INITIAL MPTS STUDY RESULTS
- DESIGN CONSIDERATIONS AND ISSUES -

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ABSTRACT

Progress in analysis, design and technology demonstration performed over the 1964-1979 time period is reviewed. Emphasis is on identifying the documentation for detail beyond the scope of the presentation and summarizing what was determined and, in retrospect, how firm those determinations appear to be. Twelve specific subsystems and technology areas are reviewed. Relevant issues or considerations are discussed and their resolution or status is presented.

Introduction and Background

Investigations of Microwave Power Transmission System (MPTS) concepts by Raytheon over the last 15 years are summarized in the attached figure. They began with, Item (1), investigations by Bill Brown in powering a high altitude platform by converting DC power on the ground to RF microwave power, transmitting it to a rotary wing platform, converting the RF power to DC, driving a rotary wing through a DC motor, controlling the platform in azimuth and elevation with a beam-riding autopilot for the helicopter. This work pointed out the potential of microwave power transmission and again Bill Brown continued to pursue this and other applications, including the Orbit-to-Orbit Transmission of Item (2), over the years.

This MPTS approach was adopted as part of Dr. Peter Glaser's Power from Space concept. Raytheon in-house investigations and reviews in the 71-72 time period determined that the concept of Microwave Power Transmission from Space was sufficiently sound to warrant further investigation and commitment of resources.

The key issues identified by the Raytheon committee review were:

(a) Major steps must be taken to assure that the billions of diodes in the ground-based rectenna are sufficiently reliable to support a long life of approximately 30 years.

(b) The entire MPTS concept must be advanced rather rapidly.

Item (a) has been pursued primarily by operating the diodes at power levels well below their time critical levels and by employing fail safe concepts where known failure modes result in open circuits and do not precipitate other failures. Item (b) has been pursued as aggressively as national support will permit. Good management practice normally would not support strong dependence on a few individual performers, however the issue is really most significant in that tube technology is suffering from lack of interest in the academic community and in the technology community in general in favor of solid state approaches. The high power handling capability of tubes over solid state was considered to be a major factor. The maturity of tube technology permitted the definition of concepts with no known failure modes, passive waste heat dissipation limited by topology considerations and by the relatively high allowable temperatures for associated magnets as compared to solid state junctions. The efficiency of the device was considered a key item. An 80% efficient device results in twice as much inefficiency and waste heat dissipation required as a 90% efficient device and low allowable temperature limits compound the problem further. High power density on orbit was considered to be fundamental to low cost and the delivery of large amounts of power to the ground.

Major System Studies

Arthur D. Little, Inc., Grumman Aerospace Corporation, Spectrolab, Inc. and Raytheon conducted integrated in-house investigations, Item (3), of the SPS concept and contracted with NASA Lewis Research Center for a Feasibility Study of SPS, Item (4), inthe 1971-72 time period. The major MPTS issues included RFI and biological considerations and the Office of Telecommunications Policy was briefed and consulted in the early period. The frequency had been established at 2.45 GHz (the ISM band) by the early studies and the study for NASA Lewis Research Center indicated that 3.3 GHz would be near optimum from the RFI point of view. Later studies by Raytheon for Lewis Research Center indicated that 2.2 GHz was near optimum from the SPS point of view, however RFI to other users of the spectrum was considered an adverse factor and the 2.45 GHz ISM band was again identified as the near optimum from many points of view.

The transmitting antenna diameter was consistently in the 1 km diameter region and the ground rectifying antenna was in the 10 km diameter region.

Biological limits for national and international applications for exposure outside the protected primary beam was assumed to be nominally 0.1 mW/cm^2. It was recognized that extensive investigation may show this to be an incorrect assumption and that in the limit it may be either higher or lower. Truncated Gaussian taper for the transmitting antenna was considered fundamental to the concept to maintain low sidelobes and to provide the flexibility in the concept for more or less taper as the dictates of biological limits required. The effects on life forms within the main beam were considered to be of concern, warranting in-depth investigation. The need for flexibility in the concept to control the main beam power density was therefore indicated. The trend toward less than low-cost-optimum levels began since the primary way of controlling main beam power density was to reduce transmitted power density and/or total transmitted power.

