on-board payload systems, and the flight radius will be no more than 1 km The wind profile will be assumed to be that in Figure 9 Emphasis will be placed on minimizing system development and operational costs The schedule of deployment will assume a Initial Operational Capability (IOC) within 4 years, thus mature technologies will be given consideration. Spectrum allocation and environmental impact will be evaluated as well No limitations have been placed on available real estate for the transmitter location, yet real estate costs will be factored into the evaluation.

8.3 System Synthesis

A typical design scenario may go as follows After determining the operational altitude, a profile for the associated wind speeds and air densities must be determined Platform airspeed must exceed wind speed by a necessary margin. Lift and drag forces can be determined, based on anticipated platform characteristics such as airfoil design, platform structural mass fraction, payload weight, etc. Once an initial platform is characterized, the amount of thrust required for the desired airspeed can be calculated In characterizing the power train, the efficiency of the motor and propeller must be considered

Motor efficiency is highest and mass lowest at high design motor speeds Propellers, however, must be large in diameter to be efficient at low speeds and hence, must turn slowly. The contrasting requirements can be fulfilled by using a gearbox with two stages of reduction.

Once the power train efficiencies are applied to the required thrust power, a fraction of the power needed from the receiver is now known Payload power and power distributed to any energy storage devices must make up the difference. Energy storage devices, such as batteries, fuel cells, or flywheels, are needed in the event of a power outage at the receiver The amount of storage will be limited by its mass, and will depend on such variables as anticipated maximum length of outage, operations required during outage, etc

Once the total power required from the receiver is known, the required area for rectenna elements can be calculated, limited by the maximum power density of the receiving device.

In Appendix A, a systems analysis for the aircraft is performed to determine the power required out of the rectenna, which was determined to be approximately 40 kW DC. For the area available for the rectenna elements, a trade-off must be performed to determine if a disk shaped rectenna is to be used, or if the available area under the wings and fuselage is to be used This analysis will assume the disk configuration, as in the SHARP Aircraft, to better match the shape of the rectenna to that of the beam from the transmitter The aircraft parameters are still believed to be valid, and are consistent with the published reports of the Canadian SHARP aircraft [15]

From the earlier sections, on WPT systems relationships and technology availability, three candidate systems have been identified. These candidate systems are summarized in Table 2 In past studies, a larger transmitting aperture is chosen for the 2 45 GHz system to maximize the collection efficiency. However, a smaller aperture may provide a more attractive initial system investment, although raising operational costs due to the inefficiency of the power transfer The 5 8 GHz system parameters are consistent with the proposed Canadian SHARP program The 35 GHz system was chosen based on available dish antennas, qualified for use in the Ka-Band

8.4 Systems Analysis

A Systems Analysis was performed on the three candidates to determine the required WPT system parameters This analysis is included in Appendix B Table 3 summarizes the values calculated in Appendix B

8.5 System Tradeoffs

The purpose of trade-off analyses is to determine the preferred solution to any given problem from the viewpoint of cost, schedule, and technical considerations As a formal decision analysis method, trade studies can be used to solve any complex problem where there is more than one selection criteria and provide the documented decision rationale for review by a higher authority The trade-off analysis methodology provides a structured analytical framework for evaluating a set of alternative concepts and designs For the WPT Hale Analysis, tradeoffs will be considered in 4 categories:

Table 2 Candidate System Summary

Systems Synthesis				
		Configuration #1 (2.45 GHz)	Configuration #2 (5.8 GHz)	Configuration #3 (35 GHz)
Aircraft/ System Parameters				
Altitude	m	2.00E+04	2.00E+04	2.00E+04
Propulsive Power	kW	25.00	25.00	25.00
Total Power	kW	40	40	40
Operational Frequency	GHz	2.45	5.8	35
Rectenna				
Type of Design		Brown's Design: Thin Film, Single Foreplane, GaAs Diode	Alden's Design Thin Film, Single Foreplane, Silicon Diode	APTI Design, Microstrip Patch, Spatial Filter, GaAs Diode
Polarization		Dual Polarized	Dual Polarized	Dual Polarized
Maximum Incident Power Density	W/m^2	600	800	1250
Conversion Efficiency	%	85	80	70
Transmitter				
Antenna Type		Phased Array, Slotted Waveguide	Phased Array, 9 meter parabolic dish subarray	Single Parabolic Dish (Astronomy Quality)
Subarray Area	m^2	0.75	63.62	n/a
Tube Type		Microwave Oven Magnetron - Amplifier	Klystron	Gyrotron
Power Output	W	300 to 1000	1000 to 10,000	200000
Tube Efficiency	%	65	70	35

1. Cost
2. System and Technology Maturity
3. System and Technology Reliability
4. Environmental and Regulatory Issues

Each design will be evaluated in the context of the above criteria The weight of the criteria with each category will be analyzed, so that the overall score in each category represents the true value of the system for the systems engineer. The weighted totals will be evaluated against each other, by converting the scores into a comparable scoring scheme Within the final evaluation, the categories themselves must be ranked As an individual is performing these trade-offs, a linear relationship will be assumed among the configuration for a given criteria.

