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Comparative Analysis of the Space Power Architecture Studies

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COMPARATIVE ANALYSIS OF THE SPACE POWER ARCHITECTURE STUDIES

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SUMMARY

The Strategic Defense Initiative Organization (SDIO) has recently completed the initial phase of Space Power Architecture Studies (SPAS). The initial effort consisted of three major contracted efforts and a comparative analysis performed by the SDIO Independent Evaluation Group (IEG) and the IEG Field Support Team. The purpose of the SPAS effort was to evaluate a wide range of power systems for SDIO applications using a wide range of attributes other than power-system mass and volume. Open cycle, closed cycle, and closed power system/weapon platform concepts were studied.

The purpose of this paper is to summarize the salient results of these studies, identify important trends and future study needs.

INTRODUCTION

The new system concepts and technologies being considered for the Strategic Defense Initiative require the development of space power systems with capabilities that significantly exceed that which could be provided by simple extensions of existing technology. The power levels required are orders of magnitude greater than those of present space-based systems and preliminary studies indicate that the power subsystem mass could possibly exceed that of the balance of the platform. In addition, the operational capabilities of the spacecraft/weapons platform could be severely compromised by the dynamic loads, thrust vectors, or effluents introduced by power subsystem operation. The development of efficient, lightweight, compact, reliable power systems with the capability to supply the large amounts of power required for pulsed applications, and to survive the natural environment and hostile threats presents a major technical challenge to the space power community. A vigorous program is being carried out to develop the components and technologies necessary to bring these systems to fruition.

However, it was strongly felt the data base must be developed to show that the power systems and components developed will not have an adverse impact on the spacecraft/weapon platforms and that they are inherently survivable to natural and hostile threat environments. These studies are focussed on multimegawatt (MMWe) level power systems (10's to 100's of megawatts).

Early studies on power systems of this type evaluated power system options from the point of view of minimum system size and mass, leading to the result that open-cycle chemical or nuclear driven gas turbines was the only system of choice. Full consideration has generally not given to other power system-weapon related issues such as high voltage effects, effluent management, dynamic interactions, natural and induced environments, thermal management, and survivability which are equally important. This is generally due to a lack of knowledge of the specific user requirements at the time of these earlier studies.

The purpose of the Space Power Architecture Studies was to reassess the options for providing megawatt levels of power, giving full consideration to these concerns and other power system attributes shown in figure 1.

The study was managed for SDIO by the Air Force Space Technology Center and implemented by contracting teams lead by General Electric, Martin-Marietta, and TRW. The contractor results have been analyzed by the IEG Field Support Team at Sandia National Laboratory and NASA Lewis Research Center and the salient results are summarized herein.

SPAS KEY ELEMENTS

The flowchart for the Space Power Architecture Studies is shown in figure 2. Initially detailed requirements were developed for the combined power system/user platform. User platforms considered were Neutral Particle Beams (NPB), Electromagnetic Launchers, Free Electron Lasers, Orbit Transfer Vehicles, NPB Discriminators and Surveillance Satellites. Requirements were generated for the needed power levels and run times, but of key importance was the generation of absolute limits on the ambient pressures, temperatures, radiation, vibrations, electromagnetic interference, etc. required for successful operation of the integrated platform. This information is absolutely necessary to determine if the platform can function properly when engulfed in effluent from various open-cycle power systems.

Candidate power systems options that could be developed to meet these requirements were screened and the most attractive options chosen for detailed conceptual design. Once the conceptual designs were completed, issues concerning the concept survivability to the natural, hostile, and self-induced environments were investigated. The advantages, disadvantages of each option, the technical feasibility issues, necessary mitigation techniques, or technology development needs to resolve these issues, potential synergisms, and adverse impacts on the user, were all identified and folded into a figure-of-merit for each power system option.

Power System Options

After the initial screening of concepts 29 power system detailed conceptual designs were generated. Since it was desirable to have overlap between the various contractor results not all the cases were unique. Cases were chosen to investigate the broadest range of nuclear and chemical heat sources and a wide variety of energy conversion options. Because it was felt that the power system effluents could be a major discriminator between systems, or indeed could be a major factor in the successful operation of the platform, the effluent issue was strongly considered in the selection of cases.

The effluent options considered are shown in figure 3. In all cases it was assumed that H_2, used to cool the weapon would be available to the power systems. In the first case shown in figure 3 the weapon uses hydrogen from the weapon and effluent from both the power system and weapon are allowed. In the second case only hydrogen effluent from the weapon is allowed, and finally the platform is closed and there is no effluent. This latter case was investigated to identify the penalties associated with being unable to resolve or mitigate the problems associated with a pure hydrogen effluent.

The power systems chosen for detailed conceptual design are listed in figure 4.