Microwave Power Transmission System Studies, Item (5), for NASA Lewis Research Center in the 74-75 period were most extensive and detailed, providing the basic relationships among performance, weight and cost. The scope was considered to be full breadth covering all the known issues. The depth was limited by time and effort that was considered appropriate for this first major investigation of the MPTS. The detailed results are reported in the four-volume report Microwave Power Transmission System Studies (NASA CR-134886, ER75-4368). A Satellite Power System Technology Risk Assessment was performed which identified in a level 5 breakdown the technology areas as they relate to microwave power transmission. The risk rating criteria categories were again at 5 levels: 1 - In Use, 2 - In Development, 3 - On the Technology Frontier, 4 - Conceptual and 5 - Invention. The configuration and technical approach was modified to not require any Invention. There were 24 items in Category 4 requiring further investigation, advanced technology development and demonstrations. Relatively standard technology development was considered to be required in all other areas.

The 24 critical items as presented in order of priority and discussed in Volume 4 of ER75-4368 are:

1. DC-RF Converters & Filters
2. Materials
3. Phase Control Subsystems
4. Waveguide
5. Structure
6. Manufacturing Modules
7. Remote Manipulators
8. Biological
9. Attitude Control
10. Ionosphere
11. Power Transfer
12. Switch Gear
13. Radio Frequency
14. Support Modules
15. Orbital Assembly Operations
16. Reliability
17. Solar Electric Propulsion Stage
18. Transportation Operations
19. SPS Flight Mechanics
20. Operations and Maintenance
21. Power Source
22. Heavy Lift Launch Vehicle
23. Socio-economic Considerations
24. Re-Supply

A Critical Technology and Ground Test Program was described in Section 13 of ER75-4368. The 48 kW Klystron and the 5 kW Crossed Field Directional Amplifier (CFDA) were considered to be the leading tube contenders, with the Amplitron version of the CFA having the highest potential performance, lowest weight, longest life and lowest cost; however, there was significant uncertainty regarding CFDA noise. The study included a major effort by Shared Applications and Raytheon Equipment Division for the Klystron and significantly less effort for the less complex Amplitron. It was recognized that the Crossed Field Amplifier should be the subject of advanced development before selection could be made.

Environmental effects relative to propagation and phase control were discussed in NASA CR-134886, Section 3. This covered Atmospheric Attenuation and Scattering Ionospheric Propagation, Ionospheric Modification by High Power Irradiation & Faraday Rotation Effects. Subsequent data and investigations in this area have necessitated updating as reported in Items (11), (17) and (18).

The purpose of Item (9) was to provide a total set of qualitative relationships between areas requiring investigation and the viable approaches for investigation. Nine major points of focus in ground based study, technology development, analysis and test were identified. This was provided to both MDAC and GAC in support of Item (10). Item (12) was provided in response to a series of issues relating to whether or not a rational program with intermediate steps could be formulated that would give progressive confidence that would support authorizations to proceed on a continuous but step-wise basis. This identified a 10-step program that although outdated indicates the characteristics required.

Studies under ECON for NASA-MSFC of Item (11) included the rationale for the ground power density region of interest between 20 and 50 mW/cm^2. It was further indicated that 23 mW/cm^2 was a reasonable value for reference purposes.

The Rectenna Technology Study, Item (14), by Bill Brown of Raytheon provided further detail on the rectenna for Boeing.

The investigations into SPS and alternate technologies of Item (15) began to identify the basis for direct comparison of SPS with other approaches for base power. Raytheon Equipment Division worked in a consultant role to identify the several sources of relevant information.

The SPS Pilot Beam and Communication Link Study, Item (17), provided relevant sizing approaches and data in those areas that were not addressed in previous activities. Interpretation of the results of this study in the area of ionospheric effects, as expressed by others working in the area of ionospheric modeling and phase control, were inconsistent with Raytheon's understanding of the problem and a draft Technical Note of Item (18), SPS Pilot Beam Ionospheric Effects Discussion of Critical Issues, was distributed to personnel working in the ionospheric modeling and phase control areas. Details from this T.N. will be included in the oral presentation.

The Solid State SPS Microwave Generation and Transmission Study, Item (19), and the Magnetron Tube Assessment Program will be reported on in other appropriate sessions.

Major Demonstrations and Technology Developments

The Reception-Conversion Subsystem (RXCV) for Microwave Power Transmission System effort of Item (6) will be reported on in other appropriate sessions. It was vitally important in that it constituted a major positive step in credibility with the technical community. The high RF to DC efficiencies (> 80%) demonstrated in the field and the high DC to DC efficiencies (54%) demonstrated and certified by JPL in the laboratory constituted progress that created signficant interest in and belief by the technical community.