8.5.1 Cost Analysis

Table 4 represents the first order cost analysis performed for the three configurations Several simplifying assumptions were made·

1 Only prime equipment - materials and real estate costs will be considered Support equipment will be considered in the reliability analyses. Any engineering development costs were disregarded, but the maturity of the technology is evaluated in the maturity analyses

2 Costs for 1 year, 2 year, and 5 year life cycles will be used in the evaluation of operational costs. The 5 year life cycle will be used in the final evaluation No support costs for maintenance, etc were included

Table 3. Systems Analysis Summary for the HALE Aircraft

Systems Analysis Summary				
		Configuration #1	Configuration #2	Configuration #3
		(2.45 GHz)	(5.8 GHz)	(35 GHz)
Aircraft/ System Parameters				
Altitude	m	2.00E+04	2.00E+04	2.00E+04
Operational Frequency	GHz	2.45	5.8	35
Propulsive Power	kW	30.00	27.50	25 00
Total Power	kW	45	42.5	40
Rectenna				
Maximum Incident Power Density	W/m^2	600	800	1250
Conversion Efficiency	%	85	80	70
Rectenna Diameter	m	11.00	10	9
Rectenna Area	m^2	95 03	78.54	63.62
Transmitter				
Transmitter Diameter	m	57.16	80	18
Transmitter Area	m^2	2566.10	5026 55	254 47
# of Subarrays		3421.00	61	1 Dish / 2 tubes
Subarray Size	m^2	0.75	63 63	n/a
Collection Efficiency	%	4%	31%	42%
RF Transmitted Power	kW	1400.00	170	144
For Atmospheric Absorption				
For 99% operation, :	%	100.00%	98.00%	71.00%
RF to Beam Efficiency (Link)	%	68%	46%	60%
RF Power Required out of Tube		2.06E+03	3.77E+02	3.38E+02
Tube Efficiency	%	65%	70%	35%
Conditioning / Support	%	95%	95%	90%
Prime Power Required	kW	3334.13	567.08	1073 11

3 For the rectenna elements, the area of each element was roughly approximated to be $(\lambda/2)^2$, and this area was divided into the total rectenna area to provide the number of elements.

4 Power costs are assumed to $ 05 kW-Hr

5. Real Estate costs were assumed to include site work needed for construction

6 Each antenna unit was costed with all control / steering facilities in place Thus, for the planar active array (2 45 GHz), all associated control logic circuitry, phase shifters, etc. are included For the 5.8 GHz and 35 GHz, the costs included the antenna pedestals.

8.5.2 Maturity Analysis

Table 5 presents the results of the trade-off analysis concerning the maturity of the technology The categories that were identified within this analysis were

1. Rectenna Design - the value for this category was determined by the amount of published and reviewed research For example, ARCO has published many conference papers, but few referred The papers that have been published do not reveal much insight into the nature of ARCO's design, as it is their intent to protect the proprietary nature of the device. However, without further review, the design was given the relatively low grade of 2. Bill Brown's designs, have been extensively

Table 4. WPT Cost Tradeoffs for the HALE Aircraft

Cost Analysis Summary				
		Configuration #1	Configuration #2	Configuration #3
		(2.45 GHz)	(5.8 GHz)	(35 GHZ)
Rectenna				
Wavelength	m	1.22E-01	5.17E-02	8.57E-03
Rectenna Area	m^2	95.03	78.54	63.62
Element Area	m^2	3.75E-03	6.69E-04	1.84E-05
# of Elements		2.54E+04	1.17E+05	3.46E+06
# of Diodes /element		1.00	4.00	1.00
Cost/diode		$6.00	$0.25	$0.50
Cost of Rectenna		1 52E+05	1.17E+05	1.73E+06
Transmitter				
Transmitter Area	m^2	2566.10	5026.55	254.47
# of Subarrays		3421.00	61	1
Subarray Cost Breakdown				
Antenna subarray		$800 00	$250,000.00	$3,000,000.00
Tube		$1,200.00	$10,000.00	$5,850,000.00
Total Subbarray Cost		$2,000 00	$260,000.00	$8,850,000 00
Total Cost		6.84E+06	1.59E+07	8.85E+06
Total Materials		6.99E+06	1.60E+07	1 06E+07
Real Estate Costs				
Cost/square meter		$450 00	$450.00	$450.00
Costs		1.15E+06	2.26E+06	1.15E+05
Total Costs (Materials+Real Estate)		8 15E+06	1.82E+07	1.07E+07
Prime Power Required	kw	3.33E+03	5.67E+02	1.07E+03
Power Costs	$/kw-hr	5.00E-02	5.00E-02	5.00E-02
1 year Life Cycle		1.46E+06	2.48E+05	4 70E+05
2 year Life Cycle		2 92E+06	4.97E+05	9 40E+05
5 year Life Cycle		7.30E+06	1.24E+06	2.35E+06
Total Costs				
1 year Life Cycle		9.61E+06	1.85E+07	1.12E+07
2 year Life Cycle		1.11E+07	1.87E+07	1.16E+07
5 year Life Cycle		1 55E+07	1.95E+07	1 30E+07

studied, tested, and analyzed in both conference papers and refereed journals Thus, his configuration was given a 5