The pulsed power options are divided into open-cycle nuclear and chemical, closed-cycle nuclear and chemical, steady-state and storage options. The options are characterized by heat source/conversion/effluent (see key on lower portion of figure 4). The operating temperatures are also listed for the 5 MWe steady-state power systems considered. All contractors considered the NDR/GT/H reference case, TRW used the NDR with MHD thus significantly increasing the output temperatures of the NDR. General Electric looked at an advanced gas-cooled, pebble-bed reactor and MHD. All contractors studied hydrogen-oxygen combustion-gas turbine combinations. General Electric and Martin-Marietta studied the cases where water was contained in the effluent and TRW and Martin-Marietta looked at cases where the water was removed and the effluent was pure hydrogen. These cases would be the chemical equivalent of the nuclear open-cycle gas-turbine cases if water were found to be an unacceptable effluent. Open-cycle HO and gel MHD systems were investigated with complex effluents due to the chemistry and seed necessary for high conductivity and an open-cycle lithium-acid battery was studied by General Electric.

Three closed-cycle nuclear power system options were studied: thermionics coupled with thermal energy storage in salts with eventual radiation to space, a liquid metal reactor with thermionic energy conversion and a radiator, and a Rankine system. Closed-cycle chemical options include HO fuel cells with either ice storage or a radiator, a lithium thionyl chloride battery and a LiH/GT/Rad combination. In this latter case all the H_2 used to cool the weapon is reacted with the lithium and there is no effluent. This was the only approach to the no-effluent case that passed the initial screening. Finally the steady-state plus storage options were looked at where thermionic, SP-100, or liquid metal Rankine power systems supplied the baseload and recharge capability and the pulsed power was supplied by rechargeable batteries, flywheels, or fuel cells.

Study Results

Typical results for each of the cases considered by the contractors are shown in figures 5 through 9.

The contractor results as presented cannot be directly compared since they are for different run times and levels of technology. The results are consistent for each contractor, however, and all exhibit similar trends. The cases are identified by the code given in figure 4 and are further delineated into the open-cycle nuclear (OCN), open-cycle chemical (OCC), closed-cycle nuclear (CCN), closed-cycle chemical (CCC), steady-state with storage (SSS).

The lightest systems are the nuclear open-cycle systems with gas-turbine or MHD conversion, followed by open-cycle chemical with a variety of conversion systems. The Martin-Marietta results indicate that the penalty for water removal from a hydrogen-oxygen gas-turbine system may not be severe - thus providing a chemical open-cycle system that is reasonably competitive with nuclear options and still has a H_2 effluent. The chemical results shown in figure 6 will be greater than the nuclear when the fuel and oxidant are added. All results show the severe mass penalties for going to closed-cycle nuclear or chemical systems and steady-state with storage systems. The one exception the liquid metal reactor with fuel cell storage.

If one looks at the TRW and Martin-Marietta results it is seen that the power conditioning and control (PC/C) is a major discriminator between the systems that generate high-voltage ac and low-voltage dc. The NPB is assumed to require 100 kV dc in this case. General Electric assumed major technological advancements in PC/C and it was not a factor in their results.

Taking all the contractor results for the pulse power applications as received, the specific mass envelopes for the various open, closed, and steady-state options are shown in figure 8 as a function of run time.

Putting the results on a consistent basis, eliminating concepts that are clearly noncompetitive, and folding in the IEG Field Support Team data base the envelopes for the most attractive options for each approach are as shown in figure 9.

The figure shows the typical specific mass penalties associated with either closing the power system or the entire platform. The steady-state systems indicated at the top of the figure allow continuous generation of 100's of megawatts, but still have hydrogen effluent from the weapon. As one goes to longer run times it is clearly obvious that every effort should be made to mitigate the effluent problem.

Power Conditioning and Control

The results presented in figures 8 and 9 do not include estimates for power conditioning and control (PC/C). PC/C can be a major discriminator between power system options. System specific masses for the most attractive open cycle systems without PC/C are shown in figure 10 as a function of run time. The figure shows that all the systems are reasonably competitive. However, if one is required to supply 100 kV dc to a NPB the lower voltage dc output systems (fuel cells, MHD) would have a significantly more complex PC/C system. Revised results using the FST estimates for PC/C are shown in figure 11. The figure shows that the relatively low-voltage systems now have significantly higher specific masses. The results would be somewhat reversed if solid-state devices were used to drive the RF for the NPB and low-voltage dc were required.

There are other PC/C factors that will also have a strong impact on the eventual choice of power systems. They are start-stop capability, fault protection, required load following or smoothing, etc. Until all the requirements for these factors are known it would be premature to select any of the open-cycle options at this time. However, an aggressive effort is being made to identify the key PC/C component development needs and high pay-off items and ensure that the necessary development projects are in place. Success in this area will diminish the impact of PC/C on the choice of power system.

