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Summary and Evaluation of the Strategic Defense Initiative Space Power Architecture Study

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ABSTRACT

The purpose of the Space Power Architecture Study (SPAS) was to identify and evaluate power subsystem options for multimegawatt electric (MMWE) space based weapons and surveillance platforms for SDI applications. These platforms included Electromagnetic Launchers (EML), Free Electron Lasers (FEL), Neutral Particle Beams (NPB), Radar Discrimination Systems (RDS) and Orbital Transfer Vehicles (OTV). SPAS did not define or design weapons or system architectures but did require the contractors to have power/weapon platform requirements traceable to an overall architecture meeting SDI mission requirements.

The SPAS was comprised of 6 Tasks. In the first Task the contractors derived the power system requirements based on in-house expertise, literature search and discussions with weapon and architecture developers. In Task 2 each contractor considered power subsystems meeting Task 1 requirements. From these the SPAS Project Office downselected to 10 different (some overlap) subsystems for each contractor to consider in Task 3 where more detailed conceptual designs for these subsystems were developed. These designs considered such power/weapon platform integration issues and tradeoffs as mass; dynamic and effluent issues, operation, service and maintainance; start up and shutdown; packaging, launch and/or space assembly; and other issues defined during Task 1. Power/weapon platform survivability to natural and hostile environments was considered in Task 4 and key technology issues and developmental needs were defined in Task 5. In Task 6 "Figure of Merit" computer modelling codes were developed for use in ranking these and other power subsystems against sets of attributes/detriments.

Both steady state and burst power systems were investigated. Steady state requirements of $<$1MWE (e.g., housekeeping and storage systems for burst) are adequately covered by the SP-100 nuclear space power system and hence were not addressed further in the SPAS study. Applications for steady power $>$1MWE were found for OTV's and surveillance platforms. Four steady state power systems were investigated: NERVA Derived Reactor (NDR) with Brayton power cycles and Liquid Metal Reactors (LMR) with Hytec, Rankine and Thermionic power cycles. Due to the major programmatic effort on burst weapon systems, data generated for these power systems was minimal. With mass as the discriminator little difference was found among them.

The majority of the burst power systems utilized H2 from the weapons and were either closed (no effluent), open (effluent release) or steady state with storage (no effluent). However, the "no effluent" refers to the power subsystem and for those cases in which the hydrogen needed for weapon cooling exceeds that needed by the power system the weapon still expells H2 overboard. The open systems included nuclear or combustion heat sources using turboalternator, magnetohydrodynamic, fuel cell or battery power conversion devices. Techniques were investigated for removing all but H2 from the products of the H2/02 combustion heat source. The closed systems used nuclear or combustion heat sources with thermionic, Rankine, turboalternator, fuel cell and battery conversion devices. For the combustion cases various techniques were employed to contain the exhaust products. The steady state systems with storage used the SP-100 or Star-M reactors as energy sources and flywheels, fuel cells or batteries to store energy for burst applications.

As with other studies the open systems are by far the lightest, most compact and simplest (most reliable) systems. However, unlike other studies the SPAS studied potential platform operational problems caused by effluents, vibration, etc.

The SPAS showed that on a theoretical basis with the use of supersonic nozzles and/or plume shields that the products of H2/02 combustion (H2, H20, 02, OH, etc) pose no problems for the power/weapon systems. However, water vapor could be a problem for sensors although no conclusive evidence has been shown. The ionization of the effluent cloud by a nuclear burst can result in a short blackout transient and/or directional interference of communications systems. Effluents from other than H2/02 combustion require further study.

Another major issue identified by the SPAS contractors was the low frequency vibration associated with the supersonic nozzles used to expel effluents from open systems. Mitigating these vibrations to meet directed energy weapon (DEW) pointing a jitter requirements will be a challenging problem. Orders of magnitude in mitigation are needed to reduce disturbances and this requires major technology advance. While analytical tools are available to study the problem their use awaits a more detailed definition of the platform to quantify and resolve issues.

The SPAS showed that the use of superconducting versus cryocooled accelerators in the weapon significantly reduces the quantity of hydrogen needed for weapon cooling. This can significantly impact power system technology needs since H2 requirements would be driven by the power system and not by the superconducting weapon. Another weapon driven power system descriminator was the use of tube type versus solid state RF generators. The former requires high voltage and would favor high voltage power supplies while the later requires low voltage and would favor low voltage power supplies since changing voltage requires the use of heavy transformers. However, cryocooling may reduce transformer and other power conditioning component masses and cause power conditioning to be less of a discriminator.

The SPAS studied, in varying degrees of throughness, survivability issues caused by natural, platform induced and/or hostile events. Of these effects the most stressful, due to their presence during the entire platform lifetime, and hence high fluence, are space debris, meteoroids and radiation. Hostile threats pose additional problems which need better definition and additional study. Also addressed but needing 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, and methods for providing long term electrical insulation in this environment also need further study.

The SPAS was a reasonable beginning to what must be a continually evolving study and downselect of 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, to satisfy new and/or revised requirements arising from better program and/or component definition, and to provide the next level of system design detail and downselection.

Acknowledgements

The Editors of this report wish to acknowledge the contributions of the staff of the NASA Lewis Research Center (LeRC), the Sandia National Laboratories (SNL) and the members of the SDIO Space Power Office Independent Evaluation Group (IEG) who participated in the review of the SPAS contractors and provided valuable input to this critique.

In particular the editors would like to recognize the contributions of D. Dobranich, D. Furgal, D. Gallup, S. Hudson, A. Marshall, R. Pepping and F. Thome who under the supervision and guidance of L. Cropp formed the SNL Team. L. Cropp deserves special recognition not only for his fine work in managing the SNL effort but for his significant technical contributions to many sections of this report.

The LeRC team was headed by J. Smith and consisted of contributors from many technical areas of the Laboratory. In particular D. Bents and B. McKissock from the Power Systems Integration Office; A. Juhasz from the Solar Dynamics and Thermal Systems Branch; C. Purvis, J. Roche and J. Staskus of the Space Environmental Effects Branch; and M. Ernst of the Structures Division.

Also recognition is deserved by J. Montgomery of the LeRC and C. Schmitt of the SNL who performed much of the typing and retyping of the many revisions and arranged travel for the many review meetings which took place during the course of this review.

Finally, while major contributors are identified with various sections of the report in the Table of Contents, much of the work was a group effort with significant contributions and review by members of the above mentioned groups.

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I. EXECUTIVE SUMMARY

I. Executive Summary

This critique of the Space Power Architecture Study (SPAS) has been made by personnel from the NASA Lewis Research Center (LeRC) and Sandia National Laboratory (SNL) for the Strategic Defense Initiative (SDI) Space Power Office (SPO) Independent Evaluation Group. The Study was conducted over a one year period beginning in December of 1986 by three prime contractors: General Electric, Martin-Marietta and TRW. The Air Force Space Technolgy Center (AFSTC) was the Contract Manager acting as agent for the SDI/SPO which was the funding organization.

The purpose of the SPAS was to identify and evaluate power subsystem options to provide power for multimegawatt electric (MMWE) space based weapons and surveillance platforms for SDI applications. These platforms included Electromagnetic Launchers (EML), Free Electron Lasers (FEL), Neutral Particle Beams (NPB), Radar Discrimination Systems (RDS) and Orbital Transfer Vehicles (OTV) However, SPAS was not a SDI weapons definition and/or design study - this information was derived from other sources. Nor was the SPAS a SDI system architecture study. However, the contractors were required to have power/weapon platform requirements tracable to an overall architecture meeting SDI mission requirements.

SPAS STUDY BOUNDS/FOCUS

Sandia NASA

- **WHAT IS IT**

  A STUDY TO IDENTIFY AND EVALUATE POWER SUBSYSTEM OPTIONS FOR PROVIDING POWER FOR MMW SPACE WEAPONS AND SURVEILLANCE PLATFORMS FOR SDIO MISSION APPLICATIONS (i.e., FEL, NPB, EML, RDS, OTV)

  FAR-TERM SYSTEMS REQUIREMENTS

- **WHAT IT ISN'T**
  - SDI WEAPONS DEFINITION AND DESIGN STUDY
    - WEAPONS KNOWLEDGE NECESSARY TO GENERATE REALISTIC REQUIREMENTS
    - ASSUMPTIONS MUST BE MADE TO LIMITED STUDY OPTIONS
  - SDI SYSTEM ARCHITECTURE STUDY
    - INVOLVEMENT IN SDI ARCHITECTURE STUDIES IMPORTANT TO PROGRAM PERFORMANCE
    - ARCHITECTURE TRACEABILITY IMPORTANT TO SPAS REQUIREMENTS CREDIBILITY
  - ASSESSMENT OF HOUSEKEEPING POWER REQUIREMENS AND OPTIONS
    - FOCUS IS MULTIMEGAWATT

JS88-006.2

SPAS Program Tasks

Task 1: Identification of User Requirements. Derive power subsystem requirements from in-house expertise, literature search and discussions with weapon and architecture developers.

Task 2: Identification of Power Subsystem Options. Each contractor then considered possible power subsystems meeting Task 1 requirements and downselected to the 15 best. The AFSTC with technology support from the SDI/SPO then downselected to 10 different (some overlap) subsystems for each contractor to consider in Task 3.

Task 3: Conceptual Designs of Space Power Subsystem Options, Conceptual designs for the power subsystems downselected to in Task 2 were developed with consideration of such power/weapon platform integration issues and tradeoffs as mass; dynamic and effluent issues; operation, service and maintainance; startup and shutdown; packaging, launch and/or space assembly; and other issues defined during Task 1.

Task 4. Power Subsystem Survivability. This Task addresses the survivability issues of the power/weapon platform associated with natural and hostile environments.

Task 5. Identification of Key Technical Issues, Potential Solutions, and Technology Development Needs. Evaluate present state-of-art and define program plans and schedules for key technology develoment and potential development costs.

Task 6. Development of Figure of Merit Models. Computer models for each power/weapon system with ranking against an array of possible attributes/detriments such that systems could be re-ranked against new missions and/or requirements.

SPAS PROGRAM TASKS

TASK 1: IDENTIFICATION OF USER REQUIREMENTS

FOCUS — TASK 2: IDENTIFICATION OF POWER SUBSYSTEM OPTIONS

TASK 3: CONCEPTUAL DESIGNS OF SPACE POWER SUBSYSTEM OPTIONS

TASK 4: POWER SUBSYSTEM SURVIVABILITY

FOCUS — TASK 5: IDENTIFICATION OF KEY TECHNICAL ISSUES, POTENTIAL SOLUTIONS, AND TECHNOLOGY DEVELOPMENT NEEDS

DEMO — TASK 6: DEVELOPMENT OF FIGURE OF MERIT

What Are We Discussing?

The contractors investigated steady state power systems for OTV and surveillance applications and burst power systems for operating EML, FEL and NPB weapons. Steady state housekeeping power requirements as determined by the contractors were in the few to few hundreds of KWE range and were required over the lifetime of the platform. These requirements were adequately covered by the SP-100 nuclear power system and hence were not addressed further in the SPAS study. Another requirement for steady state power was the possible need for an alert mode. This mode is associated with bringing the platform from the quiescent housekeeping mode up to and maintaining the platform in the battle ready mode. Such power could be required for heatup, cool down, increased refrigeration, high power sensors, etc. While this mode is ill defined at present, power requirements in the 1-10 MWe range and lifetimes of a year (system only activated during periods of crisis/impending threat) appear adequate. This mode of operation also fulfills the requirements for the OTV application and this application was the major driver for these power systems.

Burst power systems for weapon applications where applicable over a wide range of operating conditions with runtimes from 100's - 1000's of seconds at power levels in the 100's of MWe. The major effort of the SPAS was investigating these power systems and hence is the major emphasis of this critique.

The power/weapon/surveillance platforms considered in SPAS are not for near term SDI system architecture applications but are in the time frame of later deployments.

WHAT ARE WE DISCUSSING?

Sandia
NASA

SPACE POWER SYSTEMS

STEADY STATE	HOURS - YEARS 1 - 10's MWE
BURST	100's - 1000's seconds 10's - 1000's MWE

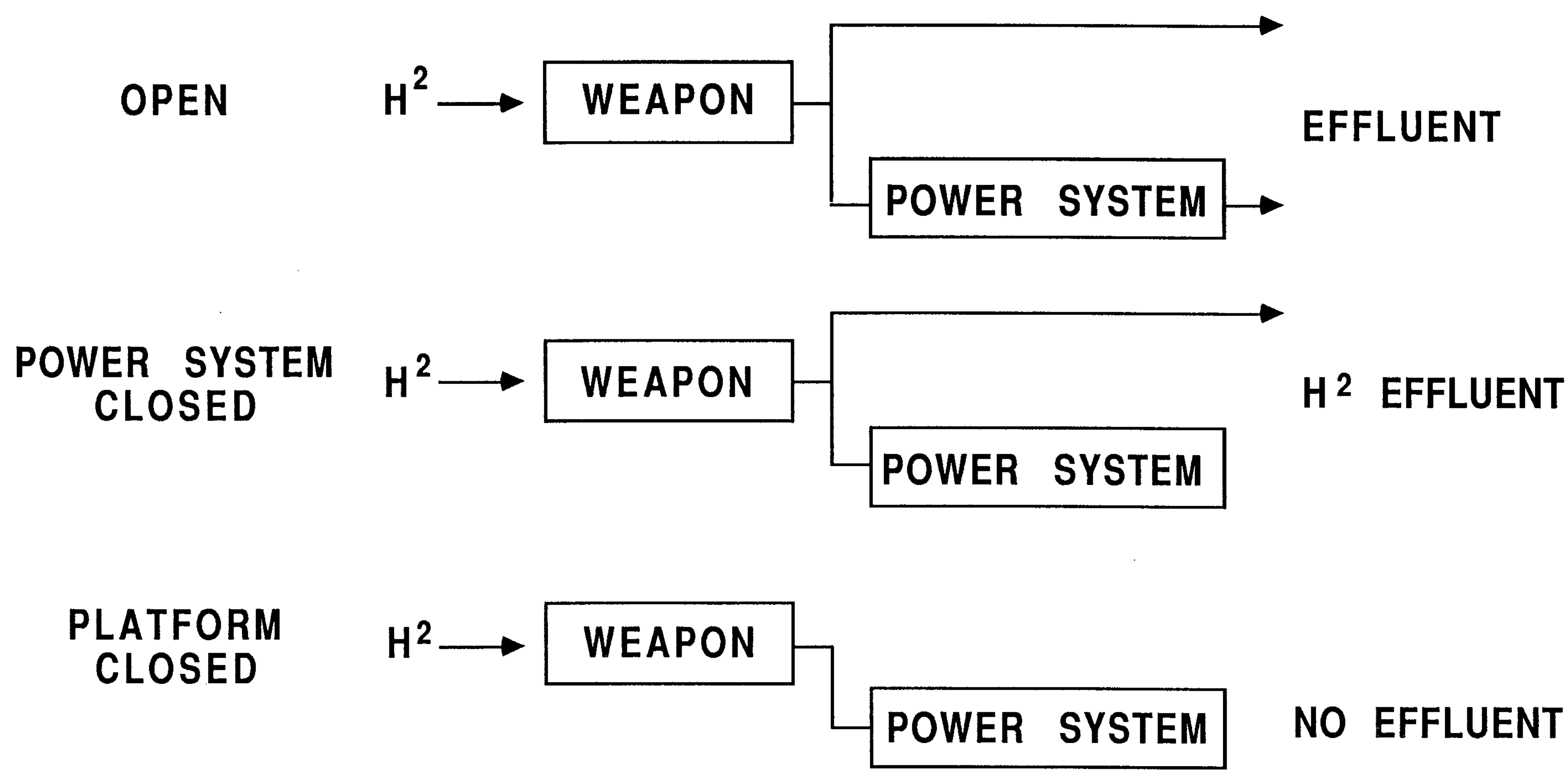
LATE PHASE DEPLOYMENT

JS88-006.1

SPAS Power Systems

The majority of the SPAS power systems utilized the H2 weapon coolant for their working fluid. Three general types of systems were investigated. In the first, the power system was open, dumping its H2 working fluid and other effluents overboard along with excess H2 from the weapon cooling system. In the second case the power system is closed. However, for the majority of cases where the weapon cooling load utilizes more H2 than is required by the power system, this excess H2 is dumped overboard so that the total power/weapon platform is not closed. In the third case, either the power system is closed and uses all the weapon H2 cooling fluid or the weapon is also closed. In this case the entire power/weapon platform is closed and no effluent is released.

SPAS POWER SYSTEMS



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Burst Systems Considered

This chart shows the burst cases considered by the contractors. While in Task 2 the contractors considered various gas-cooled reactor designs, only the NERVA reactor was considered in Task 3. This was not because the NERVA reactor was perceived better but because the study was not detailed enough to draw any conclusions regarding one design over another. All three contractors therefore to considered the NERVA derived reactor heat source using weapon H2 as a working fluid with a turboalternator power conversion unit (pcu) in an open cycle exhausting its H2 effluence to space. This provided a base reference case upon which to compare the contractors; in particular with regard to their respective technology time frames.

In the second System TRW interchanged a MHD generator for the turboalternator of System 1. The MHD generator is considered to be a direct competitor to turbines having the advantage that it is a static device with the potential for higher reliability and is not materials temperature limited. However, MHD has a potential drawback in that it requires a small molar percent seeding with an easily ionizable material such as cesium to produce an electrically conducting working fluid.

For System 3, GE analyzed a similar MHD generator case except they used a particle bed reactor as a heat source which in theory has faster response time and somewhat higher temperature capability than the NERVA reactor. The higher temperature is beneficial to the MHD system since it is not upper temperature material limited like turbines but is lower temperature limited by virtue of the strong temperature dependence of the eletrical conductivity of the H2/Cs working fluid.

A nearer term approach to providing MMWE weapon burst power than using a nuclear reactor is to carry O2 and burn the H2. The trade between nuclear and combustion depends upon deployment time frame, run time, cost and acceptance of H2O as an effluent. System 4 is the combustion alternative to System 1 but has the potential disadvantage of H2O effluent. System 5 removes the H2O by use of a heat exchanger which heats weapon hydrogen---part of it passing through the turboalternator and being exhausted to space while the other part is combusted stoichiometrically with O2 to form H2O. The H2O passes through the other side of the heat exchanger to heat the weapon H2 and inturn be cooled so that the H2O is condensed and stored as water. In this way the only effluent is H2 as in the nuclear System 1. System 6 removes the H2O effluent by using a titanium reactor after the H2-O2 combustor to reduce the working fluid to only H2 which then passes through the turbine and is exhausted to space.

System 7 is the combustion equivalent of Systems 2 and 3, but with the addition of the H2O effluent.

System 8 uses a H-O fuel cell in place of the combustion driven turbine or MHD generator considered in Systems 4 and 7 respectively.

In System 9, an MHD generator concept using beryllium gel as the fuel and inhibited red fuming nitric acid as the oxidizer is considered. The basic advantage of this system is that the fuel and oxidizer are storable at room temperature. It also could be advantageous for weapon/surveillance platforms which do not require H2 cooling (none were identified/considered in the SPAS). The major disadvantages are its non-use of readily available weapon H2 and the unknown effects of its various effluents.

Burst Systems Considered

System	TRW	GE	MM
Open Cycle Systems			
1. NDReactor-Turboalternator-H effluent	X	X	X
2. NDReactor-MHD-effluent	X		
3. PBReactor-MHD-effluent		X	
4. H-O Combustion-Turboalternator-H+W effluent		X	X
5. H-O Combustion-Turboalternator-H effluent			X
6. H-O-Ti Combustion-Turboalternator-H effluent	X		
7. H-O Combustion-MHD-effluent			X
8. H-O Fuel Cell-H+W effluent			X
9. Gel MHD-effluent	X		
10. Lithium Acid Battery-H effluent		X	
Closed Cycle Systems			
11. LMR-Thermionic-Radiator			X
12. LMR-Rankine-Radiator			X
13. THOR (Thermionic-LiH) -Radiator	X		
14. H-O-Ti-Li Combustion-Turboalternator-Radiator	X		
15. H-O Fuel Cell-Radiator			X
16. H-O Fuel Cell-Ice	X		
17. Lithium Thionyl Chloride Battery-Radiator		X	
Steady State with Storage			
18. SP-100-Flywheel		X	
19. SP-100-Fuel Cell		X	
20. Star M-Li Metal Sulfide Battery	X		

System 10 is a very advanced battery concept consisting of an alkali metal (lithium) anode, an acid feed supply and a rotary disk to remove heat and reaction products from the reaction zone at the anode surface. H2 is generated as a by-product of the electrochemical reaction, is separated from the electrolyte and vented as an effluent. This concept is in the very early stages of development.

Systems 11 and 12 were the fairly standard concepts of a liquid metal cooled reactor employing incore thermionics and an out-of-core Rankine turbine respectively. Both systems rejected heat via standard radiators.

The THOR concept considered as System 13 is another thermionic concept. In this case the reactor is formed by folding panels of individual reactor fueled, thermionic elements. When the panels are folded together the reactor goes critical and power is produced waste heat is stored in lithium-hydride which also serves as a moderator. When the panels are folded out to form a flat surface the reactor is no longer critical, no power is produced and waste heat is radiated away.

System 14 takes System 6 one step further by adding a Li reactor to react with the H2 exiting the turboalternator to form LiH2, which is condensed with waste heat being radiated away. This closes the power system, ie., no effluents are produced. However, if the weapon system requires more H2 than the power system then the total power/weapon platform will not be closed unless this additional H2 is removed. Indeed it too can be removed by the Li & H2 reaction as can the H2 effluent from any of the other systems previously discussed.

Systems 15 and 16 are H-O fuel cells operated such that the effluent is only H2O which is condensed and contained by use of a condensing radiator, a condensing heat exchanger using weapon H2 and/or stored ice.

The lithium thionyl chloride battery is a state-of=the-art device which has been used in the Minuteman Extended Survival Power Program. However, at its present state of development it is very heavy for the SPAS applications and serves only as a base point to compare other systems against near state-of-the-art batteries.

The last three Systems utilize the SP-100 (100KWe) power system to generate power over a long period of time and store energy in a flywheel, fuel cell (power an electrolyzer) or battery. High power for weapon burst is obtained by discharging the storage device over a short time.

Burst Systems Considered

	TRW	GE	MM
Open Cycle Systems			
1. NDReactor-Turboalternator-H effluent	X	X	X
2. NDReactor-MHD-effluent	X		
3. PBReactor-MHD-effluent		X	
4. H-O Combustion-Turboalternator-H+W effluent		X	X
5. H-O Combustion-Turboalternator-H effluent			X
6. H-O-Ti Combustion-Turboalternator-H effluent	X		
7. H-O Combustion-MHD-effluent			X
8. H-O Fuel Cell-H+W effluent			X
9. Gel MHD-effluent	X		
10. Lithium Acid Battery-H effluent		X	
Closed Cycle Systems			
11. LMR-Thermionic-Radiator			X
12. LMR-Rankine-Radiator			X
13. THOR (Thermionic-LiH) -Radiator	X		
14. H-O-Ti-Li Combustion-Turboalternator-Radiator	X		
15. H-O Fuel Cell-Radiator			X
16. H-O Fuel Cell-Ice	X		
17. Lithium Thionyl Chloride Battery-Radiator		X	
Steady State with Storage			
18. SP-100-Flywheel		X	
19. SP-100-Fuel Cell		X	
20. Star M-Li Metal Sulfide Battery	X		

SPAS Power System Comparisons

This chart compares the weights calculated by the SPAS contractors for the different classes of power systems by plotting specific mass as a function of run time.