2. Rectenna Diode Development - Similar to the ranking given above Brown has invested much in the way of publications concerning the use of the GaAs IMPATT diode, originally used in the NASA Goldstone experiment. Additionally, McSpadden, et al [25] have published additional reports concerning the robustness of the diodes The HP silicon diodes are known as well, the rating does depicts them both to be at a 5

3. Rectenna Development Potential- This rating is somewhat inversely proportional to the maturity of the design However, Alden's dual polarized, single foreplane has only been published for 2 years, thus further development into hardware is needed As for Brown's designs, additional optimization may occur with regard to re-radiation of harmonics, generated by the rectification process.

4 Transmitter Design
5 Antenna Development
6. Tube Development
7. Antenna/ Tube Development

As above, the ranking was determined by the amount of published data, and the availability of the subsystems from the commercial market place The 5 8 GHz design utilizes 9 meter diameter parabolic dishes, which there are now many vendors. The pedestal mounts for steering and point accuracy are well

Table 5 WPT Maturity Tradeoffs for the HALE Aircraft

Maturity Analysis Summary	Weight	Configuration #1 (2.45 GHz)	Configuration #2 (5.8 GHz)	Configuration #3 (35 GHz)
Rectenna				
Design	5	5	4	2
Diode Development	3	5	5	3
Development Potential	1	1	3	5
Weighted Score		41	38	24
Transmitter				
Design	3	5	5	3
Antenna Development	4	2	5	4
Tube Development	4	3	5	4
Development Potential	1	3	1	4
Weighted Score		38	56	45
Total Weighted Score		79	94	69

developed, as opposed to the planar array subarray, which has yet to be built in quantity

8.5.3 Reliability

The reliability tradeoffs were largely weighted by the design of the particular configuration, and are summarized in Table 6 Single point of failure items, such as the 35 GHz single 18 m dish, and two gyrotrons are significantly downgraded Active phased arrays systems enjoy the benefits of graceful degradation, i e., several units can be lost without requiring the system to shut down However, they also suffer from increased complexity, and this trade-off must be considered As the 5.8 GHz system will use a pedestal per dish to steer the beam, as opposed to an electrical system, its reliability is graded higher Generally speaking, mechanical systems will suffer more failures than electronically controlled devices such as the electronically scanned array. However, since the planar subarray with the magnetron amplifier is still under development, the reliability was downgraded The efficiency of the tube had much do to with rating of the individual tubes. Specifically, the gyrotron is relatively inefficient, thus active cooling systems must be employed for successful operation. Use of such active systems introduces additional failure mechanisms The power level required from the DC power supply was also rated, but given a low weighting in the scores. As for the rectenna, the decision criteria was based on the heat dissipation in the diode As the lower frequency design is more efficient, it was rated the highest

Table 6. WPT Reliability Tradeoffs for the HALE Aircraft

Reliability Analysis Summary	Weight	Configuration #1 (2 45 GHz)	Configuration #2 (5.8 GHz)	Configuration #3 (35 GHz)
Rectenna				
Heat Dissipation / Density	3	5	4	3
Weighted Score		15	12	9
Transmitter				
Design	5	4	4	1
Antenna	4	2	5	3
Tube	4	5	5	3
Power Supply	1	5	4	2
Cooling	2	5	5	2
Weighted Score		63	74	35
Total Weighted Score		78	86	44

8.5.4 Regulatory and Environmental Issues

In evaluating the regulatory aspects of these designs, three sub-categories were identified Spectrum allocation, transmitter interference, and rectenna harmonics. Table 7 presents the results. Note that both 2 45 and 5 8 GHz are in current ISM bands, thus precedent has been set concerning their use for the HALE system. However, 35 GHz is not in an ISM band, and permission must be sought, and is not guaranteed from the administrating body For the future deployment of such systems, the spectrum allocation could directly affect costs, as there are proposals for auctioning the allocated bands. Transmitter interference was rated as a function of power output. Brown has shown [41] that the microwave oven magnetron can be operated in a very quiet mode, if the anode (heater) current is turned down after initial warm-up. For the re-radiation of harmonics, this was also based on device efficiency APTI reveals [49] that a large percentage of the inefficiency is lost as reflection and re-radiation Mitigation measures, such as Frequency Selective Surfaces have been investigated, but will add loss to the conversion process

For environmental evaluations, it was noted that the 5 8 GHz design limited the power density to relatively small values, at the expense of larger area Such a diffuse beam will represent little harm to biota that may come into contact with the beam for relatively short periods of time. The 35 GHz system has a very high power density, and measures must be taken to ensure personnel safety. Another category was land use, and was weighted lightly as the apertures do not represent a significant use of real-estate.