Effluents

All contractor developed or had substantial code capability to examine the issue of effluents from the power system. However, none of these tools has, as yet been experimentally validated. Each contractor used high Mach number nozzles and/or plume shields to disperse the effluents from the platform and calculated the effluent density around the spacecraft such as shown in figure 12. The effluent issues are summarized in figure 13.

On a theoretical basis with the use of supersonic nozzles and/or plume shields to rapidly disperse and direct the effluent away from the platform and judicious location of the sensors, etc., it appears that H_2, O_2, and their molecular/ionic products will result in less than 1 percent attenuation of a NPB beam power and hence is no problem for this application. For sensors H_2O could be a problem although no conclusive evidence has been shown and ionization of the effluent cloud by a nuclear burst could result in an approximately 1 sec blackout transient. This latter effect also can produce a short time directional interference of communication systems. While effluents may effect certain sensor and communications systems it appears that proper effluent selection, power system design, platform position, and view angle can alleviate many potential problems.

Only the effect H_2, O_2, and their molecular/ionic products were studied in detail in the SPAS. Other effluents such as the cesium used in the MHD systems require further study.

The scope of the SPAS was such that only a cursory examination of the platform/effluent issue was possible. Further study is required particularly in the area of hostile threats, trapped charged particles, weapon operational environments, and nozzle induced vibrations.

Platform Dynamics

The platform dynamics issues and conclusions are summarized in figure 14.

In general, the SPAS contractors identified a wide variety of potential disturbances but they need better characterization which will require more detailed platform description. The major issue appears to be low-frequency vibration associated with open-cycle systems. These vibrations will make it difficult to meet directed energy weapon (DEW) pointing and jitter requirements. Orders of magnitude in mitigation are needed to reduce disturbances and this requires major technology advances. Analytical tools to study the problem are available but will give no different answer than is now available until a more detailed definition of the platform is obtained.

A greater interactions with users is needed to quantify and resolve issues.

Survivability

The survivability issues are summarized in figure 15. The contractor studied in varying degrees of thoroughness, survivability issues due to meteoroids, debris, pellets, solar UV; and radiation, neutral, plasma, electromagnetic, and thermal environments caused by natural, platform induced, and/or hostile events. Of these effects the most stressful, due to their presence during the entire lifetime of the platform, and hence, high fluence, are the debris/meteoroids and radiation. Shielding the platform against these hazards was considered to be the major survivability design driver. Hostile threats pose additional problems which need better definition and additional study.

Another important area that was addressed but needs further study is the interaction of the weapon-generated, high-voltage, and strong electromagnetic fields with the platform natural space environment and effluent clouds. The EM fields are orders of magnitude greater than have been previously studied. Methods for providing long term electrical insulation in this environment also need further study.

Many of the analytical tools for addressing the survivability issues are in place and others, along with a data base, are being developed under a SDI/SPO study.

CONCLUDING REMARKS

The SPAS were a sound beginning to what must be a continually evolving study and evaluation of space power systems for SDI applications. The study developed a preliminary data base and some analytical tools which will aid follow-on studies to resolve outstanding issues, satisfy new and/or revised requirements arising from better program and/or component definition, and provide the next level of system design detail and downselection. However, as in any good preliminary study with broad scope, but limited time and funding, it has raised as many questions as it answered. More study is needed before a definitive decision on SDI power systems can be made.

Unresolved issues requiring further and/or more detailed study involve effluents, platform dynamics, load following, and power conditioning systems including cooling scenarios. While many of the tools are in place to resolve these issues, some new and more detailed modeling is required. Most important, however, is the need for experimental verification of these analytical tools.

A number of the unresolved issues require more detail and interaction with weapon and sensor developers in order to resolve interface and/or integration issues. A mechanism for implementing this would be to develop a detailed, integrated power/weapon/sensor system platform design coordinated between power/weapon/sensor developers.

A major goal (because of its high payoff, if successful) is to solve and/or mitigate the open-cycle problems. A major technology effort to address open-cycle issues should be continued and/or initiated.