Open systems are the lightest and fall in the area between the two lines marked "Open Power Systems".

The lightest system in the band is TRW's NDReactor MHD system and the heaviest is Martin Marietta's hydrogen-oxygen combustion MHD system. In general, analysis by the Field Support Team (FST) supports the contractors' weight estimates for these open systems. It should be pointed out, however, that there are a variety of technology assumptions in these weights. Martin Marietta made more conservative assumptions than either GE or TRW, and TRW was generally the most optimistic.

The band of weights between the two dashed lines, labeled "Closed Power Systems" represents weights the contractors calculated for the following systems:

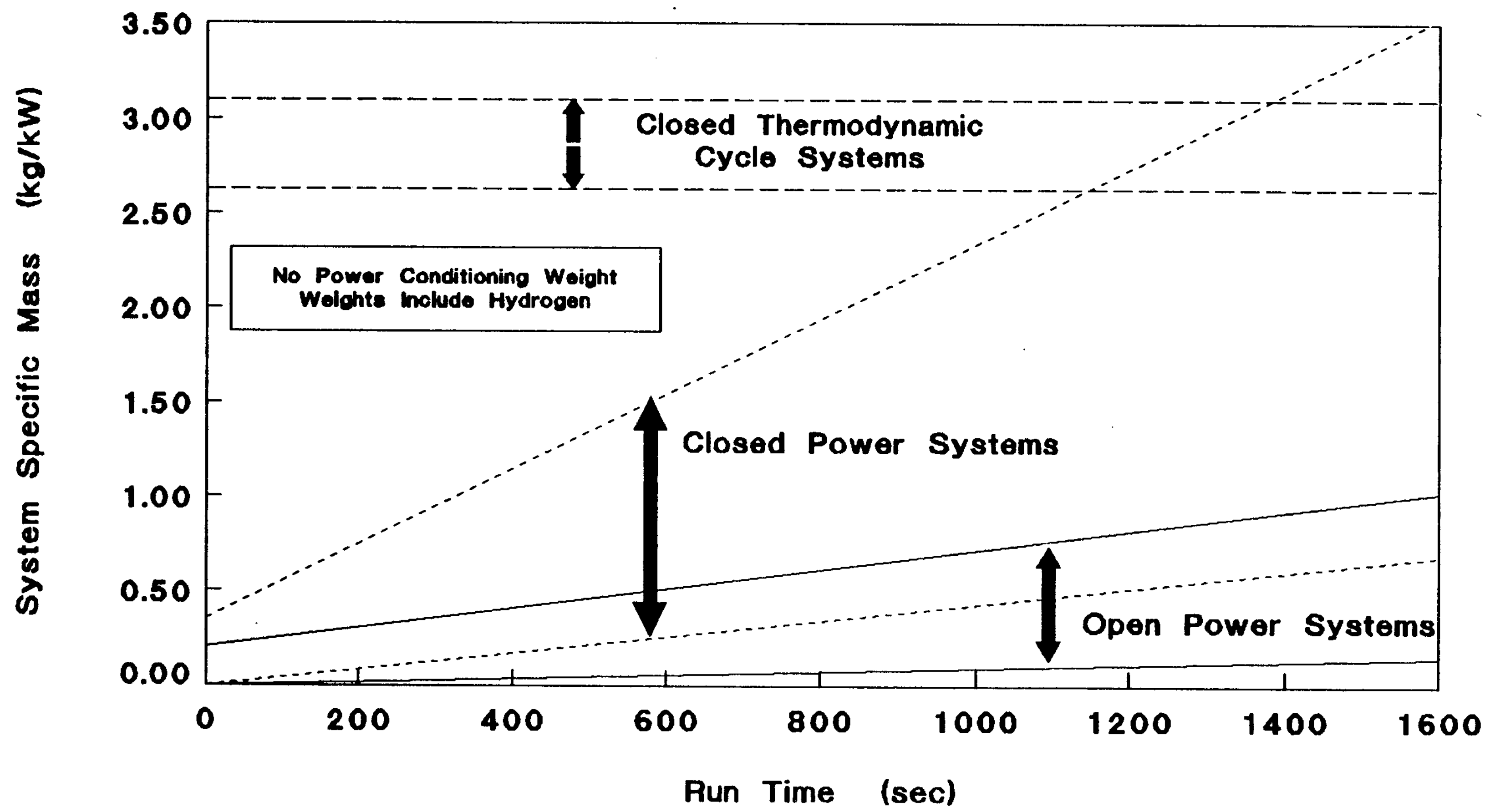
TRW Ice Cooled H-O Fuel Cell	MM Ice Cooled H-O Fuel Cell
TRW THOR Thermionic Reactor	GE Flywheel
TRW Closed Combust. Turboalt.	TRW Lithium-Metal Sulfide Battery

The lightest of these systems are the closed, ice cooled, fuel cell systems. But the weights do not agree well with weights the FST estimated for the same systems. The FST weights are somewhat heavier.

The band denoting "Closed Thermodynamic Cycle Systems" is for Martin Marietta's reactor powered Rankine and thermionic systems that use radiators to reject waste heat. The FST's weight estimates for these agree well with the contractor's estimates. However, the thermionic system was assumed to have a conversion efficiency of 27%, well beyond State-of-the-art.

The specific weights shown in this chart do not include power conditioning. The contractors had different philosophies regarding the power conditioning problem which grossly affects system weight. Therefore in order to compare power conversion systems of various contractors on a one-to-one basis, the same power conditioning must be used. In the chart shown here it was assumed to have negligible weight. While correct for comparing similar systems it may not be correct when comparing high versus low voltage systems. The subject of power condition and its effect upon power systems is discussed further, later in the "Executive Summary"..

Weight Depends on Whether the System is Open or Closed and on Run Time



Power System Issues

The SPAS generated some broad conclusions as to the status of MMWE space power systems for SDI applications in particular and space power in general. While many of the components are developed at lower power levels (watts/kilowatts) or for terrestrial applications they are not available "off-the-shelf" for the SDI applications considered in SPAS. The technology risk and development time/cost have not been factored in as a discriminator in these studies but could be a significant factor in a final downselect.

Open cycle systems are by far the lightest, most compact and simplest (most reliable) systems but can cause platform operational problems as a result of effluents. However, closing the power/weapon platform incurrs a large penalty on a weight basis. Therefore, there is a large payoff in solving/working around open cycle problems and this should receive top development priority.

While the SPAS probably did not answer all the questions it set out to answer, it developed a broad power system data base. Clearly the additional issues need to be addressed before a system downselect can be made. Therefore a focused technology program is premature at this time.

POWER SYSTEM ISSUES

- "OFF-THE-SHELF" COMPONENTS NOT AVAILABLE
  - ALL INVOLVE TECHNOLOGY RISK/DEVELOPMENT
  - TECHNICAL RISK/DEVELOPMENT VAIRES WIDELY AMONG SYSTEMS
- SYSTEM MASS
  - OPEN CYCLE NUCLEAR AND CHEMICAL SYSTEMS ARE LIGHTEST
  - CLOSING PLATFORM/POWER SYSTEM WEIGHT PROHIBITIVE
    - CHOICE OF LAST RESORT
  - PAYOFF IN SOLVING/WORKING AROUND OPEN CYCLE PROBLEMS
- SPAS DEVELOPED BROAD POWER SYSTEM DATA BASE
- SYSTEM DOWNSELECT/FOCUSED TECHNOLOGY PROGRAM PREMATURE
- NEED TO ADDRESS ADDITIONAL ISSUES

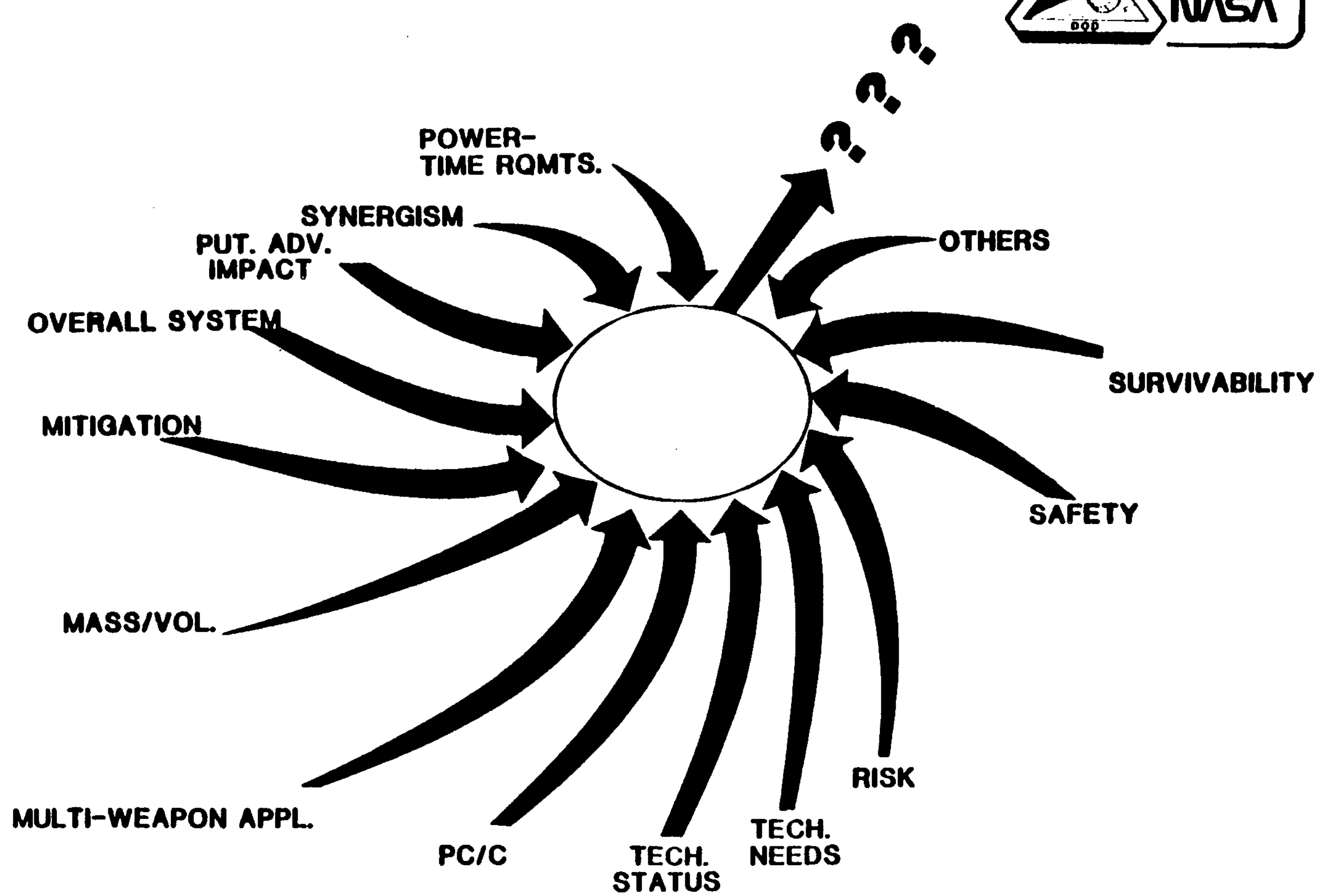
Space Power Evaluation

All studies of space power systems for SDI applications prior to SPAS compared systems based solely on a mass/volume optimization. The SPAS contract sought to address several of the other discriminators such as:

* Power Level
* Run Time
* Total Lifetime
* Number On-off Cycles
* Start Up Time (cold)
* Ramp Rates
* Dormancy
* AC or DC and Voltage
* Load Following
* Load Leveling
* Regulation
* Power Factor
* Max AC Harmonic Factor
* Maintainability
* Reliability
* Survivability
* Limits on Exhaust Products
* Environment Limit on Payload (Radiation, Thermal, Contamination Vibration, Electromagnetic
* Degree of Thrust Cancellation Required
* Cost Limits
* Mass and Envelope
* Degree of Mechanical Decoupling
* On-orbit Assembly
* Testing Requirements
* Safety

Of these discriminators the contractors identified effluents associated with the exhaust of weapon cooling and power system working fluids, platform dynamics arising from the incomplete cancellation of exhaust thrusts, power conditioning and thermal management requirements, and survivability against natural and hostile threats to be major discriminating issues which could affect system selection. These issues are discussed on following charts. The other discriminators, while not considered trivial, were considered to be of lesser importance. These are discussed at appropriate points throughout the main text.

SPACE POWER EVALUATIONS



Effluent Issues

As a result of the SPAS and studies addressing the effect of environment upon spacecraft performance, a number of analytical tools are available to analyze the effluent problem. However, all of these need experimental validation.

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 it appears that H2,O2 and their molecular/ionic products will result in less that a 1% attenuation of a NPB beam power. For sensors H2O 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 blockout 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 type selection, design, platform position and view can alleviate many potential problems.

Only the effect of H2, O2 and their molecular/ionic products were studied in detail in the SPAS. Other effluents such as the cesuim 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. Some of these issues are being addressed by SPI under a DOE contract.

EFFLUENT ISSUES

- 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
SENSORS	H_2, NAT H_2^+	NO PROBLEM
	EFFECT H_2O INCONCLUSIVE	
	NUCLEAR BURST IONIZED CLOUD $\simeq$ 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

- ON-GOING DOE STUDY AT SPI SUPPORTS SPAS CONTRACTOR RESULTS

- FURTHER STUDY NECESSARY
  - HOSTILE THREATS
  - TRAPPED CHARGED PARTICLES
  - WEAPON OPERATIONAL ENVIRONMENTS
  - NOZZLE INDUCED VIBRATIONS

Platform Dynamic Issues

The SPAS contractors identified a wide variety of disturbances but they need better characterization which will require more detailed platform description. The major issue appears to be low frequency exhaust nozzle 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 interaction with users is needed to qualify and resolve issues.

PLATFORM DYNAMIC 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

Power Conditioning May be an Important Discriminator Among Power Systems

Tube type RF generators presently look like the leading contender for NPB accelerator RF generation, particularly for the second and third stages where high frequency is needed. This is because tubes are more efficient than solid state devices for RF generation at high frequency. Tubes require high voltage power, around 100 kV. High voltage alternators can supply this voltage without using transformers. Low voltage sources will need transformers which are the heaviest components in a PC unit. Martin Marietta and TRW show large differences in mass between power conditioning units for high voltage alternators and for low voltage sources (see the power conditioning section of this report). This power conditioning mass difference gives a large advantage to high voltage turboalternator systems. The advantage is quantified on the chart following the facing chart. On the other hand, GE shows no advantage for high voltage turboalternators. They assume that transformers will be cryo-cooled and very light. The Field Support Team believes that GE's transformer mass assumption is optimistic, but that cryo-cooled transformers may remove some of the high voltage turboalternator advantage.

Solid state RF generators may be candidates for lower frequency applications such as for FEL accelerators. They need low voltage power and favor low voltage sources because high voltage sources will require step-down transformers. Again, the advantage may be reduced by using cryo-cooled transformers.

An area of considerable importance to the platform in general and to the power conditioning unit in particular that was not considered in the SPAS was the effect of load following and operational needs. Transients due to accelerator fault protection and to battle management may place additional requirements on power conditioning components and designs.

POWER CONDITIONING ISSUES

- **TUBE TYPE RF GENERATORS NEED HIGH VOLTAGE**

  HIGH VOLTAGE ALTERNATORS DO NOT NEED HEAVY TRANSFORMERS

  LOW VOLTAGE SOURCES NEED HEAVY TRANSFORMERS

  GE SAYS CRYO-COOLED TRANSFORMERS MAY NOT BE HEAVY

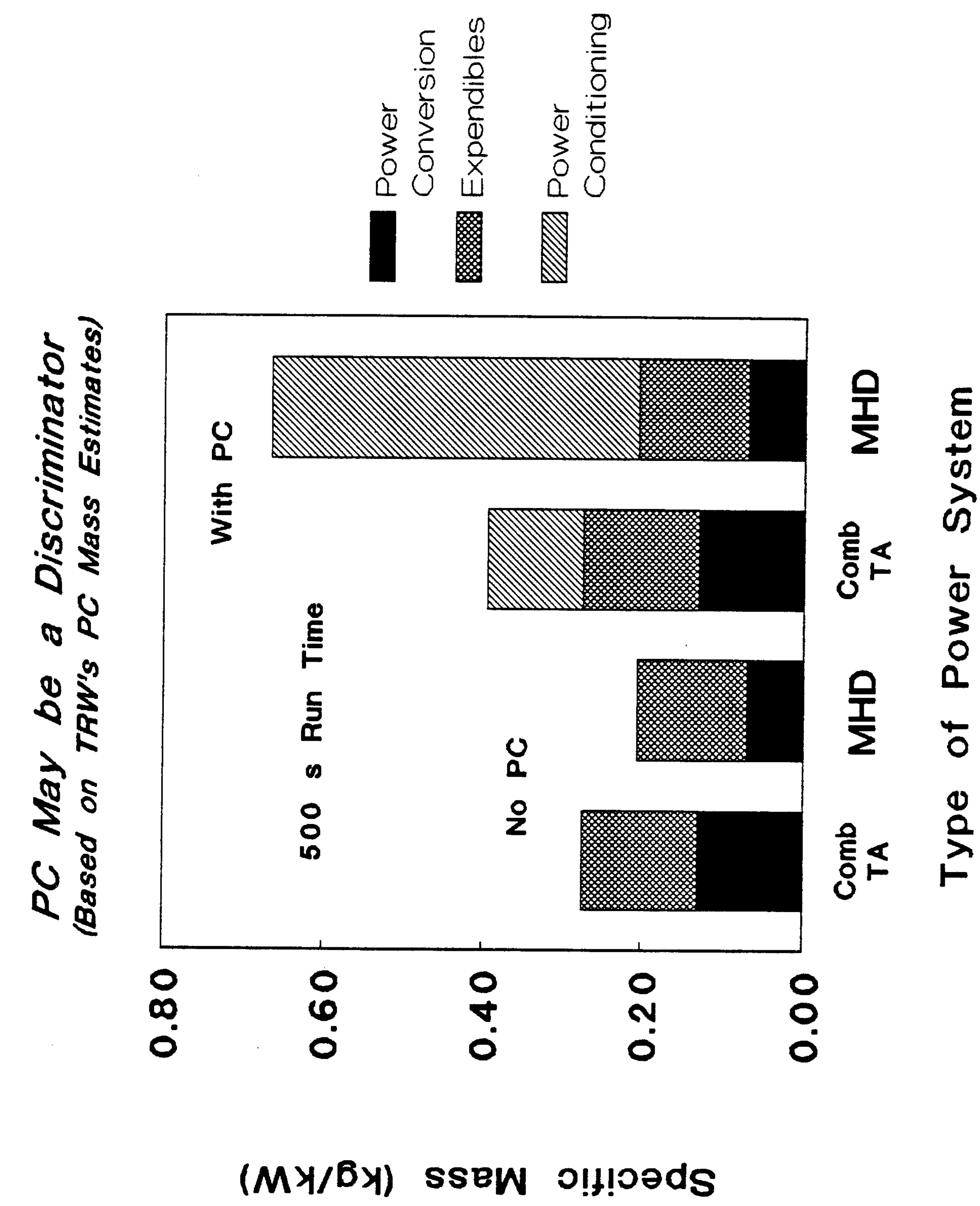
- **TUBE TYPE RF GENERATORS MAY FAVOR HV ALTERNATORS**
- **SOLID STATE RF GENERATORS NEED LOW VOLTAGE AND MAY FAVOR LOW VOLTAGE SOURCES**
- **THE EFFECT OF LOAD FOLLOWING AND OTHER OPERATIONAL NEEDS ON THESE COMPONENTS NEEDS FURTHER STUDY**

JS88-002

PC May be a Discriminator

This chart compares a combustion turboalternator system with a MHD system with and without the power conditioning mass added. Power conditioning clearly changes the relative mass of these two systems and is an important discriminator.

The masses for the turboalternator and MHD systems are simple averages of SPAS contractor results and are explained in the sections on burst power systems in this report. The average mass has little meaning because the three contractors used significantly different technologies and assumptions. However, using averages does effectively make the point about power conditioning. Power conditioning mass values were taken from TRW's report and are explained in the section on power conditioning later in this report.



PC May be a Discriminator
(Based on TRW's PC Mass Estimates)
Specific Mass (kg/kW)
0.80
0.60
0.40
0.20
0.00
500 s Run Time
No PC
With PC
Comb TA
MHD
Comb TA
MHD
Type of Power System
Power Conversion
Expendibles
Power Conditioning

Thermal Management Affects Power System Technology

The use of a superconducting versus a cryo-cooled accelerator in the weapon significantly reduces the quantity of hydrogen required for cooling. This in turn has a very significant impact upon the power system's technology needs. As an example, the cryo-cooled weapon uses sufficient hydrogen coolant so that a low temperature turbine can be used in the power system. For a superconducting accelerator, the hydrogen coolant is reduced to a level where the power system can benefit from using a high temperature turbine since higher inlet temperatures produce more work per unit mass of working fluid. If high temperature turbines are not used, the turbine will require additional hydrogen mass beyond that needed to cool the weapon at a substantial mass penalty.

All three contractors used cryogenic refrigerators to keep cryogens and the weapon cool while not in use. The refrigerators were not a significant contributor to platform mass, but such refrigerators do not exist and must be developed with a primary emphasis on reliability.

THERMAL MANAGEMENT ISSUES

- CRYO-COOLED ACCELERATORS NEED LOTS OF HYDROGEN COOLANT. HIGH TEMPERATURE TURBINES ARE NOT NEEDED.
- SUPERCONDUCTING ACCELERTORS NEED ONE-HALF AS MUCH HYDROGEN COOLANT. HIGH TEMPERATURE TURBINES MAY BE BENEFICIAL.
- CRYOGENIC REFRIGERATORS WILL NOT ADD SIGNIFICANT MASS BUT RELIABLE ONES MUST BE DEVELOPED.

JS88-001

Survivability

The SPAS 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 threats. 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 by the contractors but needs further study is the interaction of the weapon generated high voltage and strong electromagnetic fields with the platform natural space enviroment and effluent clouds. The EM fields are orders of magnitude greater than have been previously studied, and 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 funded study with S3/TRW.

SURVIVABILITY

- 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

Where Do We Go From Here?

The SPAS was a reasonable beginning to what must be a continually evolving study and downselect of 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 raised as many questions as it answered. More study is needed before a definitive downselect 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 modelling is required. Most important, however, is the need for experimental verification of these analytical tools.

A number of the unresolved issues require more detailed input from/ coordination 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 work around open-cycle problems. A major technology effort to address open cycle issues should be continued and/or initiated.

WHERE DO WE GO FROM HERE ?

- SPAS - RESONABLE BEGINNING
  DEVELOPED POWER SYSTEM DATA BASE/ANALYTICAL TOOLS
  RAISED MORE ISSUES THAN ANSWERED

- UNRESOLVED ISSUES - EFFLUENTS, DYNAMICS, LOAD FOLLOWING, POWER CONDITIONING OPTIONS

- TOOLS IN PLACE TO RESOLVE ISSUES/NEED EXPERIMENTAL VARIFICATION

- NEXT STEP - DETAILED, INTEGRATED POWER SYSTEM/WEAPON/SENSOR EFFORT
  - COORDINATED WITH USERS
  - RESOLVE INTERFACE/INTEGRATION ISSUES

- GOAL - SOLVE/WORK AROUND OPEN CYCLE PROBLEMS
  - MAJOR PAYOFF IF SUCCESFUL

II. INTRODUCTION

II. INTRODUCTION

This report represents a critique of the recently completed Space Power Architecture Study (SPAS) by personnel from the NASA Lewis Research Center (LeRC) and the Sandia National Laboratory (SNL). This group forms the Strategic Defense Initiative (SDI) Space Power Office's (SPO) Field Support Team (FST). The FST reports to the SPO's Independent Evaluation Group (IEG). The IEG is a small group of the senior technical personnel from various government agencies (DOE, DOD, NASA) which provides technical review and guidance to the SDI/SPO.