Table 7 Regulatory and Environmental Tradeoffs for the HALE Aircraft

Regulatory / Environmental Analysis Summary	Weight			
		Configuration #1	Configuration #2	Configuration #3
		(2.45 GHz)	(5.8 GHz)	(35 GHz)
Regulatory				
Spectrum Allocation	5	5	5	2
Interference, Transmitter	4	4	5	3
Rectenna Harmonics	3	5	4	2
Weighted Score		56	57	28
Environmental/Safety				
Power Density	5	2	5	1
Land Use	2	2	1	5
Weighted Score		14	27	15

8.6 System Evaluation.

The various values were brought together, and converted to a common grading scheme for evaluation. The weight of the categories was determined by how it affected the various phases of the program; costs being the most heavily weighted and required the most at the beginning of a program As was mentioned in the WPT systems section, the environmental and regulatory issues could become significant system drivers beyond that of cost, and have the ability to grind a program to a halt However, for comparison purposes, this was given the least weight. A sensitivity analysis was performed, based on how high the cost parameter was weighted with regard to the other systems It is interesting to note, that all three system could be determined a winner, dependent on how heavy the cost is weighed against the other parameters. This also represents how close in value each system to each other, with regard to its system performance, although the designs are quite different. Table 8 presents these results.

The conclusions that can be reached from this preliminary systems design analysis, is that there is no correct solution for the WPT HALE application, for the assumed constraints and configurations As the results were tightly grouped, additional analysis concerning costs, etc may be warranted, if further consideration was given to the development of such an aircraft It also interesting to note that all three configurations were tightly grouped with regard to the overall score, a result, that although unexpected, does not agree with the reports developed by the technologists who are advocating the further development of their respective technologies.

Table 8 WPT System Evaluation Summary for the HALE Aircraft

Tradeoff Analysis Summary	Weight			
		Configuration #1	Configuration #2	Configuration #3
		(2.45 GHz)	(5.8 GHz)	(35 GHz)
Costs		1.55E+07	1.95E+07	1.30E+07
Relative Costs		0.84	0.67	1.00
Weighted Values	5	4.22	3.35	5.00
Reliability Values		78	86	44
Relative Values		0.91	1.00	0.51
Weighted Values	3	2.72	3.00	1.53
Maturity Values		79	94	69
Relative Values		0.84	1.00	0.73
Weighted Values	2	1.68	2.00	1.47
Environmental / Regulatory Values		14	27	15
Relative Values		0.52	1.00	0.56
Weighted Values	1	0.52	1.00	0.56
Total Weighted Score		9.14	9.35	8.56
Sensitivity Analysis	Weight			
		Configuration #1	Configuration #2	Configuration #3
Subtotals of all but costs		4.92	6.00	3.56
Costs multipliers		0.84	0.67	1.00
Weight, Score	5	9.12	***9.35***	8.56
Weight, Score	6	9.96	***10.02***	9.56
Weight, Score	7	***10.80***	10.69	10.56
Weight, Score	8	***11.64***	11.36	11.56
Weight, Score	9	12.48	12.03	***12.56***
Weight, Score	10	13.32	12.70	***13.56***
Weight, Score	11	14.16	13.37	***14.56***
Weight, Score	12	15.00	14.04	***15.56***
Weight, Score	13	15.84	14.71	***16.56***
Weight, Score	14	16.68	15.38	***17.56***

CHAPTER IX

DEVELOPMENT OF EXPERIMENTAL RECTENNA FOR JAPANESE METS PROJECT

A systems engineering approach was recently applied successfully to a small WPT project which bears review in the context of this thesis An opportunity was provided to participate in the Institute of Space and Astronautical Sciences' (ISAS) Microwave Energy Transmission in Space (METS) experiment. Specifically, the author of this thesis was invited to provide a small rectenna to be used on the "daughter" section of an sounding rocket payload, which would receive microwave energy from the "mother" section Once funding was found for this initiative, a team consisting of graduate students from the Electromagnetics and Microwave Laboratory of Texas A&M University, consulting engineers from the Raytheon Corporation, and William C Brown

Much of the critical design parameters had already been determined by the ISAS team who was designing the transmitter subsystem The operating frequency was set at 2 41 GHz and a physical envelope in which the rectenna must fit was specified as well The only additional requirement specified was the data output of 0 to 5 Volts at the connection to the rectenna. All other design requirements were up to the design team.