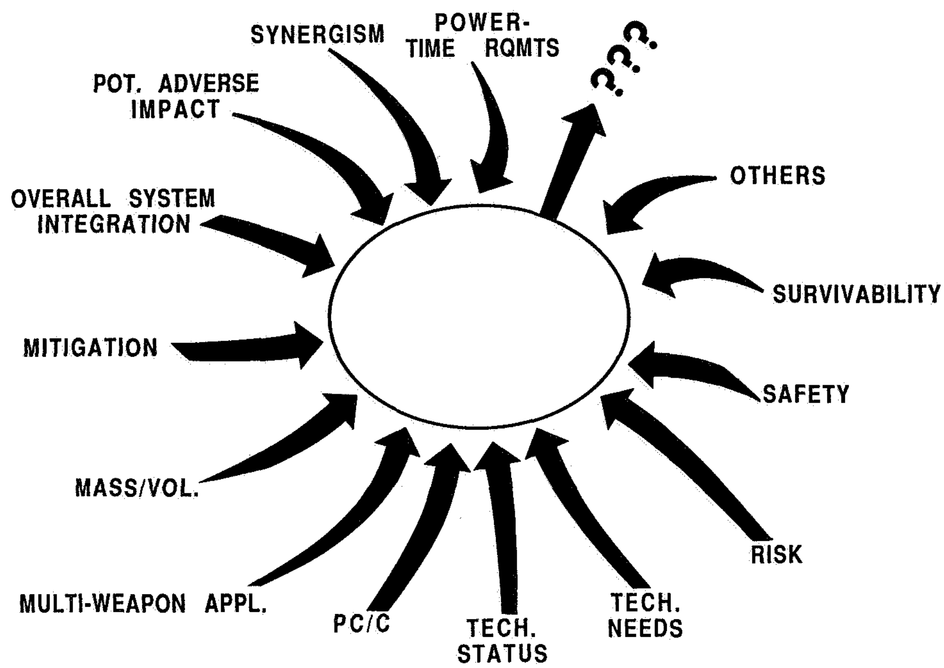

FIGURE 1. - SPACE POWER EVALUATION FACTORS.

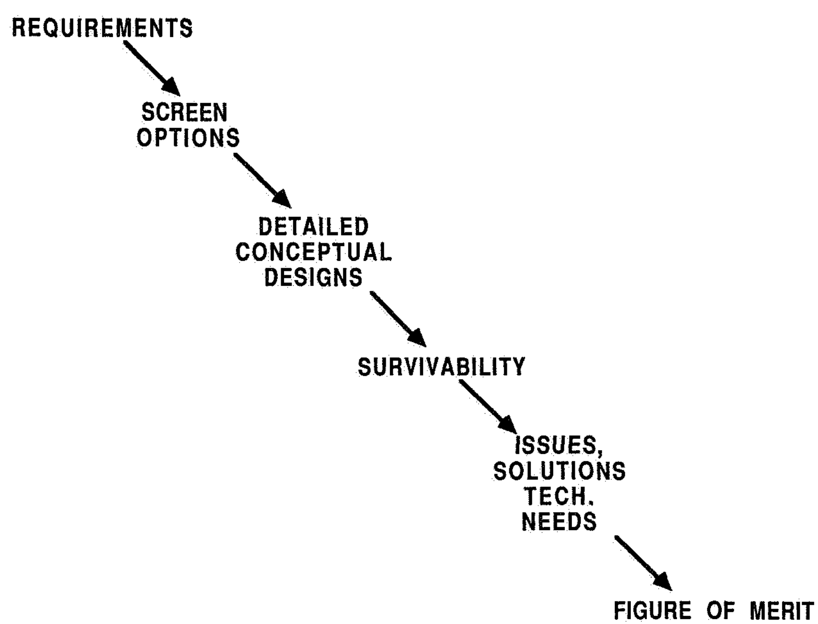

FIGURE 2. - SPACE POWER ARCHITECTURE STUDY FLOWCHART.

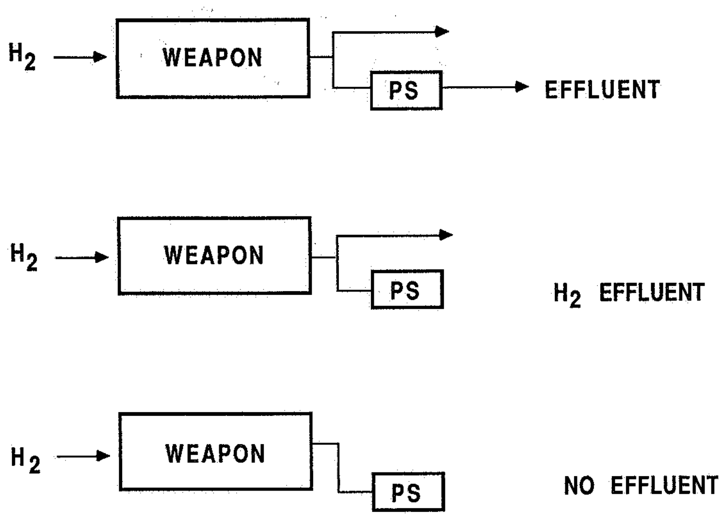

FIGURE 3. - SPAS POWER SYSTEM EFFLUENT OPTIONS.