The SPAS contracts were let and managed by the Air Force Space Technology Center (AFSTC) as agent for the SDI/SPO which provided funding and technical direction. Capt. Efron Fornoles served as contract manager.

The purpose of the SPAS was to identify and evaluate power subsystem options that could provide power for multimegawatt electric (MMWE) space based weapons and surveillance platforms for SDI mission applications. The applications included Electromagnetic Launchers (EML), Free Electron Lasers (FEL), Neutral Particle Beams (NPB), Radar Discrimination Systems (RDS) and Orbital Transfer vehicles (OTV). However, SPAS was not a SDI weapons definition and/or design study. It was concerned only with power and the power/weapon interfaces. The SPAS also was not a SDI system architecture study, however, the contractors were required to have power/weapon platform requirements traceable to an overall weapon system architecture meeting SDI mission requirements.

Three contractors were chosen to participate in the 1 year SPAS. These along with the major subcontractors are listed below:

1. General Electric, Astro-Space Division (Contract Mgr., Mr. Wen Chiu)
   GE Aircraft Engine Group
   AVCO
   United Technologies Power Systems
   Rasor Associates
   AD Little
   GE Research and Development Center
   Lockheed Missiles and Space Co.

2. Martin-Marietta Space Systems (Contract Mgr., Mr. M.P. Dougherty)
   GA Technologies
   Sundstrand Corp.
   AVCO Research Laboratories
   United Technologies power Systems

3. TRW (Contract Mgr., Mr. A. Schoenfeld)
   General Atomics
   Westinghouse
   A. Research
   United Technolotges
   Maxwell Lab

The study was structured through six tasks.

Introduction

Space Power Architecture Studies

Technical Evaluation

Sandia--NASA/LeRC

Contractors: GE, Martin Marietta, TRW

The evaluation is based on oral task reviews, task documentation, and draft final reports.

Task 1: In Task 1 the contractors identified the requirements for the power systems for the various SDI applications. These requirements were generated through in-house expertise, published reports, and direct discussions with weapon developers. The data pertained to power levels, operating times, environmental and dynamic limits, cooling and power conditioning requirements, power/weapon interface issues, etc.

Task 2: In Task 2 the contractors were to identify and characterize potentially attractive power systems based on the defined SDI applications and their requirements as identified in Task 1. The contractors then downselected to the 15 most promising systems. A further downselect to 10 systems for consideration in Task 3 was made by the AFSTC with technical input from the SDI/SPO, SPO/IEG and IEG/FST.

Task 3: Task 3 involved the conceptual design of Power Subsystem Options for the 10 selected in Task 2, concentrating on power/platform integration issues and tradeoffs between mass; dynamic and effluent issues; operation, service and maintenance; startup and shutdown; packaging, launch and/or space assembly; and other issues defined during Task 1.

Task 4: This task addressed the survivability issues associated with the power/weapon platforms including the natural space environments at the operating orbit altitudes and inclinations; induced environments caused by power/weapon system effluents, electrical fields, plasmas and radiation; and hostile environments resulting from a direct nuclear event, particle beam attack and pellet attack.

Task 5: In Task 5 developmental issues for the systems studied in Task 3 were considered. These included present state-of-the art evaluation, program plans and schedules for developing key technologies and potential development cost.

Task 6 In Task 6 the contractors developed "Figure of Merit" models for all of the power systems investigated by ranking them against an array of possible attributes/detriments. Models were computerized so that they could be used to rank systems against new missions and/or requirements.

The information sources upon which the FST's critique of the SPAS results is based consisted of the following:

1. Four oral reviews with viewgraph handouts given by each of three contractors after completion of Task 1; Task 2; Task 3; and Task 4, 5 and 6.

2. GE and M-M provided written reports on Task 3 results

3. Draft final reports by all three contractors covering all work completed in Tasks 1-6. The reports by GE and M-M consisted of written text while TRW provided only an updated/expanded version of their briefing viewgraphs.

SPAS PROGRAM TASKS

TASK 1: IDENTIFICATION OF USER REQUIREMENTS

FOCUS TASK 2: IDENTIFICATION OF POWER SUBSYSTEM OPTIONS

TASK 3: CONCEPTUAL DESIGNS OF SPACE POWER SUBSYSTEM OPTIONS

TASK 4: POWER SUBSYSTEM SURVIVABILITY

FOCUS TASK 5: IDENTIFICATION OF KEY TECHNICAL ISSUES, POTENTIAL SOLUTIONS, AND TECHNOLOGY DEVELOPMENT NEEDS

DEMO TASK 6: DEVELOPMENT OF FIGURE OF MERIT

While the above documentation generated a large amount of useful information it lacked technical detail in a number of important areas. This prevented a thorough assessment of results in some cases. This report therefore represents a best effort attempt upon the part of the LeRC/SNL Field Support Team to provide a comparative analysis of contractor results; to identify areas of difference, explain the reason for these differences and their effect upon final conclusions; and to identify those areas of major impact which require further investigation before an absolute conclusion can be drawn; and to identify the technology needs requiring development in order to implement the most promising power system/systems.

Following this Introduction, Section III discusses the major differences in contractor analyses, areas where informatin was lacking and significant results. Section IV addresses the requirements defined by the contractors in Task 1 and also the assumptions that were made by the contractors in pursuing the study. Section V contains a discussion of the Task 2 downselected power system conceptual designs investigated by the contractors in Task 3, how they compare and which systems are most promising to fulfill the SDI Architecture Requirements. Power/weapon platform interface issues concerned with effluents, platform dynamics, power conditioning, thermal management, survivability and technology needs are discussed in Section VI. These are major issues and development of space-based weapons depends upons successful resolution of them. Some of the less developed issues, subcomponents and the Figure of Merit modelling being relegated to Appendical material.

First, a comment on documentation:

1. Documentation lacked technical detail. This prevented a thorough assessment in some cases, and it may impair the future value of the work. Unless it is included in their final reports the work will probably have to be repeated.

2. Some of our assessments may be modified when and if we get more detailed information in the final report.

3. In general, much useful information was generated, and they did quite well in several areas. There are many important conclusions that can be made.

III. SUMMARY OF MAJOR RESULTS

III. SUMMARY OF MAJOR RESULTS

In this Section the major power/weapon design drivers, differences in philosophical design approaches and assumptions that lead the contractors toward their final recommendations are discussed. The lack of detailed platform design information meant that the contractors had to make various assumptions and approximations (e.g., platform stiffness) and these differed from contractor to contractor. The greatest difference in contractor approach and hence final results appears to be in the time frame of power/weapon platform deployment and therefore the degree of technology advancement available at the technology freeze date. This was not specified in the contract and since technology advancement is always subject to a dollars/risk scenario the contractors' designs varied from the more near term approach of Martin-Marietta to the more far term approaches of GE and TRW. This difference in design philosophy has a profound effect upon the power/weapon system design, contractor to contractor system comparisons and technology needs recommendations. It is the purpose of this Section to discuss these broad, overall differences and similarities.

One of the more interesting aspects of the SPAS studies was that all three contractors used designs that avoided heavy power conditioning. For their FEL and NPB systems, GE showed that by cryocooling the power conditioning unit's step-up transformer they could reduce its mass by a factor of 10. This mass savings was then arbitrarily applied to all other power conditioning components (AC and DC). Martin Marietta and TRW avoided heavy power conditioning for their turboalternator systems by presuming the use of very high voltage alternators (75 kV and 105 kV respectively). These high voltages, which are beyond state-of-the-art capabilities, allowed them to rectify to the 100 kV DC needed for tube-type RF generators without using transformers. This advantage does not apply to low voltage sources that do not use alternators; consequently, Martin Marietta and TRW require heavy power conditioning units with transformers for their low voltage sources. Thus, GE shows little power conditioning unit mass difference between turboalternator and low voltage sources while TRW and Martin Marietta show large differences.

Martin Marietta assumed the use of hydrogen cryocooled NPB and FEL accelerators. The accelerator does not contribute a large fraction of the weapon's cooling load, but it does determine the flow rate of weapon coolant required because it must be kept at a very low temperature, between 30 and 40 K. GE assumed that accelerators were supercooled using liquid helium coolant. This reduces the weapons cooling load slightly, but it reduces the flow rate of hydrogen coolant significantly. Other weapon components, RF generators and magnets, are hydrogen cooled and are not superconducting. TRW assumed that the accelerator and magnets are superconducting and used hydrogen as a coolant. This presumes that the accelerator can be superconducting at 30 K and that magnets can be superconducting at 50K. Both require advanced superconductors. The result is that Martin Marietta's hydrogen flow rate is determined by the accelerator's needs and is approximately twice that required by GE or TRW whose hydrogen flow rate is dictated by the needs of the power generation system. To balance the flow rates of hydrogen through the accelerator and through the turbine Martin-Marietta uses a relatively low turbine inlet temperature, around 800 K, compared to those used by GE and TRW, 1500 and 1700 K respectively.

These were the main conclusions and issues:

1. Light weight power conditioning
   - High voltage generators or cryogenic cooling may significantly reduce power conditioning weight.

2. Cryo vs. Supercooled weapons
   - The superconducting accelerator assumption has a profound effect on the power system
     - hydrogen use and effluent
     - refrigeration
     - system operating conditions
   - All three contractors concluded that weapons must be continuously cooled. We do not see any reasonable alternatives.

None of the contractors compared a cryocooled accelerator platform to a supercooled accelerator platform. Thus, the very important question -- which type of accelerator cooling is best for the platform -- has not been addressed and trade-offs have not been identified.

All three contractors concluded that the start-up time associated with cooling an accelerator from equilibrium temperature to operating temperature is prohibitively long; thus, they all kept their accelerators at operating temperature. This requires continuous refrigeration. Trying to cool an accelerator in a short time requires expending a lot of coolant or using a relatively large refrigerator and might result in accelerator misalignments due to differential expansions. A continuously operating refrigerator would add only a small fraction to the platform's mass, but it must be reliable.

The contractors considered the effects of misalignments due to vibrations on beam accuracy, but they were weak at determining the effect that vibration has on weapon performance due to internal misalignments caused by a vibrating weapon column. They characterized power system components as vibration sources (except for exhaust nozzles), but they were weak at determining how the source vibrations coupled to the platform structure.

There are several issues associated with hydrogen effluent:

1. Beam attenuation -- All of the contractors did reasonable calculations to show that, when exhaust nozzles are used, hydrogen column densities will deneutralize less than 1% of a neutral particle beam. The hydrogen will have no effect on a FEL beam. While the contractors' calculations were reasonable, they were analytical and have not been verified by experimental results. We believe that plans should be made for a verifying experiment.

2. Sensor signal attenuation -- They agreed that neutral and naturally ionized hydrogen will not affect IR sensors, radar, or laser sensors.

3. Electrical breakdown -- They agreed that electrical breakdown due to neutral or ionized hydrogen can be avoided by proper insulation.

4. Unbalanced nozzle thrust and vibration -- They all had methods for balancing nozzle thrust, but only TRW considered the magnitude of active and passive attenuation to meet the weapon's vibration requirement. We believe that their proposed attenuation method will be a significant technical challenge.

5. Nuclear burst induced ionization -- Both GE and TRW say that his will be a short lived problem of 1 to 3 seconds. An ionized cloud of hydrogen will radiate and may possibly interfere with IR, radar, and radio signals. In an independent study funded by DOE, Space Power Inc (SPI) has also started to quantify this problem. With 10^{15} molecules/m^3, an ionization fraction of 10^{-4} to 10^{-6} and interference beginning at 10^9 ions/m^3, the problem may be marginal. SPI also found that plasma frequencies will be below the typical radar cutoff frquencies if the radar is looking away from nozzle plane. There is some concern about plasma being trapped by a weapon's magnetic fields such as from a NPB weapon's beam turning and steering magnets.

For the first two issues, the contractors considered column densities along a

Conclusions and Issues (continued)

3. Platform Dynamics Issues
   - The contractors considered vibration sources and platform response, but didn't tie them to degradation of the weapon train within the platform.
   - This may impact platform structure and vibration source requirements and should be discussed with weapon designers.

4. Effluents
   - All three concluded that hydrogen effluent will not interfere with beams or sensors.
   - The effect of other effluents is still questionable.

path pointing away from the nozzle plane. This is justified by their calculations that show that by the time the platform can slew to a different angle, the denser cloud at that angle will have dispersed. The nozzle vibration and nuclear induced ion trapping issues keep the hydrogen effluent issue from being fully resolved.

GE believes that the water vapor exhausted from a combustion system will cause no problems if appropriate measures are taken. TRW and Martin Marietta are concerned about condensation and signal interference. This issue is not resolved, but it may not be important because Sunstrand has proposed a method to remove water from the combustion system's exhaust without a large weight penalty.

All three contractors agree that open burst mode power systems will be substantially lighter than closed systems. Among the open systems; as cooled reactor and hydrogen-oxygen combustion powered turboalternator, combustion and gas reactor powered MHD and fuel cell systems were consistently estimated to be the lightest. Martin-Marietta estimates that an open fuel cell system will be the lightest, followed by Nerva Derived Reactor (NDR) powered turboalternator, combustion turboalternator, and combustion MHD systems. TRW estimated that a gas cooled reactor powered disk MHD system will be lightest, followed by NDR turboalternator and combustion turboalternator, and fuel cell systems. TRW and Martin Marietta concluded that the closed fuel cell system is the lightest of the closed systems. GE did not include a closed fuel cell system in their studies. However, none of the contractors considered any kind of a container for capturing both weapon and power system exhaust. In fact, the only system considered that closed both the weapon and power systems was TRW's combustion turboalternator system that used titanium and lithium to absorb the platform's effluents.

Since the open systems are much lighter than closed systems and the hydrogen effluent at predicted concentration levels appears to be reasonably benign, the solution of open system problems should be a high priority technology needs issue. This will require verification of effluent analyses and resolution of remaining effluent issues -- exhaust nozzle vibration attenuation and magnetic field ion trapping.

Some of the closed energy storage systems may have a place as transient buffers or as primary power systems if required operation times are very short. In addition, if superconducting accelerator technology proves feasible, fuel cells may appear more attractive since they can take advantage of the decreased mass of hydrogen needed to cool a superconducting accelerator.

All three contractors recognized that NERVA derivative reactors may cost less to develop than other technolgies because of its previous development history.

Early in the history of SDI, it was believed that power systems would not add a large fraction to platform mass. At 0.2 to 0.5 metric tons per megawatt, open power systems will contribute nearly as much mass as the weapon.

Conclusions and Issues (continued)

5. Systems
   - All three concluded that open, burst power systems are much lighter than closed. We should emphasize open systems and try to solve open system problems since the result will be major weight reductions.
   - They recognized that the NERVA derivative reactor is a relatively low risk approach
   - Burst power systems will be heavier than anticipated by early SDI (several 10's of metric tons).

IV. REQUIREMENTS AND ASSUMPTIONS

RESULTING CONSTELLATIONS ARE SIMILAR

After their review of the available documents describing missions and platforms, the SPAS contractors were in general agreement on the number of platforms, their deployment altitudes, and the inclination of the orbits. All contractors considered both boost-phase and mid-course intercepts. An important point to be noted is that none of the contractors considered architectures in which the electric platforms performed the entire SDI mission. All assumed architectures consisted of a mix of electric platforms, ground-based lasers, and space based rocket interceptors. The space based rocket interceptors performed the larger share of the intercepts. This is in general agreement with the SDI Systems Architecture and Key Trade-off Studies.

Resulting Constellations Are Similar

No. platforms:	50 - 200
Altitudes(km):	500 - 1500
Inclinations:	60 - 90 deg

MISSIONS: Boost-phase & mid-course.
All SPAS constellations augmented a dedicated BPI constellation of SBKKVs and/or GBL.

No all-electric architectures treated.

SPAS CONTRACTORS EXAMINED EXISTING ARCHITECTURES AND SYSTEMS STUDIES

The SPAS architects drew from a common set of reference documents describing missions and platforms. Both TRW and Martin Marietta are participants in the Systems Architecture and Key Trade-off Studies and were able to draw on that in-house expertise.

SPAS Contractors Examined Existing Architectures And Systems Studies.

1. TRW: in-house expertise from SAS studies
2. MM: mostly SBL study, some in-house SAS interaction.
3. GE: SBL and SDI PAS documents.

- All had common platform description source documents, e.g. Have Sting, CARDS, SBFEL, Beam System Study.

THE SPAS CONTRACTORS USED SIMILAR DESIGN REQUIREMENTS. THEIR SYSTEMS SUPPLEMENTED KKV AND GBL SYSTEMS.

After review of the source documents (Task 1), the SPAS contractors derived similar burst power requirements for the SDI missions. Martin Marietta chose to not study a space based radar (SBR). Power levels and run times fall into the ranges of the previously issued SDI Space Power Office Requirements Guidelines. All contractors assumed SP100 availability for station keeping loads. Testing requirements varied, but the contractors did not elaborate on how these were decided. GE assumed that expendables used during tests would be periodically replaced.

Key

KKV	Kinetic Kill Vehicle
GBL	Ground Based Laser
FEL	Free Electron Laser
NPB	Neutral Particle Beam
EML	Electromagnetic Launch KKV
SBR	Space Based Radar
OTV	Orbital Transfer Vehicle
FEM	Free Electron Maser (radar)

The SPAS Contractors used similar design requirements. Their systems supplemented KKV and GBL systems.

		FEL	NPB	EML	SBR	OTV	FEM
P-burst(MW)	TRW	223	400	200			
	MM	334	200	200			
	GE	100	200	500			
Engagement(s)	TRW						
	MM		classified				
	GE						
Multimegawatt Steady State (MW)	TRW	.01-.05	.01-.11	.01-.11	1-12	1-5	1
	MM	.05	.11	.02	omitted	1-10	
	GE	.1	.1	.1	10	5	

Station Keeping 100 kW (SP100)

Testing:
- TRW 400s test during life
- MM 10 yr missions, 6s test/12 week
- GE 15 yr mission, 120s test/6 mo

V. SYSTEM STUDIES

A. BURST SYSTEMS

1. OVERVIEW

SPACE POWER SYSTEMS

This chart illustrates the difference between open and closed burst power systems.

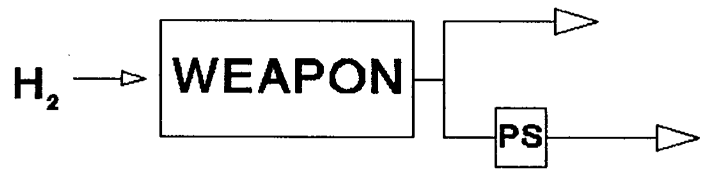
The open power system uses weapon coolant as a working fluid to produce power, then exhausts the fluid into space. For example, a reactor powered, turboalternator power system heats hydrogen weapon coolant in its reactor and expands it in its turbine to produce power. After the hydrogen has been expanded it is exhausted into space. The system is open because it has effluent. The effect this effluent has on platform performance is a primary concern and will be discussed in the section on effluents.

The closed power system produces no effluents, but weapon coolant is still exhausted into space. Closed power systems are beneficial only if the weapon produces little or no effluent. Requiring a power system to be closed, when the weapon exhausts as much effluent as an open power system, makes little sense. It is unlikely that weapons will be closed, but weapons with superconducting accelerators may use considerably less coolant than cryocooled weapons.

Some types of power systems use weapon coolant as a working fluid and absorb the working fluid. These power systems close the entire platform. Examples are systems with exhaust catching bags (not considered in SPAS), and systems that chemically react exhaust hydrogen to form a solid or liquid which is stored, such as TRW's lithium reactor that reacts hydrogen with lithium to form liquid lithium-hydride.

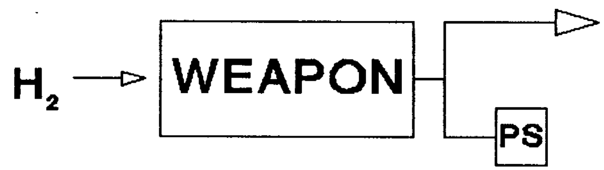
SPAS Power Systems

Open



Effluent

Pow Sys Closed



H_2 Effluent

Platform Closed

No Effluent

BURST SYSTEMS CONSIDERED

This chart shows which contractors considered which burst power systems. A very good range of systems, including nuclear, combustion, fuel cell, MHD, thermionic, battery, flywheel, and closed thermodynamic, was considered. On the other hand, only one system was considered by all three contractors. Another system was considered by two contractors, and 18 were considered by only one contractor. This made it difficult to compare results, compare assumptions, and draw consensus conclusions about individual systems especially since the contractors chose different design power levels and run times and had no requirements for standard report or data reporting formats. Furthermore, only GE showed mass scaling with time, and with power level.

Burst Systems Considered

	TRW	GE	MM
Open Cycle Systems			
NDReactor - Turboalternator - H effluent	X	X	X
NDReactor - MHD - effluent	X		
PBReactor - MHD - effluent		X	
H-O Combustion - Turboalternator - H+W effluent		X	X
H-O Combustion - Turboalternator - H effluent			X
H-O-Ti Combustion - Turboalternator - H effluent	X		
H-O Combustion - MHD - effluent			X
H-O Fuel Cell - H+W effluent			X
Gel MHD - effluent	X		
Lithium Acid Battery - H effluent		X	
Closed Cycle Systems			
LMR - Thermionic - Radiator			X
LMR - Rankine - Radiator			X
THOR (Thermionic-LiH) - Radiator	X		
H-O-Ti-Li Combustion - Turboalternator - Radiator	X		
H-O Fuel Cell - Radiator			X
H-O Fuel Cell - Ice	X		
Lithium Thionyl Chloride Battery - Radiator		X	
Steady State with Storage			
SP-100 - Flywheel		X	
SP-100 - Fuel Cell		X	
Star M - Li Metal Sulfide Battery	X		

THREE CONTRACTORS USED DIFFERENT ACCELERATOR COOLING METHODS

Three different types of accelerator cooling were considered. These influenced system design significantly. Unfortunately, none of the three contractors compared the advantages and disadvantages of superconducting versus cryocooled weapons, thus there is no basis to judge whether power system technology should be directed at power systems for superconducting weapons or at power systems for cryocooled weapons.

The Three Contractors Used Different Accelerator Cooling Methods

Sandia
NASA

MM - Cryo-cooled accelerator and magnets using hydrogen

GE - Superconducting accelerator and magnets using helium

TRW - Superconducting accelerator and magnets using hydrogen:

30K for accelerator
50K for magnets
(these are advanced superconductors)

NEUTRAL PARTICLE BEAM

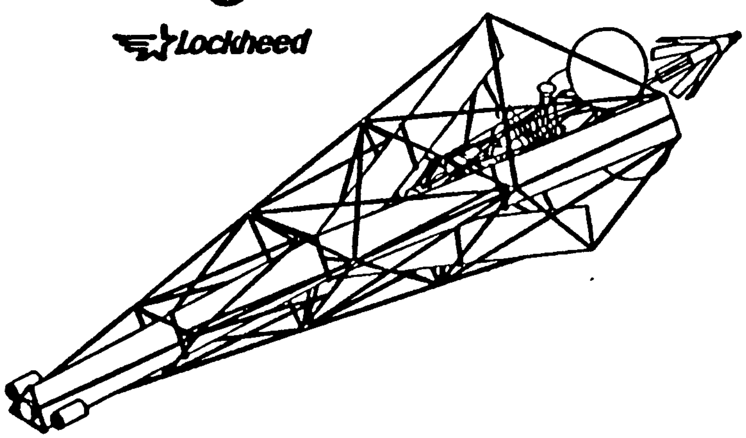
These figures give an idea of how the power systems and weapons are integrated into a platform. GE's design shows a modular power system plugged into a funneled NPB platform, TRW's sketch shows how exhaust nozzles might be configured, and Martin Marietta's gives an idea of scale. Notice that each one uses an SP-100 derived, station keeping power system.