The RF to DC Collector/Converter Technology Development, Item (7), will be reported on in other appropriate sessions. It extended the RF to DC efficiency data to low power levels and provided significant advancement in understanding of possible approaches to fabrication for low cost.

The Design and Fabrication of Crossed Field Amplifiers, Item (8), will be reported on in other appropriate sessions. Although this development was limited to a Phase I activity, it along with major contributions by R. Dickinson of JPL provided insight that precipitated Item (16). The Raytheon in-house work in Item (16) was followed by a program under contract from JPL to investigate the magnetron directional amplifier and will be reported on in other appropriate sessions. This work is a very significant system level contribution in that it has brought the most familiar microwave oven magnetron into contention, contrary to the belief that the Amplitron and Klystron were the leading contenders as reported under Item (5). This is hopefully indicative of simple but imaginative approaches that may evolve in each of the SPS areas of overall concept and technology.

The Magnetron Tube Assessment, Item (20), will be reported on in other appropriate sessions. This assessment is most important in the system performance area in that it is the investigation of an alternate technology that is relatively mature, lightweight, highly efficient and relatively simple from both the device and interface with the power grid points of view.

Relevant technologies under consideration and development, Item (13), are being investigated by Raytheon.

RAYTHEON'S PARTICIPATION IN SOLAR POWER SATELLITE PROGRAM
RELATED WORK – SYSTEM STUDIES AND TECHNOLOGIES

	DESCRIPTIVE TITLE	PRIOR TO 1970	PERIOD OF PERFORMANCE 70 71 72 73 74 75 76 77 78 79 80 81	CUSTOMER	PRIME	SUB	RELATED REPORT NUMBER
1	Microwave Powered Helicopter	1964		USAF	Raytheon		RADC-TR-65-188
2	Orbit-to-Orbit Power Transmission	1969	————Δ	NASA-MSFC	Raytheon		PT-4601
3	MPTS in Satellite Solar Power Station		—Δ	In-House			ER72-4038
4	Feasibility Study of SPS		—Δ	NASA-LeRC	Arthur D. Little	Raytheon Grumman Spectrolab	NASA CR-2357
5	Microwave Power Transmission System Studies		—Δ	NASA-LeRC	Raytheon	Shared Applic's & Grumman	NASA CR-134886
6	Reception-Conversion Subsystem (RXCV) for Microwave Power Transmission System		—Δ	NASA	JPL	Raytheon	ER75-4386
7	RF to DC Collector/Converter Technology Development		——Δ	NASA-LeRC	Raytheon		NASA CR-135194
8	Design and Fabrication of Crossed Field Amplifier		——Δ	NASA-LeRC	Raytheon		NASA CR-159410
9	Areas of Investigation Relationships to Development Approaches		Δ	In-House			
10	Space Station System Analysis Study		—Δ	NASA-MSFC NASA-JSC	GAC MDAC	Raytheon Raytheon	
11	Space Based Solar Power Conversion and Delivery System Study		—Δ	NASA-MSFC	ECON	Raytheon	ECON 77-145-1 S/C ECON-0003
12	Satellite Power System Development Plan Summary		Δ	In-House			
13	DOD Applications & DARPA Advanced Technology Development (Relevant Space Based Investigations)		——Δ——	SAMSO RADC	TRW/GAC Raytheon	Raytheon	
14	SPS System Evaluation Phase III - Rectenna Technology Study		—Δ	NASA-JSC	Boeing	G.E. Raytheon	D180-24635-1 PT-5155
15	SPS & Alternate Technology Comparisons		Δ	ANL	UE&C Inc.	Consultant	UE&C-ANL-79031
16	Crossed Field Directional Amplifiers For Use in the Solar Power Satellite		Δ	In-House			
17	SPS Pilot Beam & Communication Link Study		Δ	NASA-MSFC	Raytheon		NAS8-33157
18	SPS Pilot Beam Ionospheric Effects Discussion of Critical Issues		Δ	In-House			Draft 6/79
19	Solid State SPS Microwave Generation and Transmission Study		Δ	NASA-MSFC	Raytheon		
20	Magnetron Tube Assessment		Δ	NASA-MSFC	Raytheon		