PULSED POWER SYSTEMS - 100's MWE

(TRW)	(GE)	(MM)
	OPEN CYCLE CHEMICAL	
H_2O_2 COMBUSTION, GAS TURBINE, HYDROGEN GEL FUEL, MAGNETOHYDRODYNAMICS, COMPLEX	H_2O_2 COMBUSTION, GAS TURBINE, WATER LITHIUM-ACID, BATTERY, COMPLEX	H_2O_2 COMBUSTION, GAS TURBINE, HYDROGEN H_2O_2 COMBUSTION, GAS TURBINE, WATER H_2O_2 COMBUSTION, FUEL CELL, WATER H_2O_2 COMBUSTION, MAGNETOHYDRODYNAMICS, COMPLEX
	OPEN CYCLE NUCLEAR	
NERVA DERIVED REACTOR-GAS, GAS TURBINE, HYDROGEN NERVA DERIVED REACTOR-GAS, MAGNETOHYDRODYNAMIC, COMPLEX	NERVA DERIVED REACTOR-GAS, GAS TURBINE, HYDROGEN PEBBLE BED REACTOR-GAS, MAGNETOHYDRODYNAMIC, COMPLEX	NERVA DERIVED REACTOR-GAS, GAS TURBINE, HYDROGEN
	CLOSED CYCLE NUCLEAR	
THERMIONIC, THERMAL STORAGE, RADIATOR (NO EFFLUENT)		LIQUID METAL REACTOR, THERMIONIC, RADIATOR (NO EFFLUENT) LIQUID METAL REACTOR, RANKINE, RADIATOR (NO EFFLUENT)
	CLOSED CYCLE CHEMICAL	
LITHIUM-HYDROGEN, GAS TURBINE, RADIATOR (NO EFFLUENT) H_2O_2 COMBUSTION, FUEL CELL, ICE	LITHIUM-THIONYLCHLORIDE, BATTERY	H_2O_2 COMBUSTION, FUEL CELL, RADIATOR (NO EFFLUENT)
	SS + STORAGE	
THERMIONIC, LITHIUM/METAL SULFUR, BATTERY	SP-100, FLYWHEEL LIQUID METAL REACTOR, FUEL CELL	
	STEADY-STATE POWER SYSTEMS 5 MWE	
NERVA DERIVED REACTOR-GAS, BRAYTON (1700) LIQUID METAL REACTOR, THERMIONIC (1900)	LIQUID METAL REACTOR, AMTEC (1300) LIQUID METAL REACTOR, RADIATOR (1430)	LIQUID METAL REACTOR, THERMIONIC (1900) LIQUID METAL REACTOR, RADIATOR (1500)

FIGURE 4. - SPAS POWER SYSTEM OPTIONS.

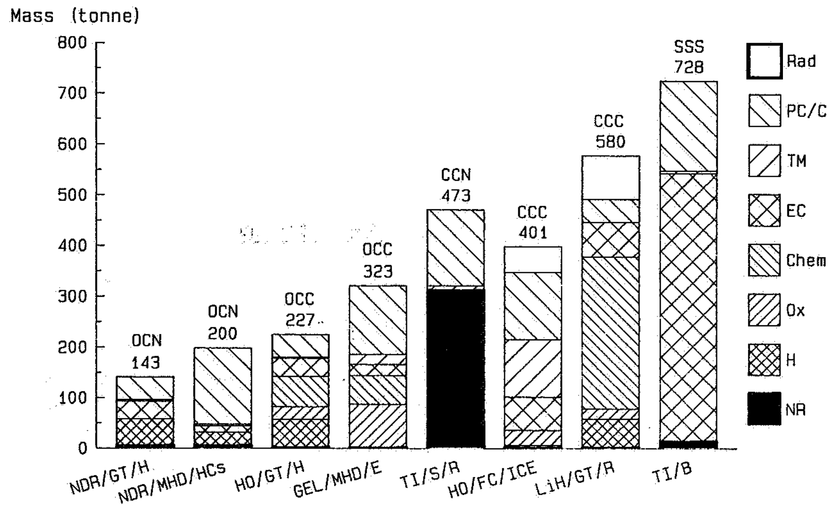

FIGURE 5. - TRW RESULTS FOR PULSED POWER SYSTEMS (NPB, 400 MWE).