As opposed to beginning the detailed design process, a series of system engineering activities were conducted to determine the remaining functional and performance requirements The group discussed its essential mission objective as to design and construct a rectenna that would

1) Withstand the rigors of the launch without detriment to the existing payload. Thus, if a trade-off was needed for performance versus structural strength, greater weighting would be given to structural strength

2) Meet the demanding cost and schedule requirements Due to the time in which the invitation to participate was received, only 30 days was allotted from program go-ahead to delivery. Additionally, a relatively small budget had been obtained, thus the design had to be easily and inexpensively built, preferably here on campus

The above were considered the system and programmatic requirements The actual transfer function of the rectenna was left as a design goal. As the primary mission of the METS experiment was to examine the interaction of the microwave beam with the ionosphere, the main beam of the transmitter would be scanned away from the daughter section. Thus, it was impossible to accurately determine an incident power density to optimize the rectenna's transfer function In the design of rectennas, generally there is a trade-off between optimizing the efficiency for a specific incident power density and optimizing for a wide range of inputs, at a lower yet more constant voltage response. Since the rectenna's function on the METS experiment was simply to demonstrate the viability of WPT technology in the space environment, the decision was made to optimize for the latter

Once the boundaries of the values of the incident power density were established via engineering analyses, the detailed design was begun Another trade-off encountered was whether to use an existing design, or to begin with a new design. The existing design represented a mature, reliable technology, whose "pedigree" had been well documented However, the chance to try a new design for this rare opportunity to fly a rectenna in space was appealing. When this issue was considered with regard to the mission requirements, the decision was made to go with the older technology This provided added benefits as it did not invoke potential export restrictions for new designs.

The specifics of the actual design will be reported elsewhere, but once the tradeoffs analyses were complete and evaluated, the detailed design was begun and constructed The rectenna was delivered to the "customer" within the specified 30 days, and on February 18, 1993 , the METS experiment was successfully launched from Kagoshima, Japan The Texas A&M Rectenna performed as was expected, delivering the required data signal for a wide range of incident power densities. The systems engineering approach played a key role in this success. The above discussion was presented anecdotally to provide limited insight into the successful application of the systems engineering approach to a WPT design problem.

CHAPTER X

CONCLUSIONS AND RECOMMENDATIONS

These efforts have resulted in two products of significance. First, the development of a WPT Systems primer will provide an invaluable resource to those individuals who will study WPT systems in the future. The collection and explanation of the relevant systems issues in a single document represents a notable contribution to the existing literature set Second, the development of a systems engineering approach tailored for the analysis of WPT systems has provided a "requirements - driven" treatment of the subject, as opposed to a "technology - driven" approach. This approach should provide systems analysts with an accurate measure of the effectiveness of a proposed system for a given set of requirements Thus, this thesis has presented a systems engineering approach for the analyses of wireless power transmission. The preceding chapters have fulfilled the requirements specified in Chapter 1 An example of using such an approach was demonstrated with defensible results.

The findings of this research effort are as follows·

1 There are many definitions and views of systems engineering, each which share a common thread

2 The most notable events in the history of WPT center around the development and demonstration of hardware.

3. Much of the development work in WPT technology has been either system feasibility studies or limited technology development

4. Very little has been published with regard to a Systems Engineering Approach to Wireless Power Transmission Systems

5. Technology is available for Pilot Projects for many of the Applications

6. Japan is taking a long-term planning approach with strategic partnerships between Industry, Academia and Government Agencies.

The findings of the analyses effort are as follows:

1. Systems Engineering Approach can successfully be applied for analysis and development of WPT Systems

2 The results of the System Engineering analysis will not necessarily indicate that no clear winner exists for the permutations of requirements and constraints considered in this thesis

3. The relative emphasis of one criterion to another can significantly affect system design.

What these findings show, in the opinion of the author of this thesis, are as follows

1. Systems Engineering is a robust approach to the analysis of a variety of engineering problems and designs Patience is required to implement this approach.

2 This thesis provides future system analysts with a general overview of WPT Systems and a valid approach for their analysis

3 Japan will continue in their paradigm of capitalizing on the U.S. taxpayer's investment into future technologies. The United States should increase its investment into'pilot projects of WPT systems or suffer the consequences

4 The WPT powered HALE may be a valid commercial application of WPT technology for the near term (within 4 years). The challenge of development is not technology driven, but by available market (economics) and approach to externalities (regulatory, safety, etc)

The history of WPT technology and its application is characterized by periodic peaks and valleys of interest and funding A large number of studies have been performed to determine the feasibility of WPT technology with regard to other technologies for a particular application The funding of such studies represents a sizable investment when compared to the modest amount of technology development that has been done. However, when the history of WPT is reviewed in most publications, the emphasis is placed on those events which demonstrated the viability of the technology In other words, the events for which WPT is best remembered represent the least amount of investment The METS project mentioned previously is an excellent example of a large "return" , as measured by the demonstration of the technology, for a relatively small investment. It is the hope of the author that a systems engineering approach to the analyses of Wireless Power Transmission Systems will allow for a more expedient transition into system development and eventually into deployment