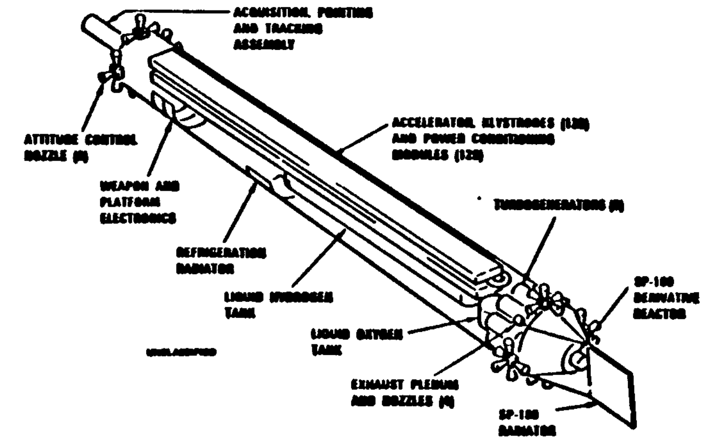
NEUTRAL PARTICLE BEAM

TRW

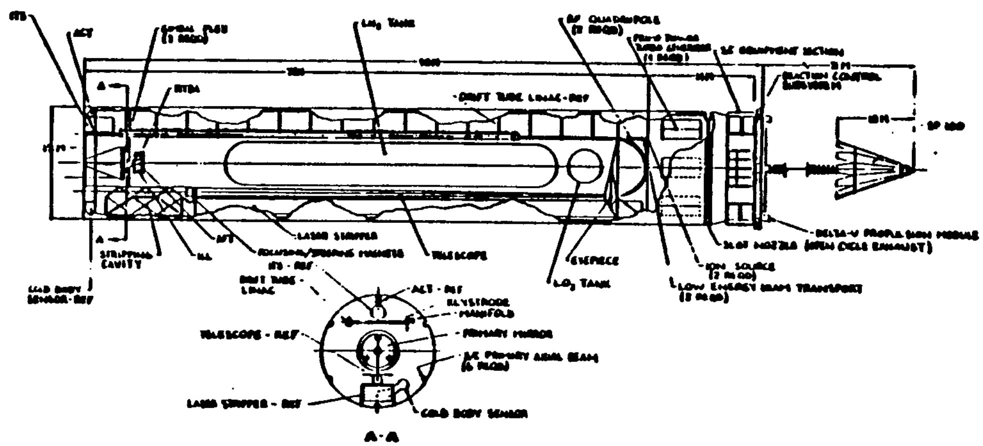
GENERAL ELECTRIC

Lockheed





MARTIN MARIETTA



NPB TM-4

This schematic gives an idea of the thermal management integration. Liquid hydrogen cools the alternator, power conditioning, and klystrodes, and is then heated by a reactor and expanded through a turbine to generate power. In this system, liquid helium is used to cool the superconducting accelerator. During steady state operation, helium keeps the accelerator cool and is in turn cooled by a refrigeration system. During burst operation, the helium is exhausted into space.

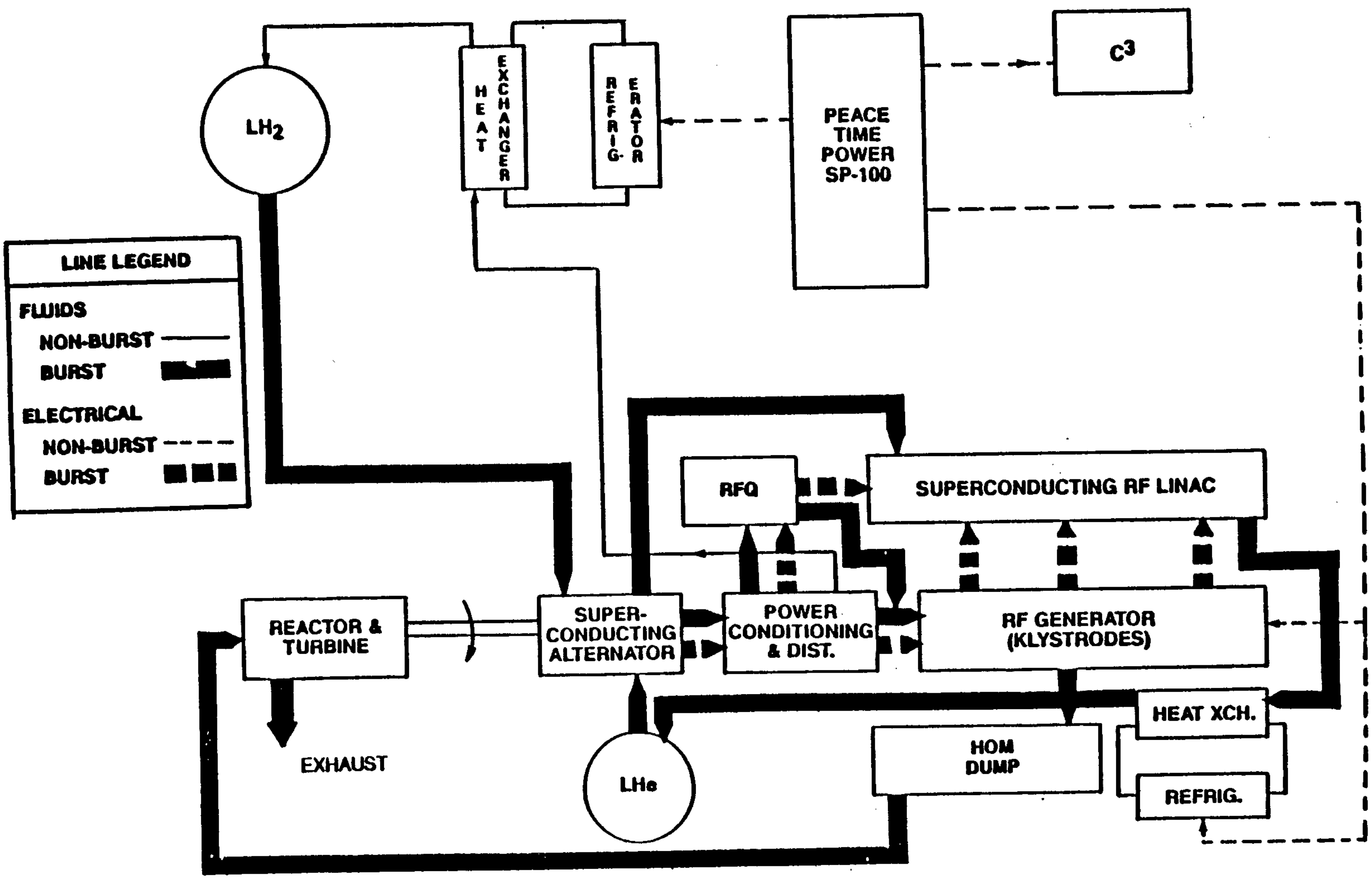
GENERAL ELECTRIC

Lockheed

NPB TM-4

AFSTC

SPACE POWER ARCHITECTURE STUDY



THE WEAPON COOLING METHOD HAS POWER SYSTEM IMPLICATIONS

As mentioned earlier, the type of weapon cooling has a significant effect on power system design. Martin Marietta's cryocooled weapon needs much more hydrogen coolant than the superconducting weapons. The weapon uses a lot of hydrogen, and this hydrogen is available to the power system. With a high hydrogen flow rate, a low turbine inlet temperature can be used and still provide enough turbine power to operate the weapon. That is why Martin Marietta selected a turbine inlet temperature of 800 K, a temperature that does not stress current turbine material technology.

GE and TRW's superconducting accelerators, on the other hand, need less hydrogen (used to cool their klystrode RF generators). The amount of hydrogen their platforms need is determined by their power systems. To reduce the hydrogen needed, GE and TRW have selected turbine inlet temperatures in the 1500 to 1600 K range, which stretches current turbine material technology. In fact, TRW is proposing a carbon composite turbine.

A fuel cell may look better for a superconducting weapon than for a cryocooled weapon, because its hydrogen use more closely matches the hydrogen coolant needs of a superconducting weapon than of a cryocooled weapon.

THE WEAPON COOLING METHOD HAS POWER SYSTEM IMPLICATIONS

The Cryo-cooled Weapon Platform Needs Twice as Much Hydrogen as Superconducting.

- Hydrogen Use is Determined by Accelerator Needs.
- No Advantage for High Temperature Turbines.

The Superconducting Weapon Platform Uses Less Hydrogen.

- Hydrogen is Determined by Power System Needs.
- High Temperature Turbines May be Beneficial.
- May be an Advantage for Fuel Cells Because They Use Less Hydrogen.

WEIGHT DEPENDS ON WHETHER THE SYSTEM IS OPEN OR CLOSED AND ON RUN TIME

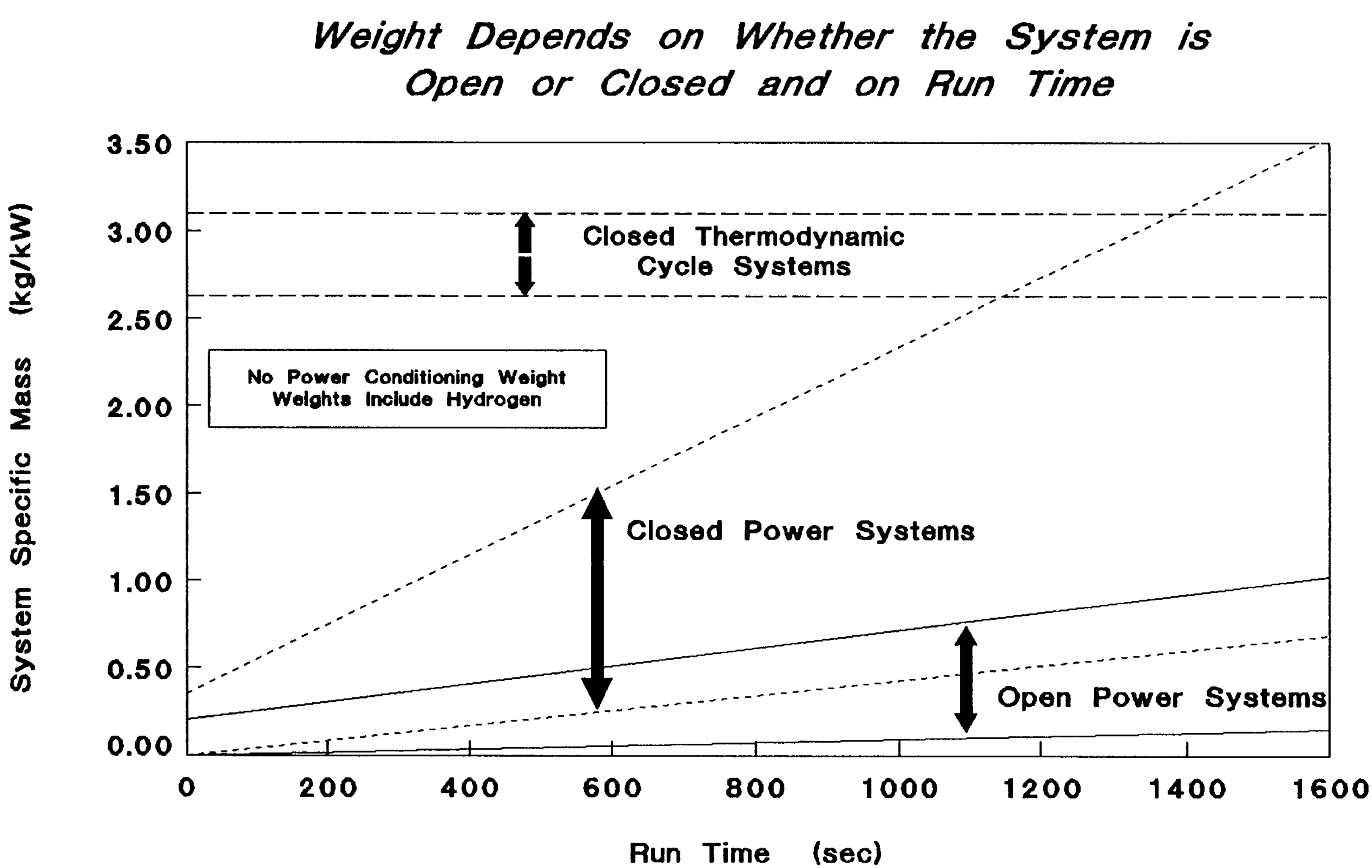
This chart compares the weights calculated by the SPAS contractors for the different classes of power systems by plotting specific mass (a system's mass divided by its power level) as a function of run time. This data was not directly available from the draft final reports since only GE provided run time scaling. So, we divided the contractors' tabulated weights into fixed and time dependent weights to make this chart.

These weights do not include power conditioning which can be a significant part of platform weight and may significantly handicap some types of power systems but not others for some applications. The effect of power conditioning weight will be discussed later in this section.

Open systems are the lightest and fall in the area between the two lines marked "Open Power Systems". They include the following:

- TRW NDReactor MHD
- GE NDReactor Turboalternator
- GE PBReactor MHD
- GE Open H-O Fuel Cell
- MM NDReactor Turboalternator
- TRW Gel MHD
- MM Combust Turbalt (No H_2O)
- TRW NDReactor Turboalternator
- MM Fuel Cell
- GE H-O Combust Turboalternator
- TRW H-O Combust Turboalternator
- GE Battery
- MM H-O Combust Turboalternator
- MM Combustion MHD

Not included in this band is GE's lithium-thionyl chloride battery system which is not closed because it exhausts hydrogen which cools the battery. It has twice the weight of the heaviest open system line shown in the chart. The lightest system in the band is TRW's NDReactor MHD system and the heaviest is Martin Marietta's hydrogen-oxygen combustion MHD system. In general, analysis by the Field Support Team (FST) supports the contractors' weight estimates for the turboalternator and open fuel cell systems. We must point out, however, that there are a variety of technology assumptions in these weights. Martin Marietta made more conservative assumptions than either GE or TRW, and TRW was generally the most optimistic. For example, Martin Marietta assumed an MHD channel performance


Weight Depends on Whether the System is
Open or Closed and on Run Time
System Specific Mass (kg/kW)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
200
400
600
800
1000
1200
1400
1600
Run Time (sec)
Closed Thermodynamic
Cycle Systems
No Power Conditioning Weight
Weights Include Hydrogen
Closed Power Systems
Open Power Systems

consistent with state-of-the-art technology while TRW assumed a very advanced disk MHD channel with an enthalpy extraction several times that used by Martin Marietta. Also, for all of these systems, Martin Marietta assumed a hydrogen usage rate twice that assumed by GE or TRW for reasons mentioned earlier.

The band of weights between the two dashed lines, is labeled "Closed Power Systems represents weights the contractors calculated for the following systems:

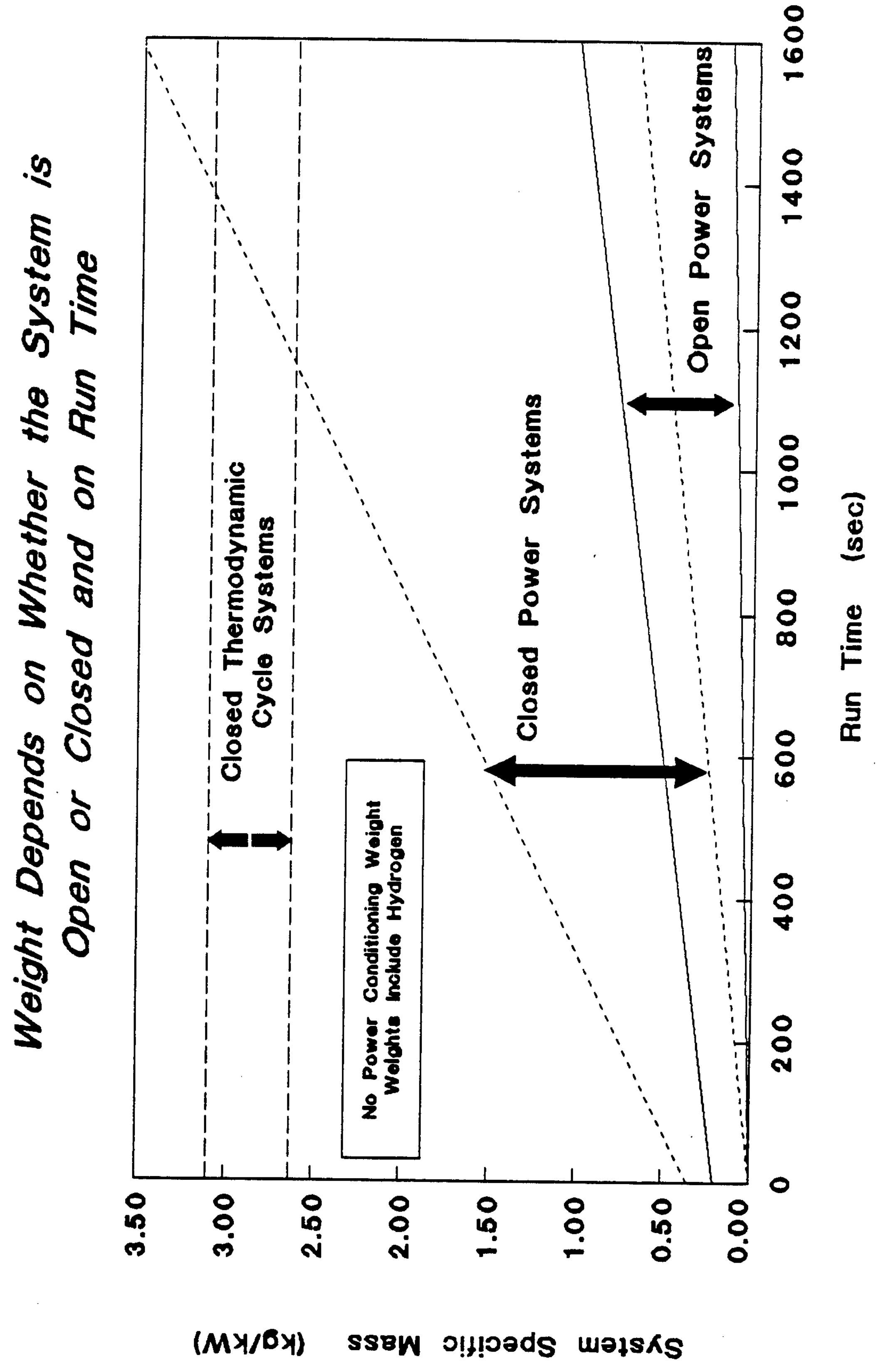
TRW Ice Cooled H-O Fuel Cell	MM H-O Fuel Cell
TRW THOR Thermionic Reactor	GE Flywheel
TRW Closed Combust Turboalt	TRW Lithium-Metal Sulfide Battery

The lightest of these systems are the closed, ice cooled, fuel cell systems. But, the closed, ice cooled, fuel cell, flywheel, and closed combustion turboalternator weights do not agree well with weights the FST estimated for the same systems. The FST weights are somewhat heavier. Details on these differences will be given in later sections. After the fuel cells, the lightest closed system is THOR, an in-core thermionic reactor with an integral LiH heat absorber. Its weight is based on a conversion efficiency of 27% which is well beyond state-of-the-art and must be considered very advanced. Thus, there is reason to believe that these open and closed regions should not overlap.

The band denoting "Closed Thermodynamic Cycle Systems" is for Martin Marietta's reactor powered Rankine and thermionic systems that use radiators to reject waste heat. The FST's weight estimates for these agree well with the contractor's estimates. However, the thermionic system was assumed to have a conversion efficiency of 27%, well beyond State-of-the-art.

There are several points that must be made here.

1. The lightest of the open systems is significantly lighter than the lightest of the closed systems. This difference increases as run time increases. For very short run times (shorter than about 200 seconds) the difference may not be large compared to the total platform weight, and the closed systems may be competitive.


Weight Depends on Whether the System is Open or Closed and on Run Time
System Specific Mass (kg/kW)
Run Time (sec)
Closed Thermodynamic Cycle Systems
No Power Conditioning Weight
Weights Include Hydrogen
Closed Power Systems
Open Power Systems
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
0
200
400
600
800
1000
1200
1400
1600

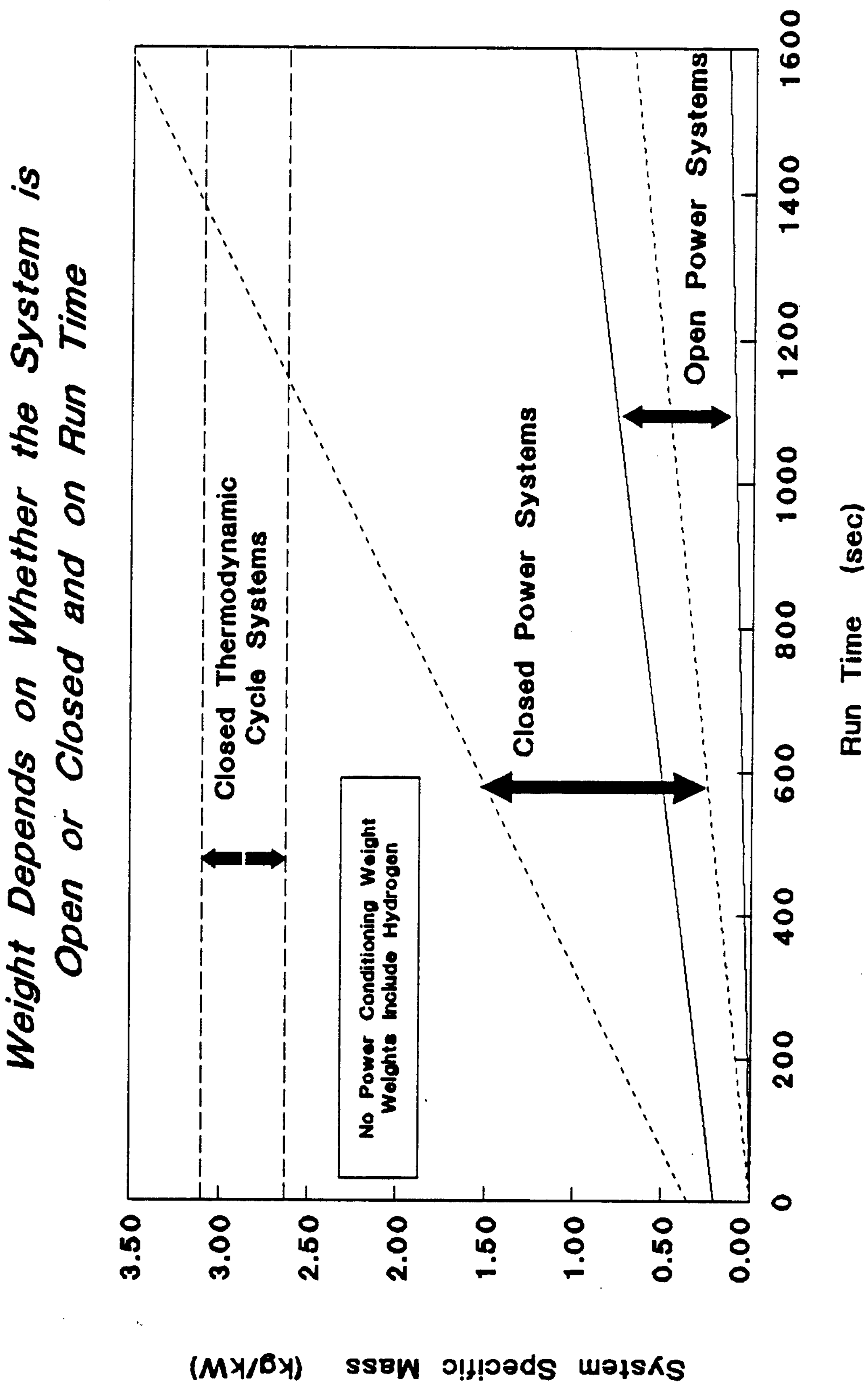
WEIGHT DEPENDS ON WHETHER THE SYSTEM IS OPEN OR CLOSED AND ON RUN TIME (cont.)