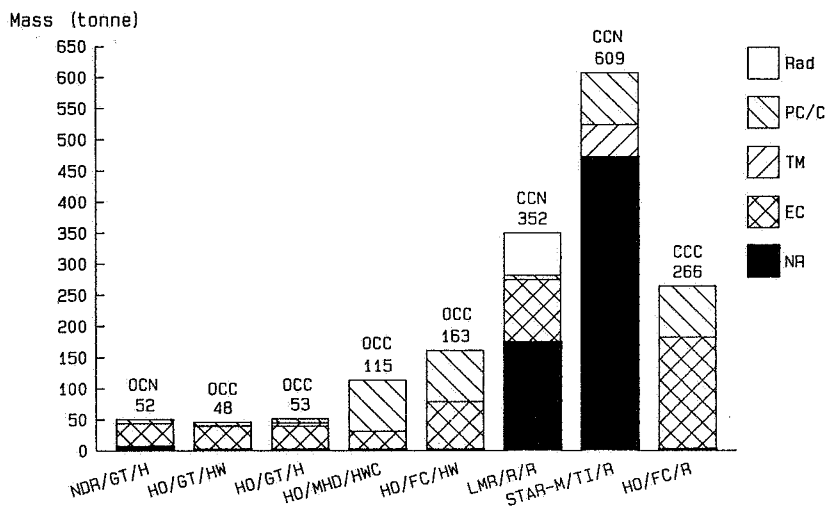

FIGURE 6. - MARTIN MARIETTA RESULTS FOR PULSED POWER SYSTEMS (NPB, 400 MWE, DRY MASSES).

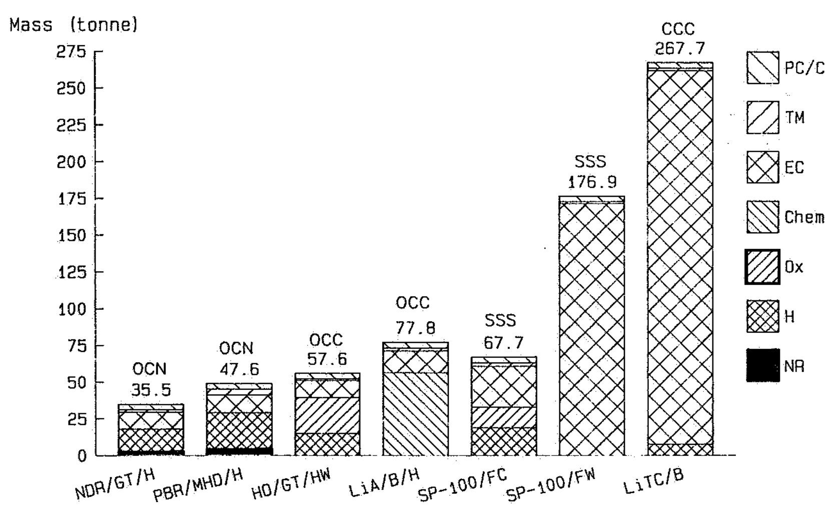

FIGURE 7. - GENERAL ELECTRIC RESULTS FOR PULSED POWER SYSTEMS (NPB, 200 MWE).

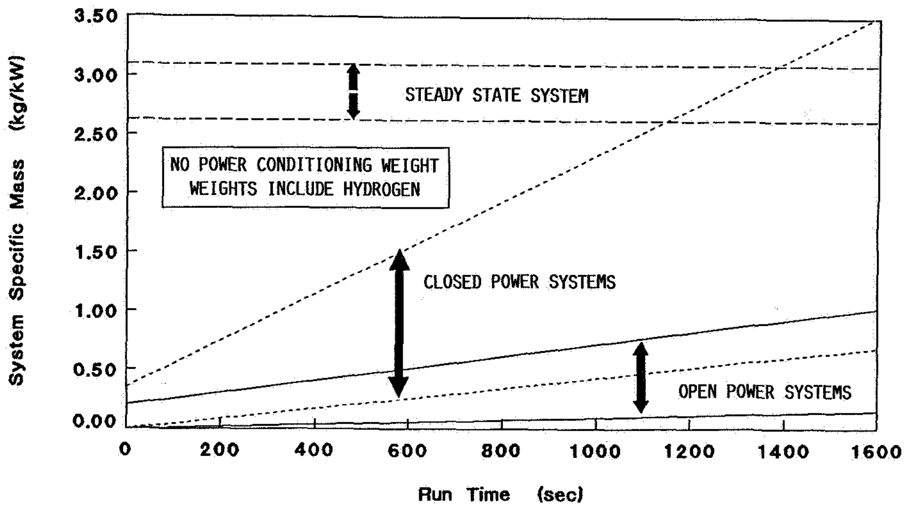

FIGURE 8. - PERFORMANCE ENVELOPES FOR POWER SYSTEM OPTIONS.