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APPENDIX A

WIRELESS POWER TRANSMISSION POWERED HALE AIRCRAFT ANALYSIS

Previous analyses rigorously defined the aircraft platform parameters, and thus it is prudent to use typical values from these analyses in defining a HALE platform Typical parameter values are summarized in Table 9 . Once these values are assumed, the remainder of the platform characteristics can be calculated as follows The aircraft design procedure was synthesized from a variety of sources, and was perfomred to provide confidence to the assumption of aircraft parameters

To calculate the planform reference area S_{ref}, use the following relationship·

$$S_{ref} = \frac{b^2}{A}$$

where b = Wingspan
A = Aspect Ratio

Thus, the planform reference area is calculated to be 96 43 m^2.

Next, the coefficients of lift and drag can be determined Both coefficients depend on the profile drag coefficient, and the Oswald Aircraft Efficiency Factor, e The profile drag coefficient is assumed to be a typical value of .010 The Oswald efficiency factor is assumed to vary linearly with the Aspect ratio

$$e = 1 - (.009)A$$

Thus, the coefficients of lift and drag are calculated using the following relationships

$$C_L = \sqrt{3C_{D,0}\pi Ae}$$

$$C_d = C_{D,0} + \frac{C_l^2}{\pi e A}$$

where	$C_{d,0}$	=	010 (Profile Drag coefficient)
	A		21
	e	=	811

Thus, Cl and Cd are calculated to be 1 267, and 040 This results in a lift to drag ratio of 32, which is consistent with the values in Tables 9

Table 9 Summary of Typical Values for WPT HALE Aircraft Analyses

Parameter	Symbol	Units	Typical Values
Altitude	h	km	20 00
Airspeed	v	m/s	50 00
Wing Span	ws	m	45 00
Aspect Ratio	AR		21 00
Planform Area	Sref	m^2	96 43
Lift to Drag Ratio	L/D		32 00
Coefficient of Lift	Cl		1 27
Coefficient of Drag (total)	Cd		0 04
Profile Drag Coefficient	Cd,o		0 01
Oswald Airplane Efficiency factor	e		0 81

The airplane characteristics can now be related to the power system First, the thrust force must be determined, using the relationship

$$T = \frac{1}{2} C_d \rho_a v^2 S_{ref}$$

where ρ = Air Density at altitude. Assume a typical value of .0888 kg/cubic meter

v = Aircraft Airspeed

Thrust is determined to be 428 Newtons (kg m/ s^2)

The power required at the propeller to deliver this thrust is:

$$P_m = \frac{Tv}{\eta_{propeller}}$$

where η propeller = Efficiency of Propeller (Assumed to be 85%)

Thus, power required at propeller is determined to approximately 25 kW, which is equivalent to 33 76 horsepower Taking into account the efficiencies of the gearbox and motors, the propulsive power required is

$$P_{propulsion} = P_m \eta_{gearbox} \eta_{motor}$$

where η_{gear} = Efficiency of gearbox (Assumed to be 99%)

η_{motor} = Efficiency of motor (Assumed to be 94%)

The power required out of the rectenna is the determined by payload power and power dedicated for energy storage

$$P_{dc,rectenna} = P_{propulsion} + P_{payload} + P_{\substack{energy\\storage}}$$

Total Power required out of the rectenna is determined to be approximately 40 kW DC

APPENDIX B

WIRELESS POWER TRANSMISSION POWERED HALE AIRCRAFT SYSTEM ANALYSIS

	2.45 GHz	5.8 GHz	35 GHz
Begin by specifying user power.			
Power, DC	40000.00	40000.00	40000.00
From known power density limitations, and assumption of peak to average ratio, calculate needed rectenna areas and diameters			
Rect, Dia	12.00	10.60	9.00
Area, Rect	113.10	88.25	63.62
Assume 3 dB spot size to equal rectenna area			
3 dB spot, dia	12.00	10.60	9.00
3 dB Area	113.10	88.25	63.62
Given the desired 3dB spot size, and height and wavelength, calculate required transmitter diameter.			
Frequency	2.45E+09	5.80E+09	3.50E+10
Wavelength	0.12	0.05	0.01
Height	2.00E+04	2.00E+04	2.00E+04
D, trans	208.16	99.54	19.43
a, trans	34032.83	7782.61	296.46
Decision is made that these apertures are too large. Continue with new assumptions for			
Assume new transmitter size, and subarray size, given specifics of the proposed designs.			
Xtrans, Dia	57.16	80.00	18.00
Xtrans Area	2566.10	5026.55	254.47
# of subarrays	3421.47	61.00	1.00
Based on Goubau tapers, calculate efficiency			
Tau	0.22	0.64	0.74
EFF (Tau)	0.05	0.34	0.42
Back up power through rectennna and beaming efficiency to determine value of RF Transmitted Power			
DC Required	4.00E+04	4.00E+04	4.00E+04
Rectenna Efficiency	0.85	0.80	0.70
Beaming efficiency	0.05	0.34	0.42
RF Transmitted Power	9.96E+05	1.47E+05	1.35E+05