2. These weights do not include power conditioning . Power conditioning weight may significantly discriminate between low and high voltage systems. This will be discussed later in this section.

3. These weights do include the weight of fuels, coolants, and working fluids needed by the power systems. The open systems' fuels and working fluids can double as weapon coolants, giving them a weight benefit when used with weapons that need large quantities of cooling fluids. With the exception of the "hydrogen absorber", the closed systems cannot get the same benefit.

4. Some of these systems (Martin Marietta's closed fuel cell, GE's open fuel cell, TRW's lithium-metal sulfide battery, and GE's lithium-thionyl chloride battery) are rechargeable after tests and will get a benefit if total test time is significant when compared to engagement time.

Following this chart are four charts from the contractors' draft final reports showing how the contractors compared the weights of their systems. These charts should be reviewed cautiously because, in some cases, weights published in other parts of their reports do not agree with the numbers in these charts.


Weight Depends on Whether the System is
Open or Closed and on Run Time
Closed Thermodynamic
Cycle Systems
No Power Conditioning Weight
Weights Include Hydrogen
Closed Power Systems
Open Power Systems
System Specific Mass (kg/kW)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
200
400
600
800
1000
1200
1400
1600
Run Time (sec)

POWER SUBSYSTEM (DRY), AND SPACE PLATFORM (DRY AND WET) MASS COMPARISONS

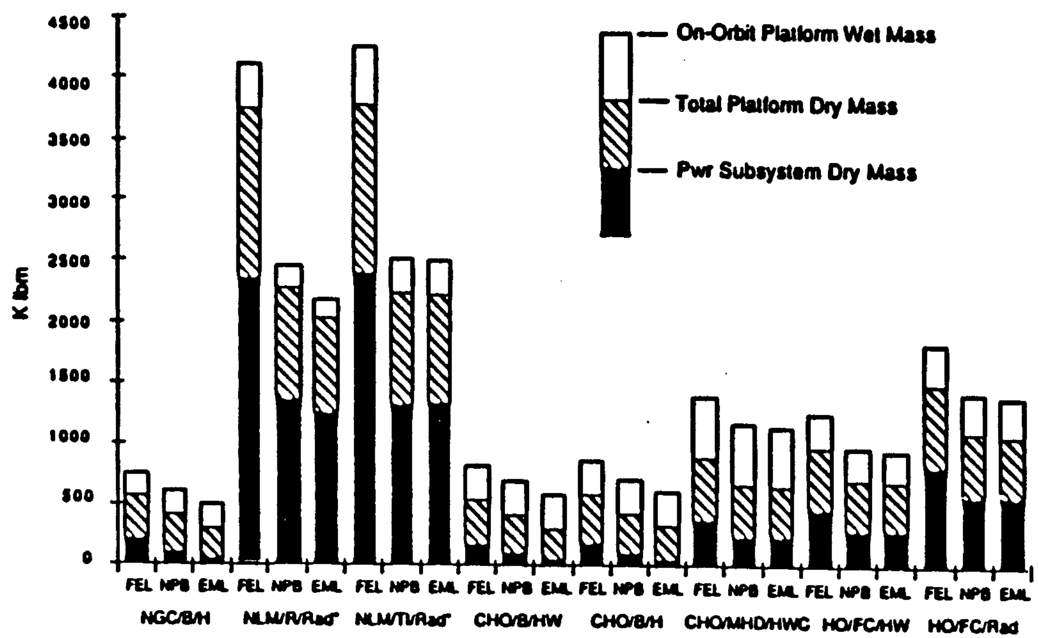
This is Martin Marietta's summary of burst system masses. The mass for each type of system is shown for three weapon types: FEL -- free electron laser, NPB -- Neutral particle beam, and EML -- electromagnetic launch. Notice that weapon mass is included in the platform mass. The types of power systems are designated by three letter groups separated by slashes. The first letter group specifies the power source. The second specifies the type of power conversion, and the third specifies effluent species.

Martin Marietta has included the power conditioning mass with power conversion mass in this chart.

NGC -- gas cooled reactor
NLM -- liquid metal reactor
CHO -- hydrogen-oxygen combustion
HO -- hydrogen-oxygen for a fuel cell

B -- Brayton (actually it is an open gas system and not a cycle)
R -- Rankine
TI -- thermionic
MHD -- magnetohydrodynamic
FC -- fuel cell

H -- hydrogen effluent
Rad -- closed system using a radiator to dissipate heat
HW -- hydrogen and water effluent
HWC -- hydrogen, water, and cesium effluent



* Wet masses for these closed cycle power subsystems represent RCS and ΔV reactant masses.

<u>Power Subsystem (Dry), and Space Platform (Dry and Wet) Mass Comparisons</u>

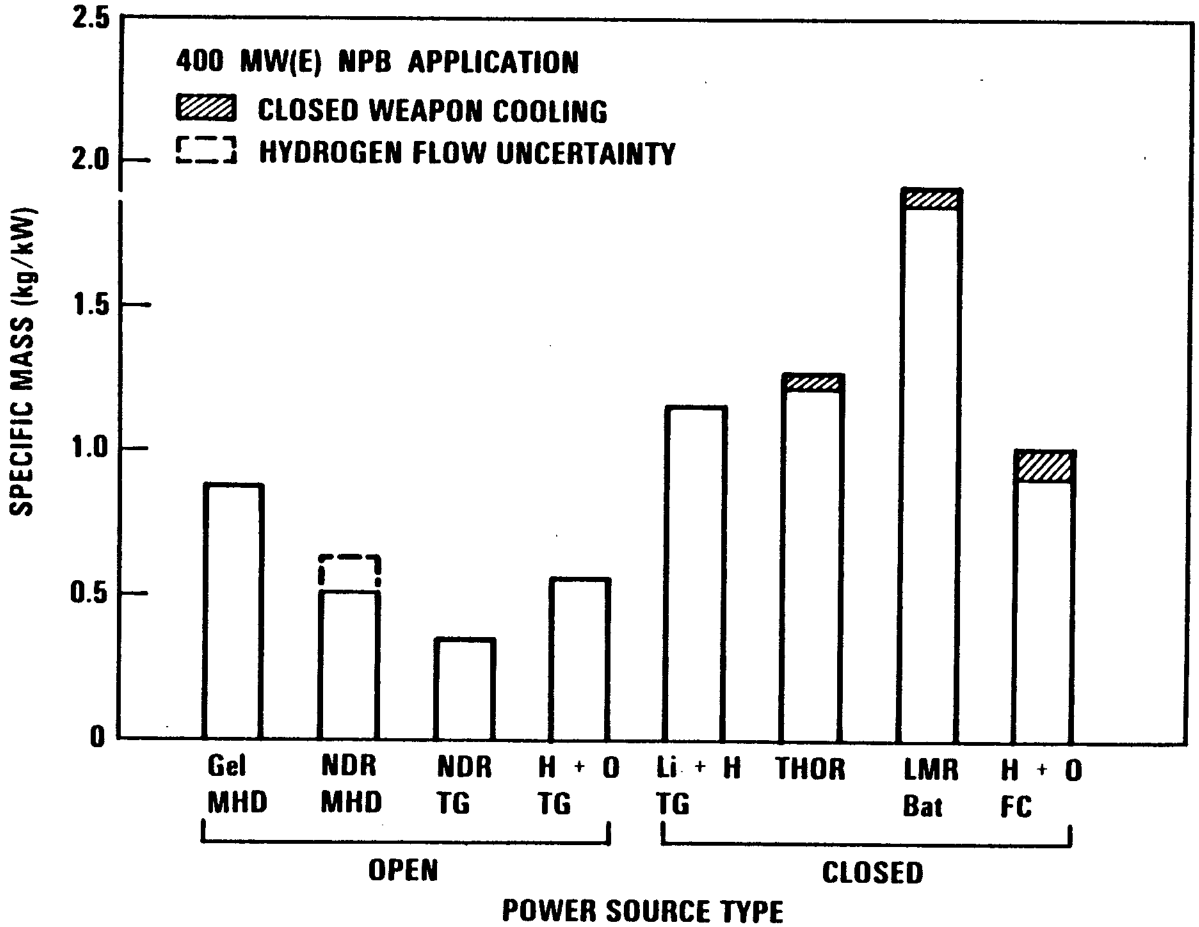
MASS COMPARISON (NPB)

This chart shows TRW's mass summaries for a NPB platform. The weights are for the power system and power conditioning and include necessary working fluids and fuels.

- Gel -- nitric acid and buffers react with a beryllium gel
- NDR -- NERVA derivative reactor
- H+O -- hydrogen and oxygen combustion
- Li+H-- This system burns hydrogen in oxygen, reduces the water using Ti to form hydrogen and TiO_2, and uses Li to react with and capture the exhausted hydrogen
- THOR-- GA's burst thermionic reactor
- LMR -- liquid metal reactor

- MHD -- magnetohydrodynamic
- TG -- turbogenerator
- Bat -- battery
- FC -- fuel cell

Mass Comparison (NPB)



SPECIFIC MASS COMPARISON (SCALED FROM NPB)

This chart shows GE's burst power system mass (including power conditioning) comparisons for a NPB platform. They do not include weapon mass, but they do include the mass of working fluid and fuels. A key for the types of systems is shown on the following chart.

This chart was generated during Task 2 and has not been updated. The masses of several systems changed significantly during Task 3. GE will include an updated chart in their final report. Comparisons done elsewhere in this report do not use the values in this chart but have attempted to use GE's updated values.

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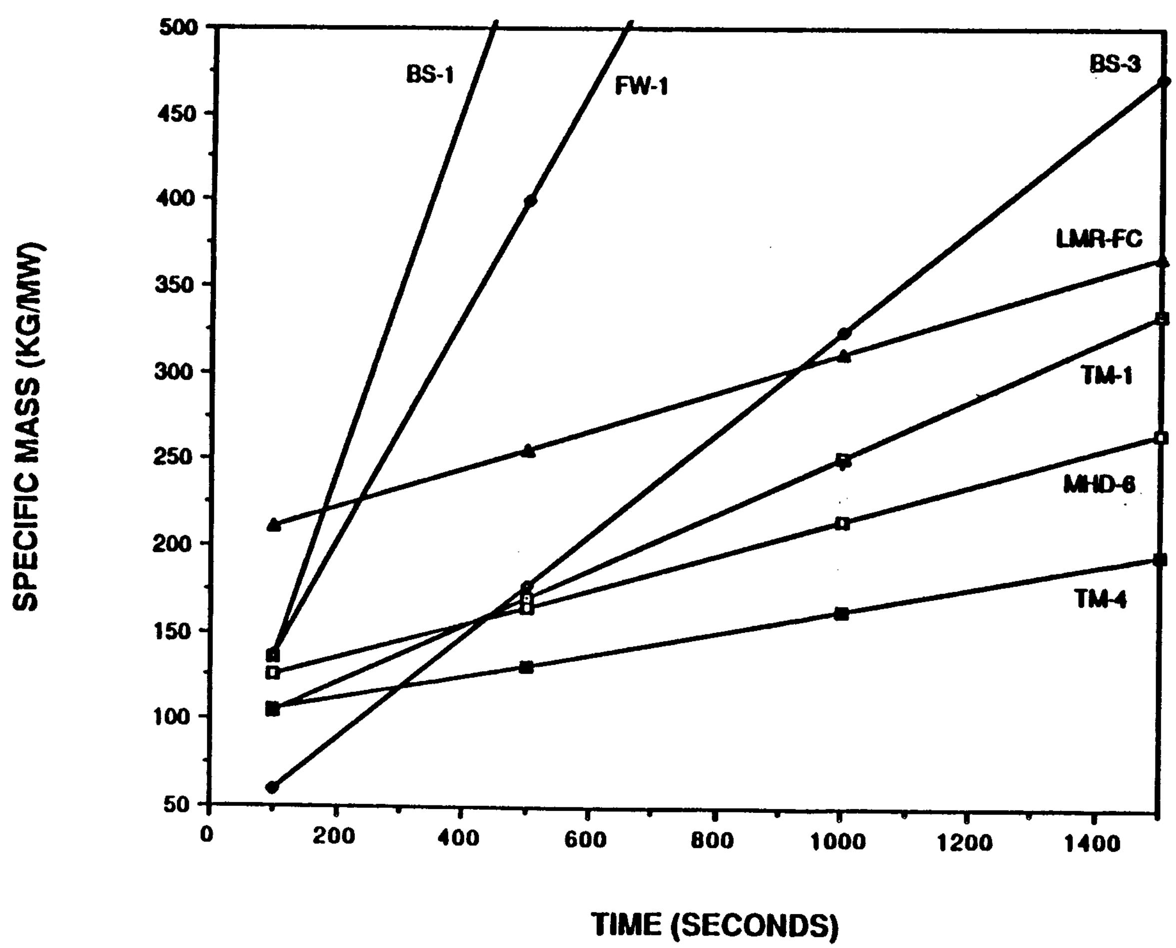
SPACE POWER ARCHITECTURE STUDY
AFSTC

SPECIFIC MASS COMPARISON (SCALED FROM NPB)



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Lockheed

POWER SUBSYSTEMS SELECTED BY AIRFORCE

AFSTC
SPACE POWER ARCHITECTURE STUDY

SUBSYSTEM	DESCRIPTION	HEAT SOURCE	CONVERTER	HEAT REJECTION
TM-1	COMBUSTION DRIVEN BRAYTON SYSTEM	H_2O_2 COMBUSTOR	TURBINE/GENERATOR	OPEN CYCLE
FC-6	SOLID OXIDE FUEL CELL	H_2O_2	REGEN S.O. FUEL CELL	CLOSED CYCLE
FW-1	FLYWHEEL SYSTEM	SP-100	FLYWHEEL/GEN	SP-100 RADIATOR
BS-1	BATTERY SYSTEM	NONE	LI THIONYL-CHLORIDE BAT.	CLOSED CYCLE
BS-S	DYNAMIC BATTERY	NONE	LI-H_2	CLOSED CYCLE
TM-4	NERVA DERIV (1500) BRAYTON SYSTEM	HTGR (NERVA)	TUBINE/GENERATOR	OPEN CYCLE
MHD-6	NUCLEAR REACTOR DRIVEN MHD	PARTICLE BED REACTOR	MHD WITH HYDROGEN	OPEN CYCLE
LMR-FC	LOW POWER LMR DRVN GENERATOR W/SOLID OXIDE FUEL CELL	LIQ MIL REACTOR	CONVERTER OF CHOICE TO CHARGE S.O. FUEL CELL	CLOSED CYCLE
AMTLC	ION CELL TEG	LIQ MIL REACTOR	HYTEC	CLOSED CYCLE
LMR-TM	POTASSIUM RANKINE SYSTEM	LIQ MIL REACTOR	RANKINE TURBINE/GEN	CLOSED CYCLE

OPEN, BURST POWER SYSTEMS HAVE SIMILAR WEIGHTS WITHOUT POWER CONDITIONING

This chart shows that without power conditioning, the open power system weights are quite similar. It shows average weights for open, NERVA derivative reactor--turboalternator, hydrogen-- oxygen combustion turboalternator, MHD, and open hydrogen-- oxygen fuel systems. The lines are simple averages of SPAS contractor weight estimates. Averaging makes little sense because the contractors made a variety of technology assumptions, but we will use the averages to make observations about power conditioning and hydrogen sharing. Keep in mind that the averages include turbine inlet temperatures that range from 800 to 1500 K, MHD technologies that range from state-of-the-art to very advanced, and that combustion and reactor MHD systems have been averaged together. The averages are very close to each other in weight, but there are examples of each type of specific system that are heavier or lighter than all of the averages.

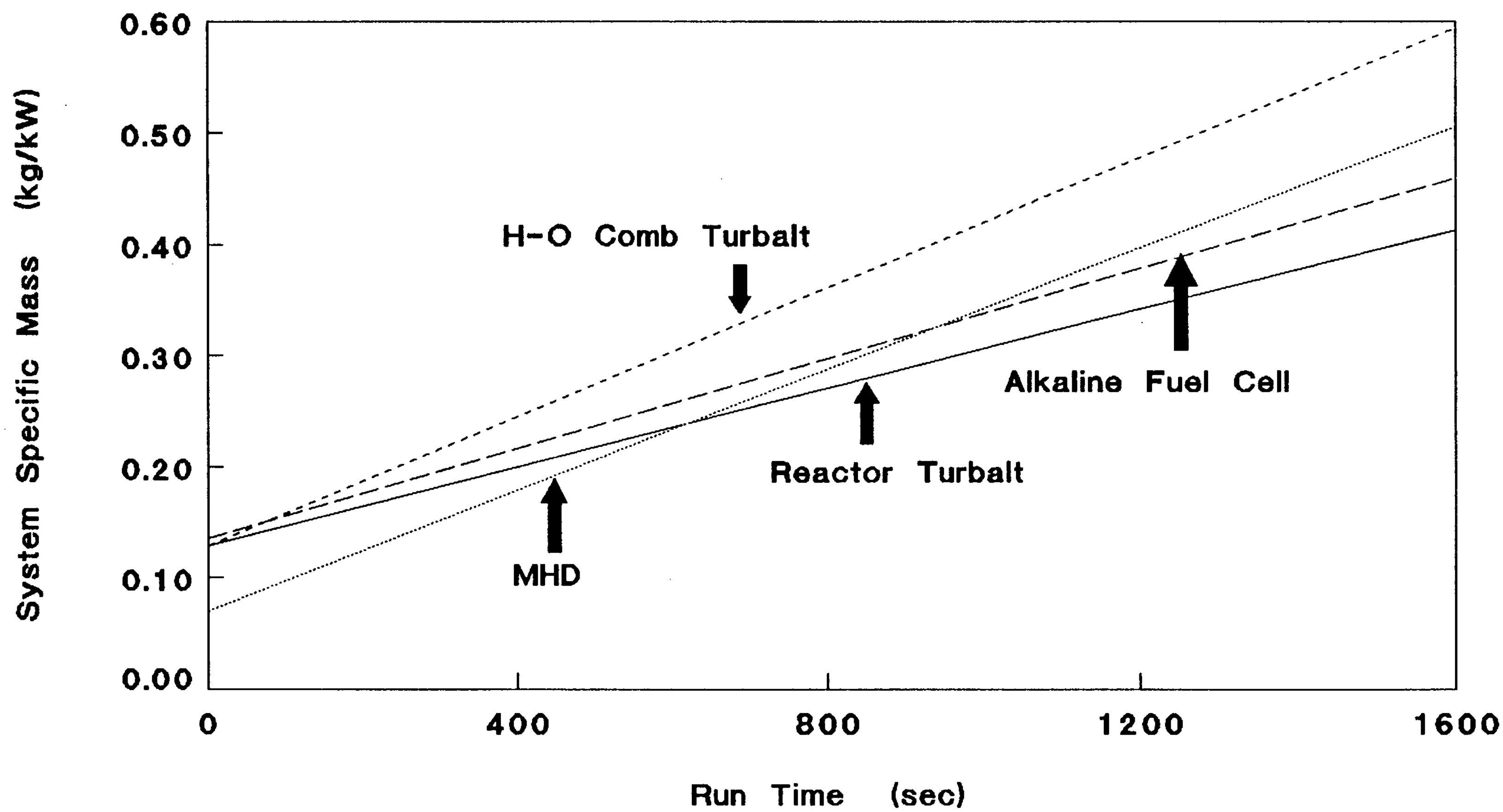
Since GE was the only contractor to show weight scaling with run time, we had to construct a time dependency for the other two contractors by breaking their system weights into fixed and time dependent components. We scaled the time dependent component linearly with time.

The technology level of these four systems is not consistent. The fuel cell and MHD system weights require much more technology advancement than the turboalternator systems' weights. The turboalternator weights can be achieved with modest technology advancement. The fuel cell weights require power densities and efficiencies that are beyond state-of-the-art. The MHD weights will require advanced channel designs, superconducting magnets, and maybe a nonequilibrium conversion process.

Power conditioning is not included in this weight, and the following chart will illustrate how power conditioning can discriminate among systems when power conditioning is much heavier for low voltage than for high voltage sources.

The weights of all necessary reactants and working fluids are included in this chart. The second following chart will illustrate how free hydrogen, donated by the weapon, discriminates among systems.