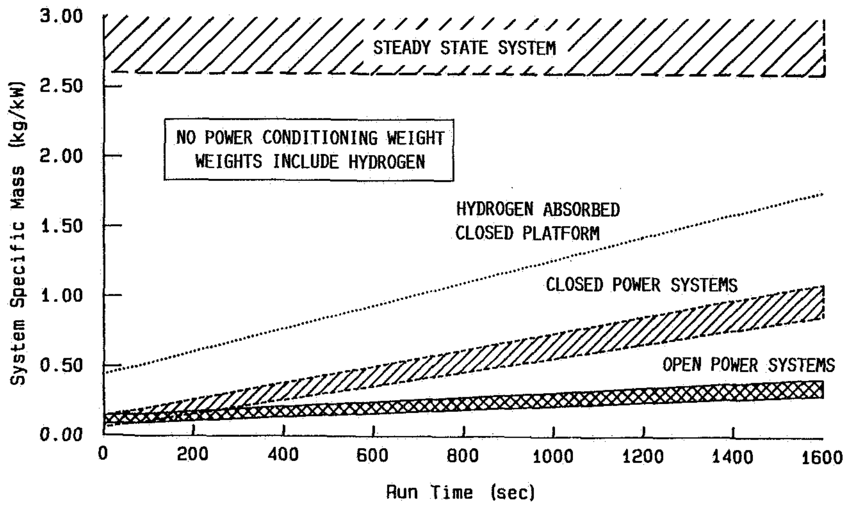

FIGURE 9. - REVISED PERFORMANCE ENVELOPES.

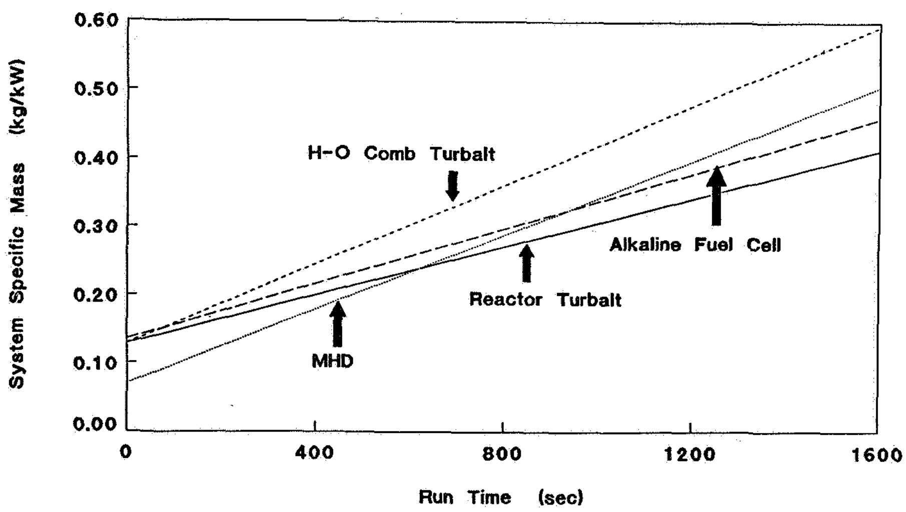

FIGURE 10. - POWER SYSTEM SPECIFIC MASS VERSUS RUN TIME WITHOUT POWER CONDITIONING AND CONTROL.

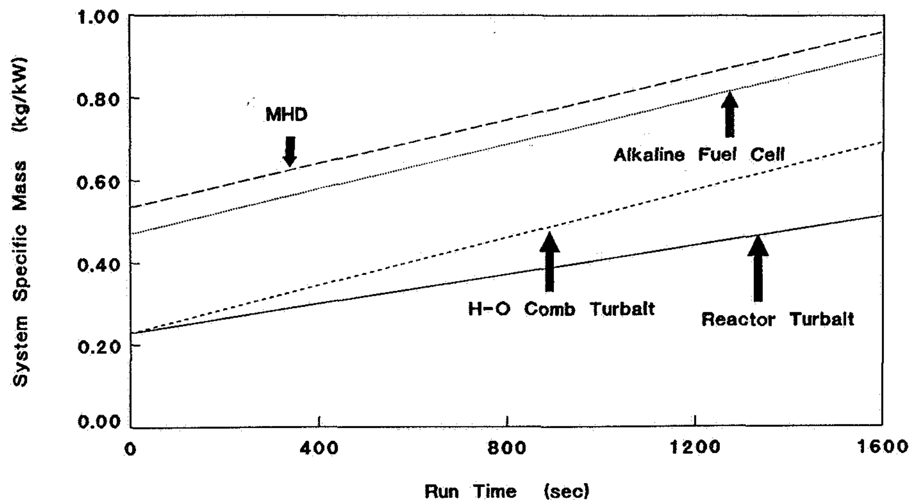

FIGURE 11. - OPEN CYCLE POWER SYSTEM SPECIFIC MASSES WITH POWER CONDITIONING AND CONTROL.