Evaluate above values, given the relationships for power density			
Peak Power Density factor	4.28E-04	4.70E-03	8.66E-03
Peak Power Density	426.24	692.10	1168.23
Needed Peak	600.00	800.00	1250.00
Ratios	1.41	1.16	1.07
Increase RF Transmitted Power by ratio			
RF Transmitted Power (increased)	1.40E+06	1.70E+05	1.44E+05
New Peak Power Dens	600.00	800.00	1250.00
Given the Goubau tapers, approximate the peak to average power density ratio to derive average power density ratio			
Average Distrib	0.98	0.88	0.77
Average RF Dens	588.00	704.00	962.50
Evaluate the DC power delivered by multiplying the average RF Density by the area of the			
Area of Rectennas	113.10	88.25	63.62
Resulting Power	6.65E+04	6.21E+04	6.12E+04
Efficiency of Rect	0.85	0.80	0.70
DC power delivered	5.65E+04	4.97E+04	4.29E+04
Evaluate these values by backing the increase RF transmitted power through the beaming efficiencies and peak rectenna efficiencies			
Check out	5.63E+04	4.62E+04	4.28E+04
Inspection reveals good collaboration of the data (expected).			***FREEZE***
Note that for the 35 GHz system, the value is close enough to the needed power density to freeze that design. However, the larger values of DC power delivered for the 2.45 and 5.8 GHz indicate that another iteration is required			
For Atmospheric Absorption			
For 99% operation, Assume the loss as:	1.00	0.98	0.71
For 99.9% operation, Assume the loss as:	1.00	0.83	0.26
Thus, for the 2.45 and 5.8 GHz systems, enough is built into the system to tolerate these outages. However, the 35 GHz system must be resized for this additional power. Note that this additional loss will be accounted for in the			

	2.45 GHz	5.8 GHz	
Begin, again, by specifying user power:			
Power, DC	40000.00	40000.00	
Decrease size of rectenna from initial guess to reduce aircraft drag(as of yet unaccounted for in power requirements for different size			
Rect, Dia	10.00	9.50	
Area, Rect	78.54	70.88	
Assume same size transmitters			
Frequency	2.45E+09	5.80E+09	
Wavelength	0.12	0.05	
Height	2.00E+04	2.00E+04	
Xtrans, Dia	57.16	80.00	
Xtrans Area	2566.10	5026.55	
# of subarrays	3421.47	61.00	
Based on Goubau tapers, calculate efficiency			
Tau	0.18	0.58	
EFF (Tau)	0.03	0.28	
Note that due to smaller rectennas, efficiency will decrease (linearly with diameter			
Back up power through rectennna and beaming efficiency to determine value of RF Transmitted Power			
DC Required	4.00E+04	4.00E+04	
Rectenna Efficiency	0.85	0.80	
Beaming efficiency	0.03	0.28	
RF Transmitted Power	1.42E+06	1.77E+05	
Evaluate above values, given the relationships for power density			
Peak Power Density factor	4.28E-04	4.70E-03	
Peak Power Density	609.30	829.33	
Needed Peak	600.00	800.00	
Ratio	0.98	0.96	
Increase RF Transmitted Power by ratio			
RF Transmitted Power (increased)	1.40E+06	1.70E+05	
New Peak Power Dens	600.00	800.00	

Given the Goubau tapers, approximate the peak to average power density ratio to derive average power density ratio (note, the tapers have decreased slightly as the rectenna area			
Average Distrib	0.95	0.82	
Average RF Dens	570.00	656.00	
Evaluate the DC power delivered by multiplying the average RF Density by the area of the			
Area of Rectennas	78.54	70.88	
Resulting Power	4.48E+04	4.65E+04	
Efficiency of Rect	0.85	0.80	
DC power delivered	3.81E+04	3.72E+04	
Evaluate these values by backing the increase RF transmitted power through the beaming efficiencies and peak rectenna efficiencies			
Check out	3.94E+04	3.86E+04	
Inspection reveals good collaboration of the data (expected).			
Note that the power delivered is too low, thus the rectenna area must be increased At this next iteration, an increase in power delivered will also be introduced, as these rectennas will be larger than the baselined 35 GHz system.			