Open, Burst Power Systems Have Similar Weights Without Power Conditioning



BUT WHEN YOU ADD POWER CONDITIONING
(Based on TRW's PC Weight Estimates)

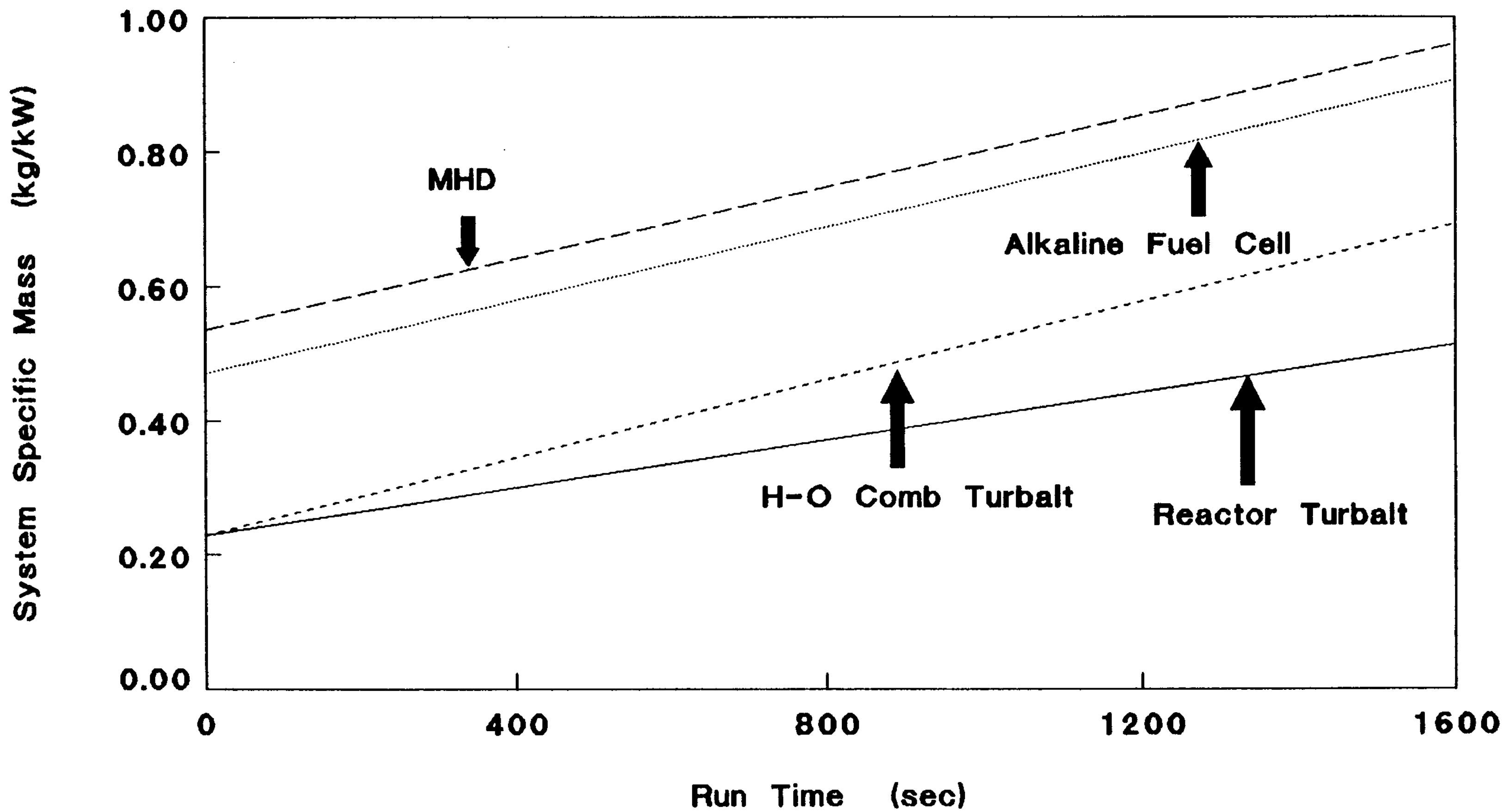
The previous chart did not include the weight of power conditioning. GE proposes the use of very light, cryocooled power conditioning equipment that would cause very little weight differences between the open power systems. On the other hand, Martin Marietta and TRW propose using very high voltage alternators so that heavy transformers are unnecessary to boost voltage to a value needed by klystrode RF generators. Thus, they have lightweight power conditioning for turboalternator systems but not for low voltage systems such as MHD and fuel cells. In this chart we have added TRW's power conditioning weights (0.1 kg/kW for turboalternator systems and 0.4 kg/kW for low voltage systems) to the open power systems. Which of these last two charts applies depends on the success with developing high voltage alternators and/or lightweight, cryocooled power conditioning equipment. It also depends on whether the RF generators need high voltage for tube type RF generators (assumed in the facing chart) or low voltage for solid state RF generators.

The Field Support Team believes that tube type RF generators will be used for NPB accelerators which require high frequency RF power, because solid state RF generators have relatively low efficiency at these high frequencies. But, FEL accelerators may use lower frequencies than NPB accelerators and may be able to use solid state, low voltage RF generators. Other applications such as EML weapons or radars may also use low voltage power. Low voltage applications may favor low voltage sources because step-down transformers will be required if high voltage sources are used.

Thus, the effects of power conditioning shown in the facing chart may be reversed for low voltage applications. But, for any application, power conditioning will probably be an important discriminator.

But When You Add Power Conditioning

(Based on TRW's PC Weight Estimates)

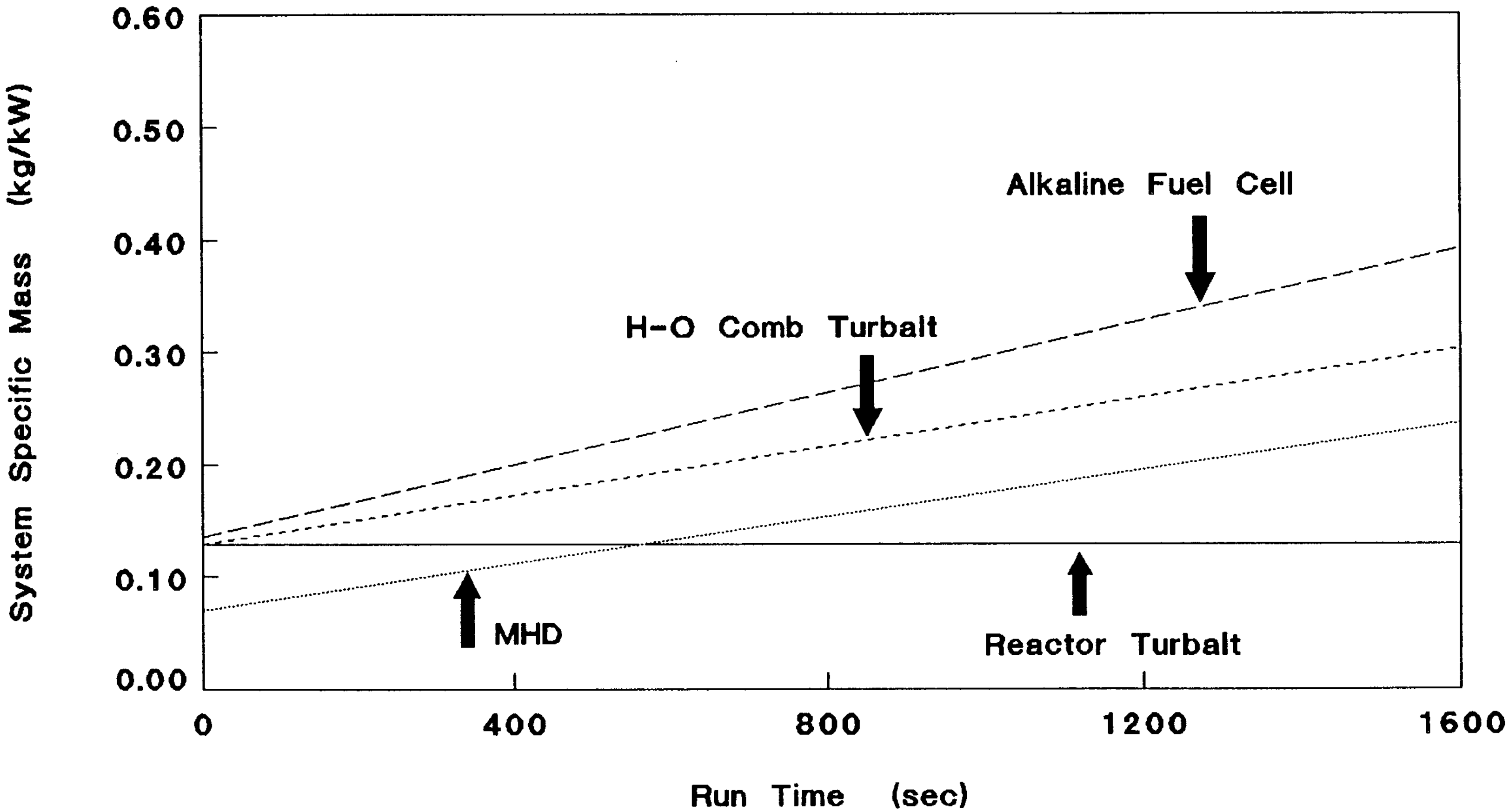


THESE WEIGHTS DO NOT INCLUDE HYDROGEN
OR POWER CONDITIONING

This chart illustrates what happens when the hydrogen used as a power system coolant, reactant, or working fluid is charged to the weapon and not to the power system. The least benefit is obtained by the power systems that use the least hydrogen. For example, a high enthalpy extraction MHD channel would get less benefit than a low enthalpy extraction channel. A fuel cell would get less benefit than a hydrogen--oxygen combustion turboalternator system. Closed systems, except those which use and absorb hydrogen, would get no benefit.

Of the "average" systems in this chart, the reactor --turboalternator systems gets the most benefit and the open fuel cell gets the least.

These Weights Do Not Include Hydrogen or Power Conditioning



NPB/FEL S/S SPECIFIC MASS vs OPERATING POWER

GE was the only contractor to show power system weight scaling with power level. Notice that the nuclear powered systems become relatively heavier at low power levels. This is because the reactors cannot be scaled down at lower power levels, because they have a minimum mass requirement to achieve criticality. However, this penalty is not sufficient to make them heavier than closed systems.

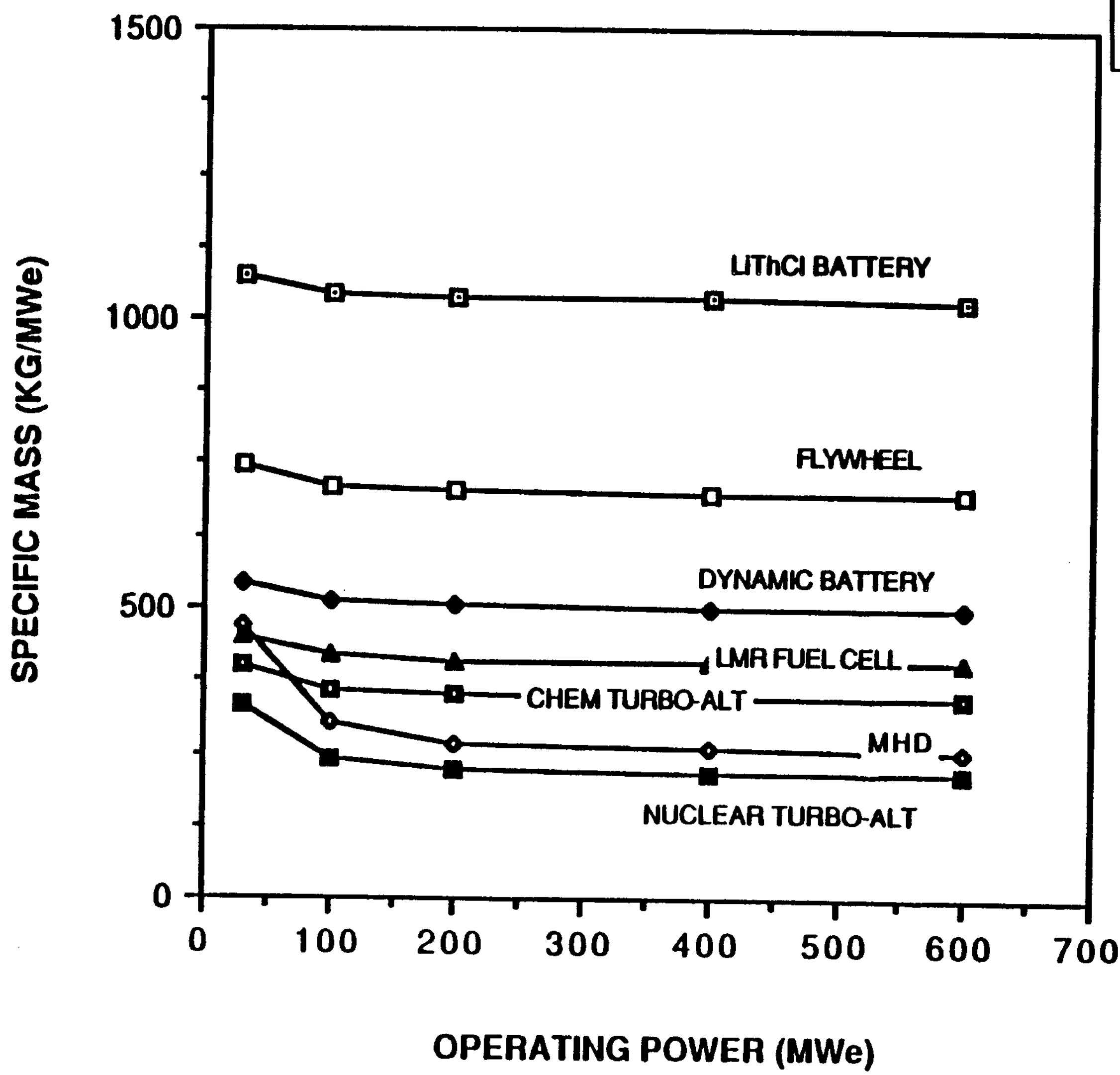
The term S/S on the chart signifies that these are power subsystem specific mass values.

GENERAL ELECTRIC

Lockheed

NPB/FEL S/S SPECIFIC MASS VS OPERATING POWER

AFSTC SPACE POWER ARCHITECTURE STUDY



BURST POWER SYSTEM CONCLUSIONS:

All three contractors agree that open, burst, space power systems are significantly lighter than closed systems. We have pointed out some errors, inconsistencies, and disagreements in the system designs used, but none of them are serious enough to change the above conclusion.

The selection of a particular open system will depend on refined system integration studies, technology advances, and other considerations besides weight, because their weights are too similar to make a choice based on weight alone. The selection will depend heavily on whether high voltage alternators and/or lightweight, cryocooled power conditioning equipment can be developed and on the voltage and other attributes required by specific users.

While open systems are lighter at long run times, closed systems may be competitive at run times less than around 200 seconds if such run times have a place in the SDI architecture. Closed systems may be required if further studies uncover a phenomenon that makes platforms intolerant to hydrogen effluent.

Burst Power System Conclusions:

There were many burst mode inconsistencies and errors, but none serious enough to invalidate the main conclusion -Open systems are lighter than closed.

The different open systems--reactor-TG, H-O combustion TG, MHD, open H-O fuel cell are too close in mass to chose among them without considering other attributes.

Closed Energy Storage Systems may compete at very short run times. They may be necessary if hydrogen effluent cannot be tolerated.

Martin Marietta and TRW elected to use high voltage alternators to avoid the mass penalty associated with transformers. They did not perform a trade-off to verify that this approach is the low mass option. There are several instances where the contractors selected components, operating parameters, or system designs without performing optimizing trade-off analyses. They selected either superconducting or cryocooled accelerators without discussing their advantages over alternatives. They selected reactor types without a comparison to others. We did not see the optimization process that led to selected turbine pressure ratios or inlet temperatures. Turbine speeds were selected without a combined turbine-alternator optimization. There were no refrigerator-cryogen tank insulation trade-offs. There were no trade-offs to determine if single tanks were better that multiple tanks. Perhaps one of the more disappointing aspects of SPAS was that the contractors used point designs. They did almost no trade-offs, comparisons, or optimizations. This kept us from determining whether the selected technology path was superior to others or whether it was selected for superficial reasons.

TRW and Martin Marietta proposed using high voltage alternators to avoid heavy step up transformers. Their high voltage alternator assumption favors systems using rotating power conversion machinery over systems that use low voltage power conversion devices such as thermionics, fuel cells, or MHD. These high voltage systems have an advantage because their power conditioning units will be much lighter than those for the low voltage DC systems, unless GE's assumption (described in the next paragraph) is true. TRW estimates 0.413 kg/kW for low voltage DC to high voltage DC and 0.124 kg/kW for high voltage turboalternator to high voltage DC power conditioning. Martin Marietta estimates 0.407 kg/kW and 0.067 kg/kW respectively. They also selected high voltage tube type instead of low voltage solid state RF generators which favors high voltage sources. This may be a valid selection for high frequency neutral particle beam weapons since tube RF sources are lighter than solid state sources at high frequency, but it may not be valid for the free electron laser which uses lower frequency RF power.

GE's lightweight, cryocooled power conditioning units do not discriminate between high and low voltage sources. This is because GE estimates such a low transformer weight that the low voltage sources, which need transformers in their power conditioning units, are not significantly penalized. However, the Field Support Team is concerned

Burst Power System Conclusions, cont.

The contractors considered point designs without tradeoffs or comparisons. This makes it difficult to determine which technologies merit development.

All three contractors had ideas for reducing PC weight:

- TRW and Martin Marietta used high voltage alternators
  - (This doesn't help low voltage systems)
- GE assumed cryo-cooled PC
  - (helps both high and low voltage systems)

Open systems got an advantage because they could use hydrogen from the weapon.

that GE's weight estimates for cryocooled power conditioning may be too optimistic and that their penalty to low voltage power supplies should be greater.

The contractors have pointed out, by tabulating total platform weight, that open systems which use hydrogen as a coolant, reactant, or working fluid can take advantage of the hydrogen used to cool the weapon. TRW and GE required hydrogen as a weapon coolant even though they assumed superconducting weapons. Both used it for RF generator cooling, and TRW used it to cool their accelerator and magnets which incorporated advanced superconductors.

Burst Power System Conclusions, cont.

The contractors considered point designs without tradeoffs or comparisons. This makes it difficult to determine which technologies merit development.

All three contractors had ideas for reducing PC weight:

- TRW and Martin Marietta used high voltage alternators
  - (This doesn't help low voltage systems)
- GE assumed cryo-cooled PC
  - (helps both high and low voltage systems)

Open systems got an advantage because they could use hydrogen from the weapon.

V. SYSTEM STUDIES

A. BURST SYSTEMS

2. OPEN SYSTEMS

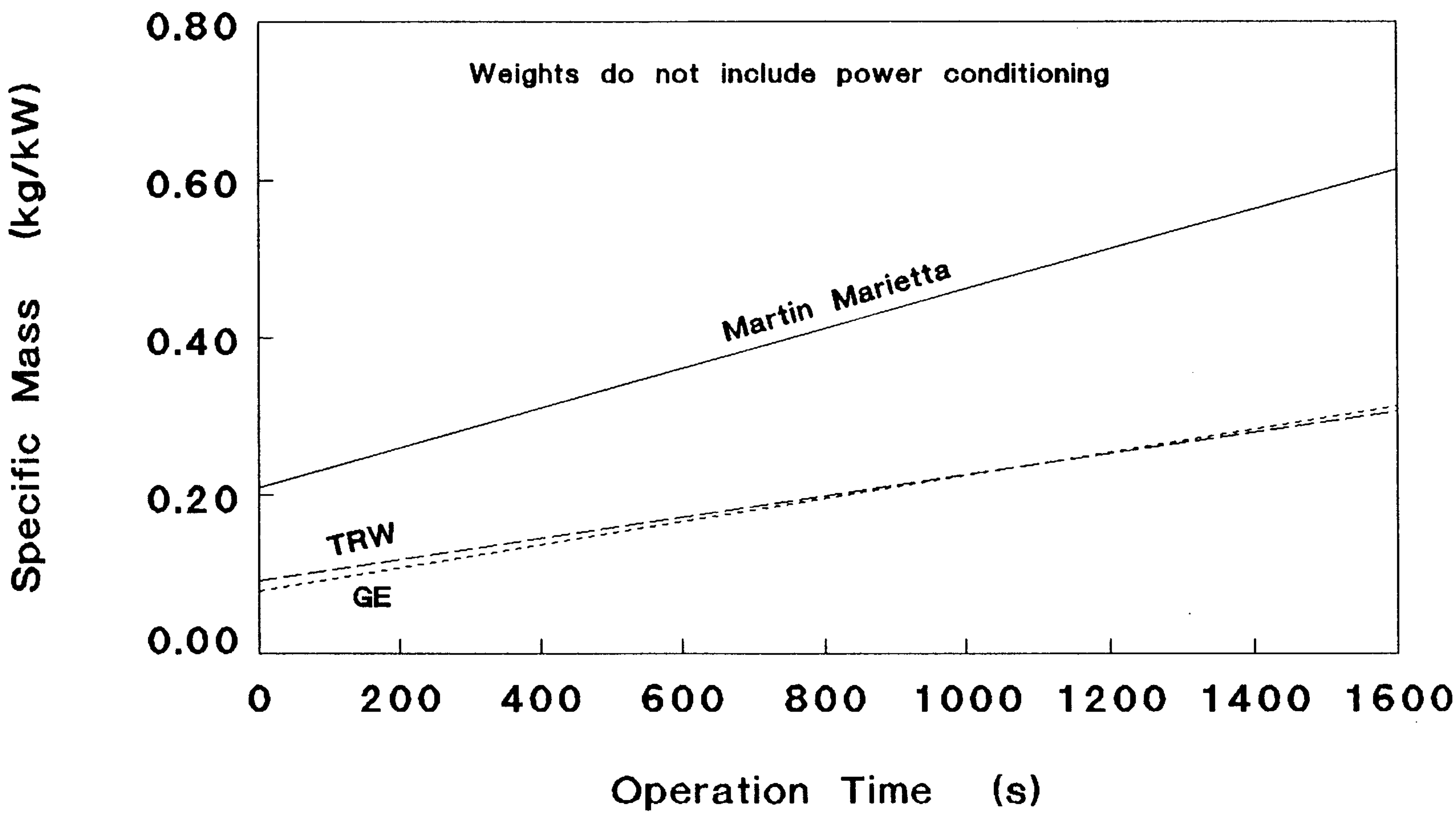
a. TURBOALTERNATOR SYSTEMS

MM REACTOR-TURBOALTERNATOR POWER SYSTEM WEIGHT ESTIMATE IS HIGHER THAN GE, TRW'S

This chart compares the contractors' weight estimates for an open, burst mode, gas cooled reactor NPB power system that uses a turboalternator for power generation. Martin Marietta and TRW did not scale system mass with operation time. To find this scaling, we drew a line between their mass estimate at the design operation time and their mass estimates for a "dry" system (zero operation time). We normalized system mass by dividing by system power to remove differences due to different power levels. Martin Marietta's system is heavier than the other two. There are two reasons for this. Martin Marietta's generator is substantially heavier than either TRW's or GE's (see the following table), and they use twice as much hydrogen as the other two contractors. Martin Marietta also uses a very light tank which has no meteoroid protection, and this light tank tends to offset the greater quantity of hydrogen making their hydrogen mass penalty smaller than it should be.

The weights in the chart do not include power conditioning. Power conditioning will be discussed in a later section.

MM Reactor-Turboalternator Power System Weight Estimate is Higher than GE, TRW's



THE MARTIN MARIETTA SYSTEM IS HEAVIER BECAUSE OF GENERATOR WEIGHT AND MORE HYDROGEN FOR WEAPON COOLING

These component mass breakdowns show the different assumptions the three contractors made for an open, reactor burst power system that powers a NPB platform. Their reactor weights are within normal error bands of what we calculate for similar reactors, except that GE has a shield which we believe is unnecessary. We also compared their turbine masses and performances with values calculated using our models. TRW and Martin Marietta's turbine masses are reasonable, but we think they overestimated their hydrogen flow rate by about 10 to 20% based on an enthalpy balance. GE's turbine is a little light but not totally unreasonable. Martin Marietta's generator weight, 0.16 kg/kW, is quite heavy. They elected to use a Lundell-Rice generator because of its high speed capability which will allow its associated turbine to operate at a high speed thereby reducing its mass and reducing its number of stages. Martin Marietta did not show mass comparisons in their report between systems using more conventional generators and those using the Lundell-Rice generator, thus it is not clear that this rather heavy, unconventional machine would in fact give a system mass benefit. In our models we have used 0.05 kg/kW which agrees well with the masses used by TRW and GE. However, Martin Marietta and TRW are both using very high voltage (75 kV and 105 kV respectively) generators, and there may be a mass penalty associated with the high voltage. All three use very low power conditioning masses. GE assumes a very low mass because they use cryocooled transformers. Cryocooling keeps conductor size and magnetic core size compact. Martin Marietta and TRW use low mass, power conditioning units because their high voltage generators obviate the need for transformers. (The dominant weight in a power conditioning unit that boosts voltage is its transformer.) We must point out that neither Martin Marietta nor TRW did a trade-off analysis to show that the disadvantages associated with high generator voltage are compensated for by lower power conditioning mass.