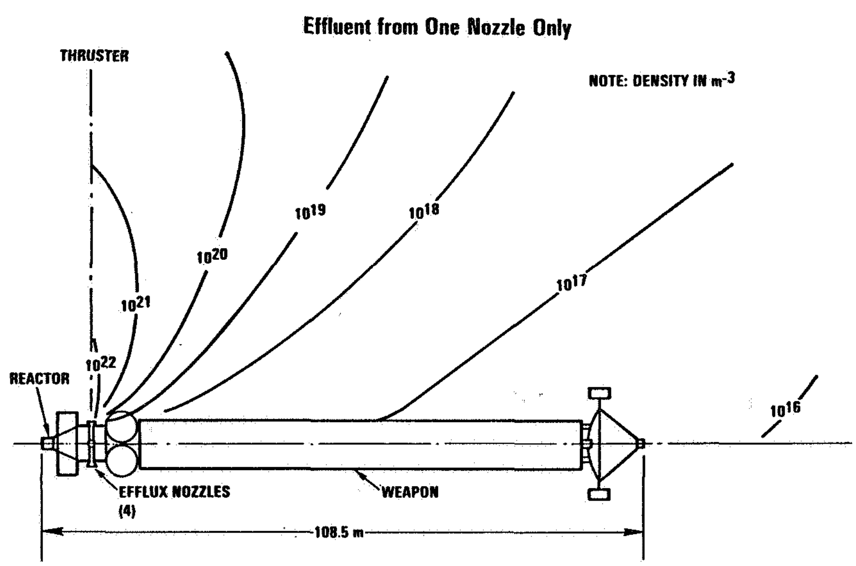

FIGURE 12. - NEUTRAL H_2 NUMBER DENSITY - EXAMPLE FOR GAS TURBINE GENERATOR.

- SOME ANALYTICAL TOOLS AVAILABLE/NEED VALIDATION
- NEED TO DEVELOP EXPERIMENTAL DATA BASE
- THEORETICALLY - USING SUPERSONIC NOZZLES AND/OR PLUME SHIELDS

NPB ATTENUATION	H_2, H_2O	NO PROBLEM
	H_2, NAT H_{2+}	NO PROBLEM
	EFFECT H_2O INCONCLUSIVE	
	NUCLEAR BURST IONIZED CLOUD ≃ 1 SEC TRANSIENT	
COMMUNICATION	NUCLEAR BURST IONIZED CLOUD - SHORT TIME DIRECTIONAL INTERFERENCE	

  OTHER EFFLUENTS REQUIRE FURTHER STUDY

- MAY AFFECT SENSOR TYPE/DESIGN, PLATFORM POSITION/VIEW
- ONGOING DOE STUDY AT SPI SUPPORTS SPAS CONTRACTOR RESULTS
- FURTHER STUDY NECESSARY
  - HOSTILE THREATS
  - TRAPPED CHARGED PARTICLES
  - WEAPON OPERATIONAL ENVIRONMENTS
  - NOZZLE INDUCED VIBRATIONS

FIGURE 13. - SUMMARY OF EFFLUENT ISSUES.

- WIDE VARIETY OF DISTURBANCES/NEED BETTER CHARACTERIZATION
  MAIN ISSUE - LOW FREQUENCY VIBRATION FROM OPEN CYCLE SYSTEMS
- WILL BE DIFFICULT TO MEET DEW PLATFORM POINTING AND JITTER REQUIREMENTS
  - NOT IMPOSSIBLE
- ORDERS OF MAGNITUDE IN MITIGATION NEEDED TO REDUCE DISTURBANCES
  - REQUIRES MAJOR TECHNOLOGY ADVANCES
- ANALYTICAL TOOLS AVAILABLE
- NEED BETTER MORE COMPLETE PLATFORM DESIGN
  - MORE INTERACTION WITH USERS TO QUANTIFY/RESOLVE ISSUES

FIGURE 14. - SUMMARY OF PLATFORM DYNAMIC ISSUES.

- DEBRIS/METEOROID AND RADIATION SHIELDING ARE DESIGN DRIVERS
- HOSTILE THREATS POSE ADDITIONAL PROBLEMS
- NEED IMPROVED UNDERSTANDING OF STRATEGIES FOR HIGH VOLTAGE AND STRONG FIELD SYSTEM IN SPACE ENVIRONMENT
- SOME ANALYTICAL TOOLS IN PLACE
- SDIO/SPO STUDY DEVELOPING ANALYTICAL TOOLS/DATA BASE

FIGURE 15. - SUMMARY OF SURVIVABILITY ISSUES.

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