	2.45 GHz	5.8 GHz	
Begin, again, by specifying user power. Power will increase by 3.5 kw per meter of diameter increase over baseline. The diameter of the 2.45 GHz rectenna will be 11.0 meter, and the 5.8 GHz will be 10.0 meter			
Power, DC	45000.00	42500.00	
Increase size of rectenna as stated above			
Rect, Dia	11.00	10.00	
Area, Rect	95.03	78.54	
Assume same size transmitters.			
Frequency	2.45E+09	5.80E+09	
Wavelength	0.12	0.05	
Height	2.00E+04	2.00E+04	
Xtrans, Dia	57.16	80.00	
Xtrans Area	2566.10	5026.55	
# of subarrays	3421.00	61.00	
Based on Goubau tapers, calculate efficiency			
Tau	0.20	0.61	
EFF (Tau)	0.04	0.31	
Back up power through rectennna and beaming efficiency to determine value of RF Transmitted Power			
DC Required	4.50E+04	4.25E+04	
Rectenna Efficiency	0.85	0.80	
Beaming efficiency	0.04	0.31	
RF Transmitted Power	1.33E+06	1.68E+05	
Evaluate above values, given the relationships for power density			
Peak Power Density factor	4.28E-04	4.70E-03	
Peak Power Density	568.48	787.59	
Needed Peak	600.00	800.00	
Ratio	1.06	1.02	
Increase RF Transmitted Power by ratio			
RF Transmitted Power (increased)	1.40E+06	1.70E+05	
New Peak Power Dens	600.00	800.00	

Given the Goubau tapers, approximate the peak to average power density ratio to derive average power density ratio			
Average Distrib	0.97	0.85	
Average RF Dens	579.00	683.20	
Evaluate the DC power delivered by multiplying the average RF Density by the area of the			
Area of Rectennas	95.03	78.54	
Resulting Power	5.50E+04	5.37E+04	
Efficiency of Rect	0.85	0.80	
DC power delivered	4.68E+04	4.29E+04	
Evaluate these values by backing the increase RF transmitted power through the beaming efficiencies and peak rectenna efficiencies			
Check out	4.75E+04	4.32E+04	
These values now freeze the design of the other two systems.			

Transmitter Link Budget			
	2.45 GHz	5.8 GHz	35 GHz
RF Transmitted Power Required (MW)	1.40E+06	1.70E+05	1.44E+05
Transmitter Area	2566.10	5026.55	254.47
Transmitter Power Density	545.57	33.82	565.88
Average Area of Subarray	0.75	63.62	254.47
Power from each subarray	409.18	2151.56	144000.00
# of Subarrays	3421	61	1
Number of Subarrays*Area	2565.75	3880.65	254.47
Fill Factor	1.00	1.30	1.00
Power from each subarray	409.18	2786.89	144000.00
Tube RF Output Power Determination			
For Atmospheric Absorption			
For 99% operation, Assume the loss as:	1.00	0.98	0.71
Aperture Efficiency	0.90	0.60	0.60
Scan Loss	0.75	1.00	1.00
Fill Factor	1.00	0.77	1.00
XMTR RF Link	0.68	0.45	0.43
Total RF Required	2.07E+06	3.74E+05	3.38E+05
Power Output per Subarray	6.06E+02	6.14E+03	3.38E+05
Tube Efficiency	0.65	0.70	0.35
Conditioning/Support	0.95	0.95	0.90
Overall DC- Transmitted RF Efficiency	0.4168125	0.301879554	0.13419
Prime Power Required	3.36E+06	5.63E+05	1.07E+06

VITA

Alan Madden Brown received his BSEE degree from Texas A&M University in 1986. His course work and senior research concentrated on microwave circuits and systems He was employed as a Radar Systems Engineer by the Fort Worth Division of the General Dynamics Corporation from 1986 to 1991 Mr. Brown was hired by the Electrical Engineering Department of Texas A&M University in 1991 to lead a NASA-sponsored Space Shuttle Flight Experiment on Microwave Power Beaming This program required technical and programmatic interfaces with academic, governmental, and industrial entities His work with the Center for Space Power , a NASA Center for Commercial Development of Space, in conjunction with this program, has resulted in Mr Brown being named the Center's Assistant Director for Projects for all wireless power transmission activities

These activities included acting as the study manager for a WPT Commercialization Study commissioned by NASA Headquarters, performing systems analyses for both the Center and external customers (Raytheon, A D. Little, Center for Remote Sensing) Mr Brown was the program chairman for the WPT'93 Conference held in San Antonio, Texas in February 1993 At the Conference, the results of the WPT Study were presented by Brown, as the moderator of the WPT Commercialization Round Table He also served as the Co-Principal Investigator for the USA portion of the Japanese METS Experiment, which was funded by NASA Lewis. Mr Brown can be reached at the Austin Division of the Lockheed Missiles and Space Company at P O. Box 17100, Austin, Texas 78760-7100