TRW and GE use about the same mass of hydrogen per kWh of electrical energy supplied to the weapon. Recall that they both use superconducting accelerators with very low cooling requirements, and their hydrogen use is determined by power system needs. (While their accelerator cooling requirements are small, their weapons still need hydrogen coolant for the weapons' RF generators. This can be done with power system hydrogen before it is used by the power system.) Martin Marietta uses twice as much hydrogen per kWh of electrical energy supplied to the weapon as TRW or GE. They use a cryocooled accelerator which determines the

The Martin Marietta System is Heavier Because of Generator Weight and more Hydrogen for Weapon Cooling

Power System	TRW	MM	GE
Reactor (kg/kW)	.009	.022	.020
Turbine	.023	.024	.012
Generator	.060	.164	.047
	.092	.210	.079
Hydrogen			
Hydrogen (kg/kWh)	.329	.792	.324
Tank, etc.	.154	.116	.203
	.483	.908	.527

THE MARTIN MARIETTA SYSTEM IS HEAVIER BECAUSE OF GENERATOR WEIGHT AND MORE HYDROGEN FOR WEAPON COOLING (cont.)

hydrogen requirement. (While the accelerator's cooling requirement is not large, it must be kept very cold, and the allowed temperature rise in the coolant is only a few degrees. Because of this a large flow rate is needed.) GE and TRW have tank weights which suggest some meteoroid protection, but Martin Marietta's tank has no meteoroid protection.

Keep in mind that each of these systems uses a different technology. Martin Marietta uses an 800 K turbine inlet temperature while TRW and GE use temperatures between 1500 and 1600 K. In fact, TRW assumes the use of a carbon composite turbine.

Total power system weights for the three systems agree fairly well with those that we, the Field Support Team, calculated when we use the same parameters that the contractors used. The parameters they used, turbine inlet temperatures and hydrogen flow rates, were quite different.

The Martin Marietta System is Heavier Because of Generator Weight and more Hydrogen for Weapon Cooling

Power System	TRW	MM	GE
Reactor (kg/kW)	.009	.022	.020
Turbine	.023	.024	.012
Generator	.060	.164	.047
	.092	.210	.079
Hydrogen			
Hydrogen (kg/kWh)	.329	.792	.324
Tank, etc.	.154	.116	.203
	.483	.908	.527

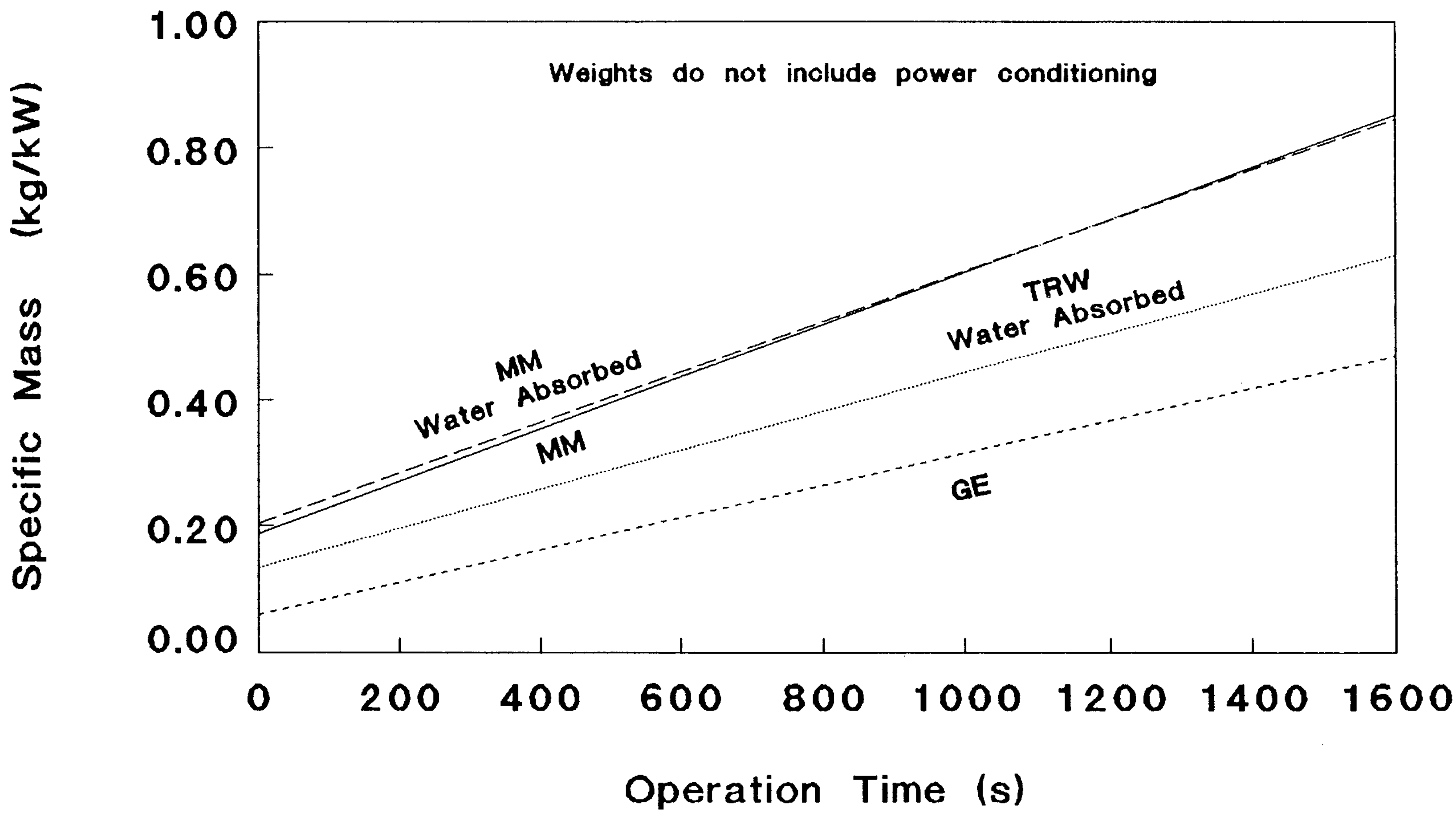
MM ESTIMATED HIGHER COMBUSTION-TURBO-ALTERNATOR SYSTEM WEIGHTS THAN GE OR TRW

This chart compares hydrogen-oxygen combustion systems. The differences between the three contractors are the same as for the open reactor systems. The penalty associated with removing water from the power system exhaust is also shown here. Both TRW and Martin Marietta proposed designs for removing water from the power system's exhaust. TRW used a titanium reactor and Martin Marietta used a method proposed by Sundstrand. Sundstrand's method burns a stoichiometric mixture of hydrogen and oxygen to heat hydrogen in a combustion heat exchanger. The hydrogen leaving the heat exchanger is divided into two paths. The larger goes to the turbine, and the smaller supplies hydrogen for combustion. The combustion products are condensed by cold hydrogen in a heat exchanger and stored. Sundstrand's water removal equipment adds very little mass to the system as can be seen by comparing the two Martin Marietta curves. TRW's method is somewhat heavier as can be seen in the following table.

It appears that Martin Marietta's water absorbing system becomes slightly lighter than the non-absorbing system when operation time exceeds 1100 seconds. Their data indicates that the water absorbing system uses less oxygen than the other system, and this offsets the mass added by the combustor and heat exchangers needed by the water absorbing system when operation time exceeds 1100 sec. The water removal system comprises heat exchangers in the combustor and in the water condenser. Their weights depend on power level and not on run time; hence, the water removal equipment does not get heavier with increasing run time as one might expect. Since the oxygen saved does depend on run time, the slopes of the two curves are different. We have not estimated heat exchanger, combustor, or oxygen weights for the water absorbing system and cannot verify this conclusion. Recall that Martin Marietta did not scale with operation time; thus, they may not be aware of this result.

As before, these system weights agree fairly well with those that the Field Support Team calculated for similar systems.

MM Estimated Higher Combustion-Turbo-alternator System Weights than GE or TRW



THIS COMPARES H-O COMBUSTION SYSTEM WEIGHTS MM AND TRW HAVE WATER ABSORBING EQUIPMENT

This chart shows specific weights for combustion turboalternator systems. Martin Marietta considered a system that exhausts both water and hydrogen into space and a system that absorbs the water and only exhausts hydrogen. GE considered only a system that exhausts both hydrogen and water into space, and TRW only considered one that absorbs the water. Most of the component mass differences in this table were discussed in a preceding chart on the reactor powered turboalternator system. This chart also includes specific masses for water absorption equipment in the columns labeled "H only". Martin Marietta's water absorption equipment is claimed to weigh only 0.016 kg/kW + 0.034 kg/kWh, while TRW's weighs 0.375 kg/kWh.

TRW and GE use a heat exchanger to preheat hydrogen entering the combustor, but they estimated very different weights for it.

Martin Marietta absorbs water using Sundstrand's idea for separating the flow of combustion hydrogen from that going to the turbine. Steam, resulting from combustion, is condensed using cold hydrogen. TRW absorbs water with a titanium reactor. Hydrogen and oxygen react to form water which passes through the titanium reactor and is reduced. The resulting hydrogen powers the turbine, and the TiO_2 is stored as a solid.

An important conclusion here is that the water from hydrogen-oxygen combustion can be absorbed with little mass penalty. Thus, if hydrogen is an acceptable effluent, then combustion systems can be used even if water effluent is not acceptable.

This Compares H-O Combustion System Weights MM and TRW Have Water Absorbing Equipment

	MM	GE	MM	TRW
Power System	H+W Effl	H+W Effl	H only	H only
Turbine (kg/kW)	.024	.013	.024	.023
Generator	.164	.047	.164	.060
HX & Combustor		.001		.052
Water absorber			.016	
	.188	.060	.204	.135
Fuel				
H (kg/kWh)	.792	.331	.792	.356
H Tank	.116	.214	.116	.154
O	.558	.351	.504	.156
O tank	.013	.025	.013	.023
Water Absorber			.034	.375
	1.479	.921	1.459	1.113

V. SYSTEM STUDIES

A. BURST SYSTEMS

2. OPEN SYSTEMS

b. MHD SYSTEMS

IV.A.2.b. MHD SYSTEMS

MHD power systems have several potential advantages over more conventional approaches to space-based power systems. These advantages include: no moving parts, simplicity and reliability of operation, potential for high enthalpy extraction via high temperature capability, very rapid startup and shutdown capability, large pulse length flexibility, favorable scaling to large size and the ability to provide load protection by shorting the MHD generator output terminals. The major disadvantages of these systems, as analyzed by the contractors, are their need for seeding the working fluid with an easily ionizable material, e.g.; cesium, in order to obtain an electrical conducting working fluid and their output voltage (1-10 KV) which requires the use of heavy inverters to match the loads considered in this study.

Four MHD systems were downselected from Task 2 for analysis in Task 3. The Martin Marietta H2-O2 combustion driven, open cycle and the GE particle bed reactor heated H2, open cycle MHD systems were chosen for direct comparison to turboalternators operating with the same heat sources. The TRW Gel combustion driven, open cycle was selected because its oxident (inhibited red fuming nitric acid) and fuel (Beryllium gel) are storable at room temperature and hence could have a significant advantage over systems requiring long term cryogenic storage. The fourth MHD system is based on the concept of non-equilibrium ionization, which as considered by TRW offers the potential for very large enthalpy extractions and hence very high specific powers.

MHD POWER CONVERSION CONCEPTS

1. MARTIN-MARIETTA
   H_2-O_2 COMBUSTION DRIVEN, OPEN CYCLE
   EFFLUENT—H, O, CESIUM COMPOUNDS @ $\simeq$ 2100 K

2. GENERAL ELECTRIC
   PBR H_2 HEATED (3000 K), OPEN CYCLE
   EFFLUENT—H_2 AND CESIUM @ $\simeq$ 2400 K

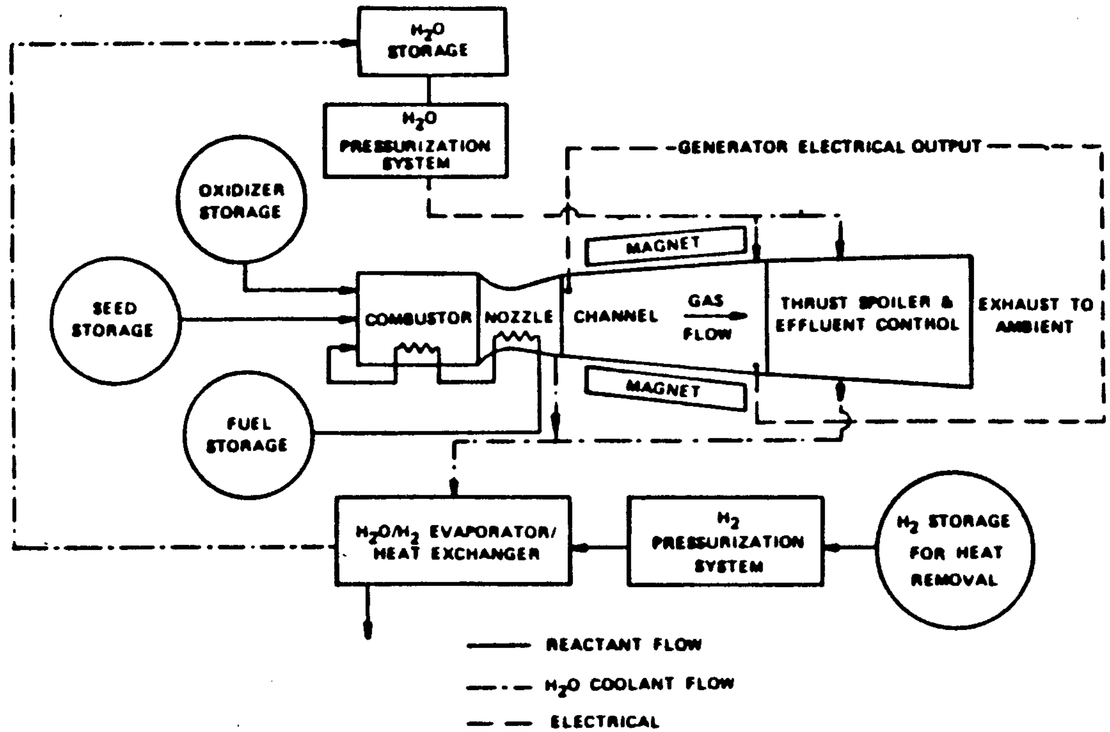
3. TRW
   GEL COMBUSTION DRIVEN, OPEN CYCLE
   EFFLUENT—BEO, N_2, NO_X, KOH, LIO2 @ $\simeq$ 2200 K

4. TRW
   NDR H_2 HEATED (2900 K), OPEN NON-EQUILIBRIUM CYCLE
   EFFLUENT—H_2 AND CESIUM @ 800 K

MM - H2 Combustion Driven MHD

The MHD system uses nearly stoichiometric burning of H2/02 to provide the input enthalpy and a small percent of cesium to provide the electrical conductivity to the MHD channel. The MHD channel utilizes a superconducting magnet with a 6 tesla field strength to provide interaction with the working fluid. The cycle is open and exhausts the working fluid to space at approximately 2100K.

The combustor and nozzle are cooled by the burn H2 prior to injection into the combustor while the channel and diffuser are cooled by a separate pressurized, closed H20 system which in turn is cooled by stored hydrogen which is then exhausted to space.

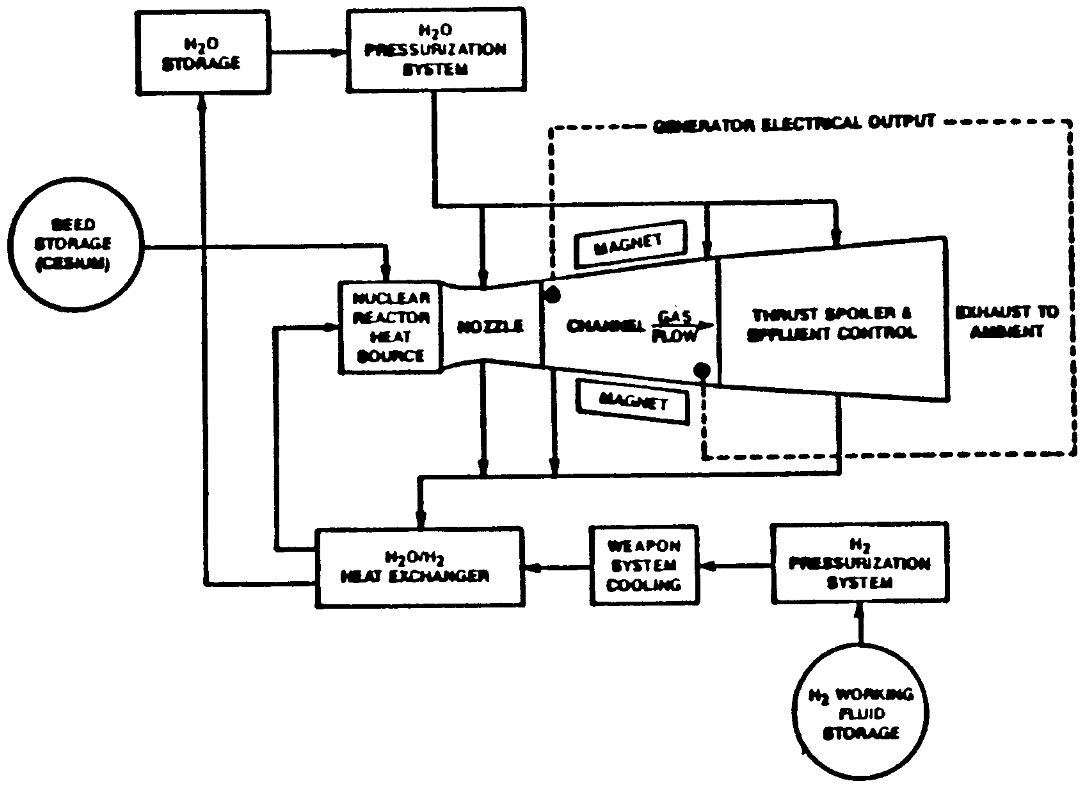


Combustion-Driven MHD Power System Schematic

Martin-Marietta Concept

GE - PBR H2 Heat MHD Generator

In this concept H_2 is heated in a particle bed reactor to 3000K, seeded with cesium to provide electrical conductivity and passed through an MHD generator. The generator components are all water cooled with the heat exchanged via a H_2O/H_2 evaporator/heat exchanger to the H_2 inflow to the combustor. In this application there is sufficient H_2 mass flow through the generator to cool the H_2O so that only the MHD generator effluent is exhausted from the MHD generator. The MHD generator was a single radial outflow disk using a Helmoltz pair of cryo-cooled magnets having a peak magnetic field strength of 4 tesla.



Particle Bed Reactor Heat H2 MHD Power
System Schematic - GE Concept

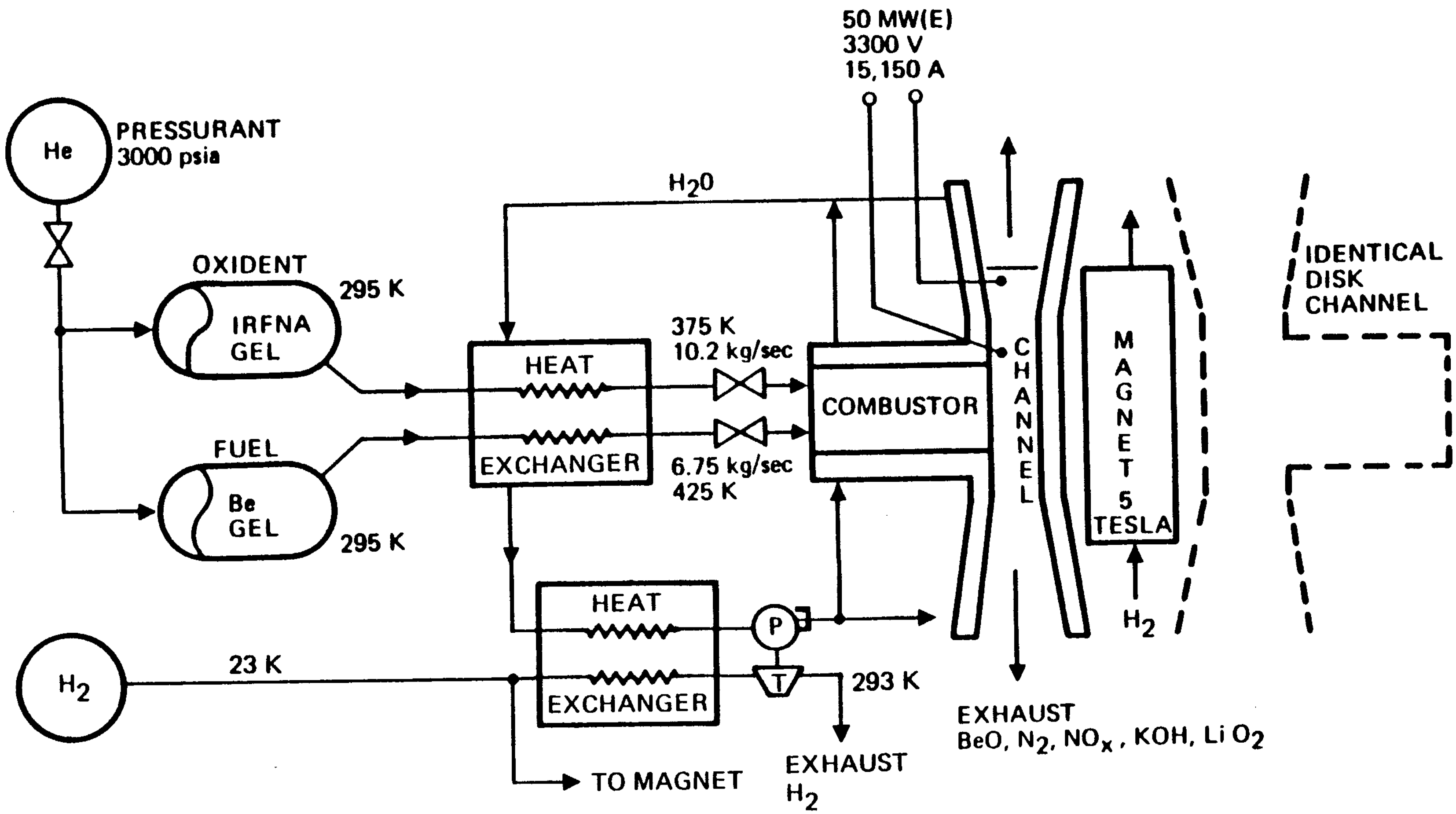
TRW-GEL Combustion Driven MHD Generator

This concept uses beryllium as a fuel and inhibited red fuming nitric acid as the oxidizer. The basic advantage of the system is that the fuel and oxidizer are storable at room temperature.

The MHD generator configuration chosen is that of the radial flow disk type. This configuration has a distinct advantage over the linear configuration in the design of the magnet. In the linear design the magnet is a pair of saddle coils requiring complicated windings and complex support structure. The disk requires a conventional coil magnet which has the added advantage of being usable to provide the magnet field to 2 MHD channels - one on either side of the coil. The magnetic field strength was 5 tesla.

The combustor and channel are water cooled with some partial recovery of the heat by exchanging it to the incoming fuel/ox before the water is cooled by stored H_2 which is exhausted while the water is recirculated.

Disk Channel MHD
Beryllium-Nitric Acid Reactor
Concept Schematic
Open Cycle Magnetohydrodynamics

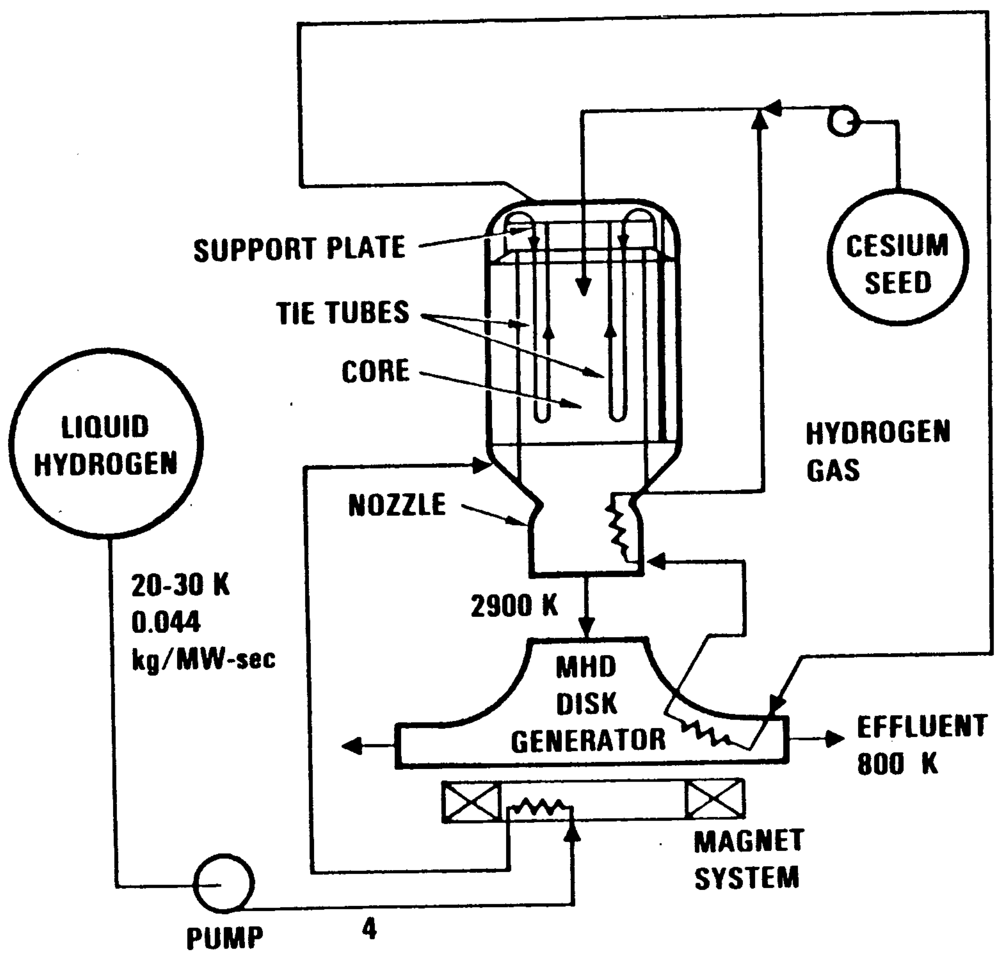


TRW - NDR H2 Heated MHD Non-equilibrium Generator

In this concept a NERVA derived nuclear reactor is used to heat H_2 to 2900K. The heated H_2 seeded with a small percent of cesium to provide electrical conductivity is used as the MHD generator working fluid. Unlike other MHD concepts considered in SPAS this generator operates on the non-equilibrium principle in which Joule heating of the electrons allows their temperature and hence the conductivity of the gas to be higher than it would be if associated with the gas temperature. In this manner enthalpy in theory can be extracted to much lower temperatures (800K versus 2200K).

While non-equilibrium MHD power devices have been tested the application considered here is far beyond anything that has been demonstrated to date and the proprietary nature of the concept did not allow any detailed information to be presented. Without further detail this concept must be considered speculative at best.

Power Source Concept
NDR/MHD



- NERVA Derivative Reactor (NDR)
- Open cycle MHD disk generator
- Cesium seeded hydrogen working fluid
- 1% cesium fraction in effluent

Mass Comparison of MHD System Vs. Power
1000 Sec. Operation

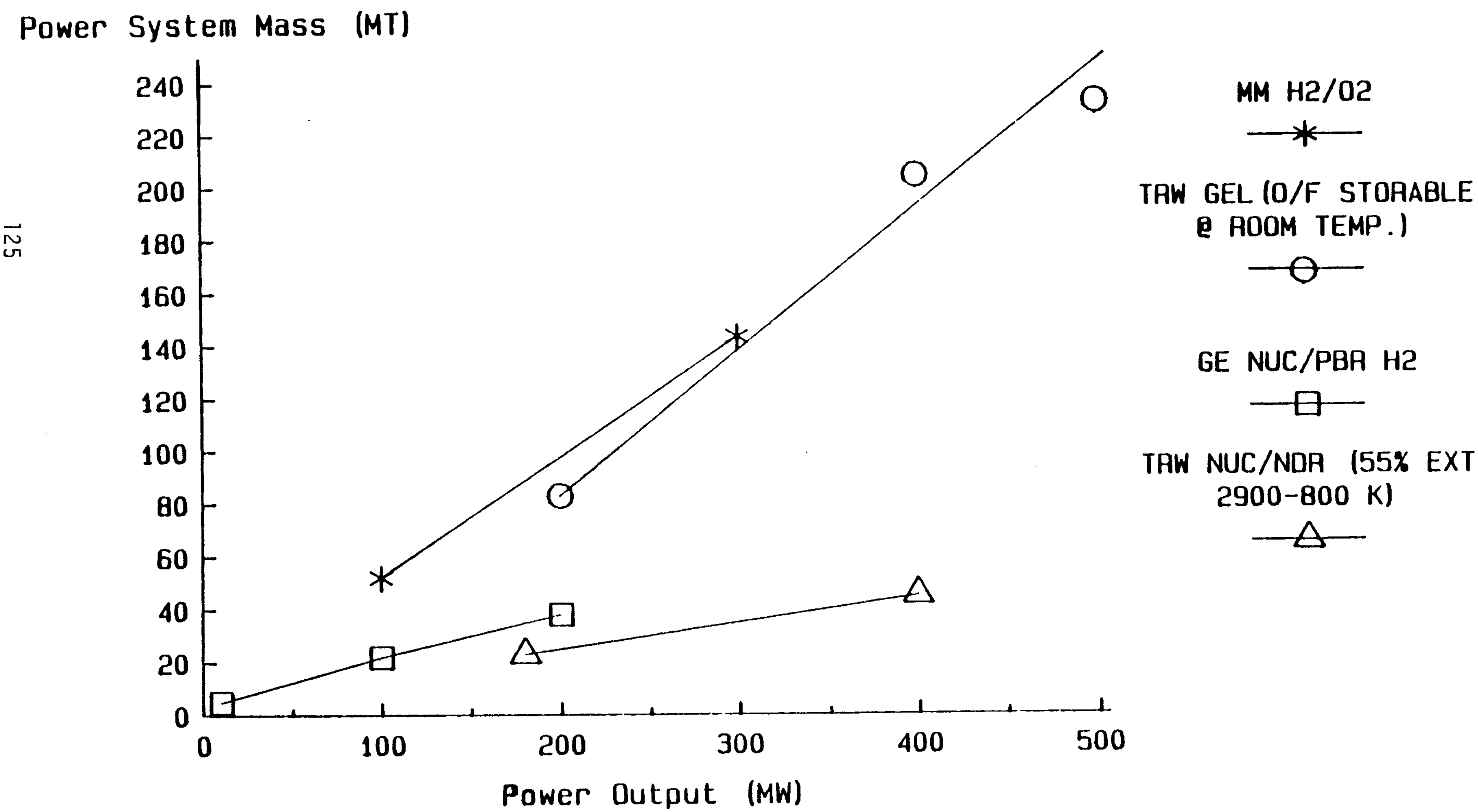
In order to compare the MHD subsystems on same basis the curves are shown without the power conditioning subsystems which vary in weight between contractors by large amounts due to factors not associated with the MHD process.

The best system on a mass basis is the TRW NDR concept utilizing non-equilibrium MHD. The non-equilibrium process allows in theory enthalpy extractions up to 55% for the system as compared to the 15-20% realilzable for the other MHD concepts. However, the details of this concept were considered proprietary by the offeror and hence no technical judgement as to the realism of this concept could be made. Until such information is available this concept should be considered speculative at best.

The two combustion concepts have the highest mass and on that basis are comparable. The advantage of the GEL system is that the fuel and oxident are storable at room temperature while other concepts require long term storage of cryogens. It's disadvantage is that it cannot utilize "free" hydrogen from the weapon if it is available. No credit for free hydrogen is shown on these curves.

The GE PBR H2 heated MHD concept has a mass approximately twice that of the TRW non-equilibrium case as a result of its substantially lower enthalpy extraction but represents a factor of two reduction in mass as compared to the combustion cases. Its lower mass relative to the combustion cases is due to not requiring an oxidizer which for a run time of 1000 sec represents a sizable fraction of the system weight.

Mass Comparison of MHD Systems vs Power
1000 sec



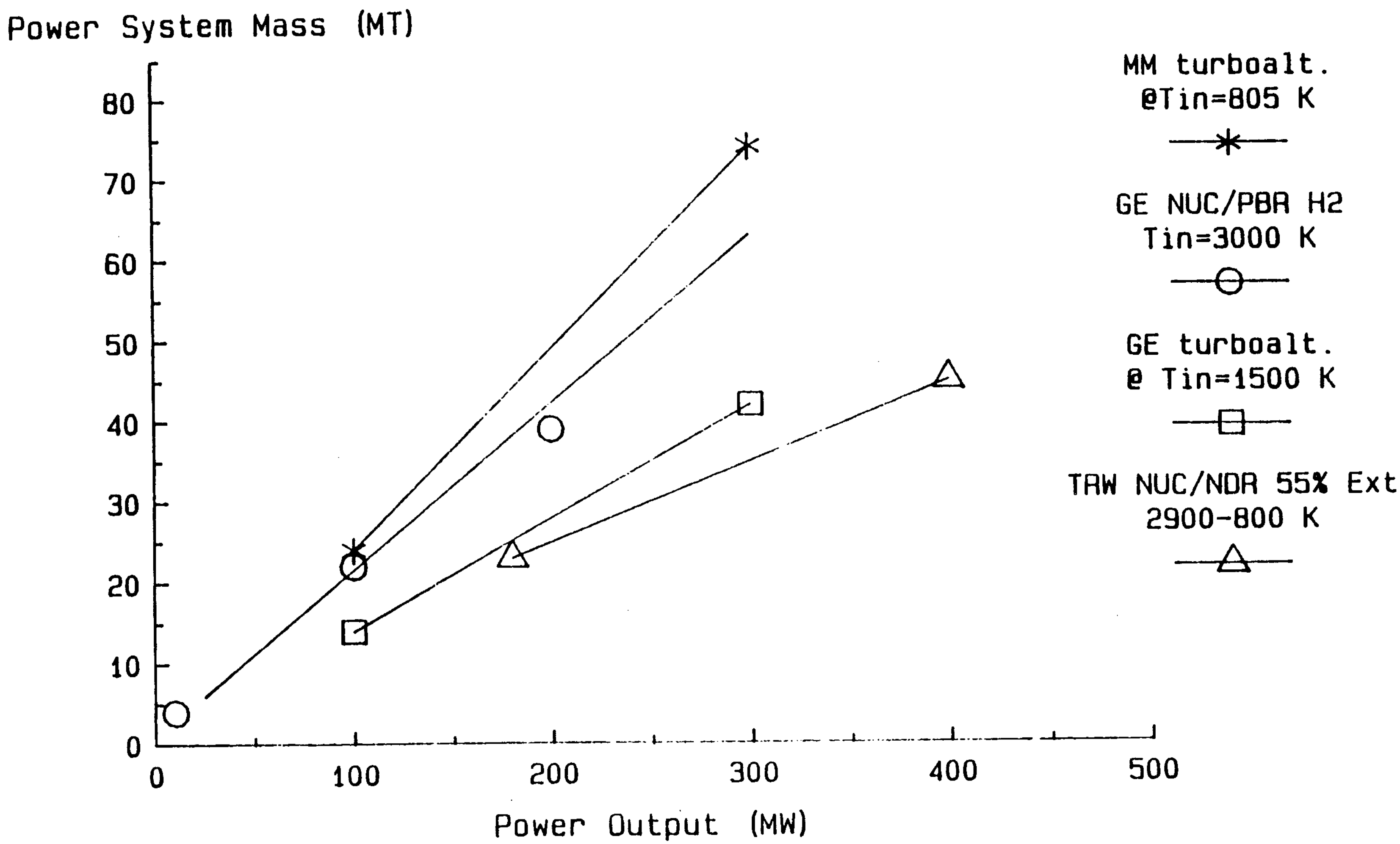
Mass Comparison of MHD Vs. Turboalternators
1000 Sec

Having shown that nuclear systems are lighter than combustion systems, the MHD versus turboalternator (TA) comparison is made for the nuclear heated systems only. In order to make a consistant comparison between contractors the systems are compared without power conditioning due to the large difference between contractors on PC philosophy as previously discussed. This exclusion tends to favor MHD. If high voltage turboalternators (70-100 KV) prove feasible they would require little further conditioning to match weapon requirements. However the MHD generator output of a few KV requires considerable more interface conditioning and hence weight.

The system with the greatest mass was the MM TA. This results from the MM design which cryo-cooled the weapon so that the weapon has more H2 than power system needs. This allowed MM to lower the turbine inlet temperature to 800K which makes the system in the range of SOA. The GE TA is much lighter than MM TA because of the S.C. weapon (NPB & FEL) design which grossly reduces cooling so that the power conversion system dominates H2 requirements and leads to the desirability of a high efficiency (high temperature-1500K) turbine which will require a fair degree of development. This higher efficiency results in less expendables being required by the GE TA power system and hence a lower power system mass.The TRW MHD system is the lightest for reasons given previously in the MHD comparison and must be considered as very speculative.

Based on the above discussion related to different contractor weapon/power cooling concepts, power conditioning philosophy, technology time frame, etc. the subsystem comparison only represents a comparison of results as presented and does not represent a direct comparison of turboalternator versus MHD subject to the same overall constraints. Furthermore, the SPAS exercise was to optimize the overall weapon/power system with different contractor philosophies as to what this optimum should be based on all factors: mass, volume, vibration, effluents, etc. Therefore, the results presented do not necessarily represent optimized subsystems.

Comparison of Contractor Results for MHD and Turboalternator Subsystems - 1000 sec Different Contractor - Weapon/Power System Philosophies



V. SYSTEM STUDIES

A. BURST SYSTEMS

2. OPEN SYSTEMS

c. FUEL CELL SYSTEMS

OPEN BURST SYSTEMS--FUEL CELL

Open systems appear to be the most competitive prime power sources for electrically driven weapons. The most attractive open burst power sources were those which made use of the weapon coolant as a working fluid and/or chemical energy supply. That is because the weapon accelerator cavity, which must be maintained at cryogenic temperatures to operate, is normally cooled with liquid hydrogen using vaporization to control temperature. At multimegawatt power levels copious amounts are required. Usually the flow required to provide this cooling is so great that the weapon effectively cannot be made closed cycle; copious amounts of hydrogen will be vented overboard. Since more hydrogen is used for weapon cooling than what is needed for power generation, there is little incentive to maximize generator efficiency. All of the hydrogen working fluid/fuel can be charged to the weapon. A low temperature combustion turbine, flowing excess hydrogen, provides the lowest specific weight source.

If the weapon accelerator cavity could be made superconducting, however, the amount of cooling required would drop sharply. Effluent from the weapon would be greatly reduced; theoretically closed cycle operation might be possible. In this case (G.E. assumed superconducting accelerator cavities) a significant fraction of the working fluid/fuel is charged to the power source and not the weapon--which provides strong incentive to minimize the amount of working fluid/fuel needed per electrical megawatt-second delivered.

The open cycle fuel cell was identified as the most attractive electrochemical power source because it was synergistic with the weapon (using weapon coolant as fuel) and operates at high efficiency. It was also lower in vibration and dynamic effects than the combustion turbine.

The fuel cell converter specific weight is higher than that of the turboalternator, but it uses less reactants because its conversion efficiency is higher than combustion systems (sixty-to-seventy percent not Carnot limited); resulting in less waste heat to reject. This is a big advantage if the power system has to be closed cycle, but has no impact for open cycle. Unlike turbine driven rotating machines the fuel cell is inherently a low voltage device. This imposes a power conditioning penalty unless low voltage solid state amplifiers are used to drive the accelerator cavity. However, individual cells can be stacked in series to yield outputs of up to hundreds of volts.

Two fuel cell technologies were considered for burst power: the high power density (HPD) alkaline fuel cell developed by United Technologies Corporation (UTC) and the high temperature monolithic solid oxide fuel cell (SOFC) developed by Argonne National Labs (ANL). Martin-Marietta and TRW were furnished alkaline fuel cell technology information and complete SDI burst power system designs (both open and closed cycle) by UTC under subcontract. G.E. took a system design for their solid oxide fuel cell systems, originally proposed by ANL for SDI application. This design was for a very advanced high temperature closed cycle regenerative system. G.E. used portions of this design for their open cycle systems.

OPEN BURST SYSTEMS -- FUEL CELLS

The contractors investigated three open burst systems based on fuel cells.

Martin-Marietta

1.) Open cycle HPD alkaline (vent spent hydrogen and product water overboard)

2.) Open cycle HPD alkaline (vent hydrogen but condense the water)

GE

3.) Open Cycle (design is based on closed RFC) high temperature monolithic solid oxide fuel cell

TRW--no open cycle fuel cell systems.

The two Martin designs were based on alkaline fuel cell technology developed by UTC, the GE system was based on high temperature monolithic solid oxide fuel cell technology (Argonne National Labs.). All three of these systems used weapon coolant as fuel with stored cryogenic oxygen. Spent working fluid and waste heat were vented directly overboard; however the second Martin design (alkaline fuel cell) condensed the product water out of the exhaust stream by flowing excess weapon coolant through a condenser.

Martin Fuel Cell System

Martin provided four (4) stored energy burst prime power systems designs for each of the weapon platforms (EML, FEL, and NPB), based on high performance advanced alkaline fuel cell technology.
The information and system designs were furnished by UTC (UTC acted as subcontractor to all three SPAS primes for fuel cell systems and technology): they provided five (5) different configurations to Martin:

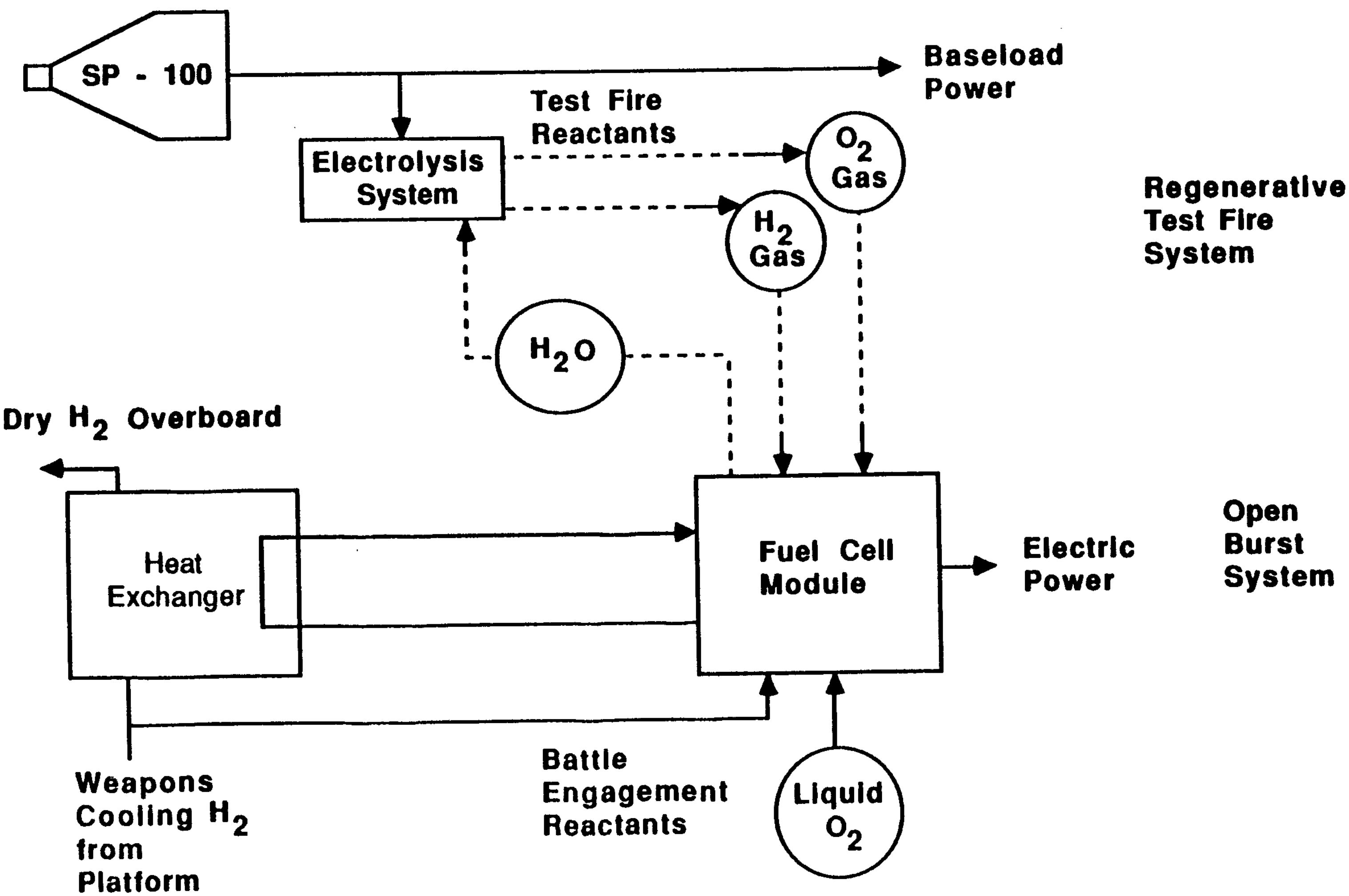
1. open cycle
2. open cycle but condense the water
3. closed cycle, steam cooling, expandable bag radiator
4. closed cycle, steam cooling, ice heat sink
5. closed cycle, methanol vapor cooling, expandable bag radiator

Martin Marietta originally presented them all in Task II, but the gov't downselected to options 2 and 4 only. At UTC's behest, Martin carried options 1 through 4 on through task 3 but presented only the downselected options in the task 3 report Appendix A summary.

Alkaline Fuel Cells Technology Issues

Performance, mass predictions for alkaline fuel cell systems are very optimistic. Stack power densities are unprecedented; have not yet been demonstrated. For example, they estimate their (Martin) open cycle stack (directly gas cooled by cryo hydrogen, oxygen streams) at 26 kWe/kg. High power densities have been shown in individual cell tests (1975 Air Force program demonstrated cell operation over 5000 ASF in pulsed mode, 3000 ASF continuous) but not yet in an integrated stack test. There is a stack test planned--the Air Force 50 kWe demonstrator program--goal is 0.31 lb/kWe (7.33 kWe/kg)--stack only, excluding ancillary components--by 1989 UTC has run individual cells at high power density. But no one has ever built a stack that runs at these power densities. High power density is more difficult to achieve in a stack due to reactant and coolant distribution, thermal management, but they are claiming a five-fold increase over the HFD power density numbers derived from individual cell tests.

Fuel Cell Open System - HO/FC/H



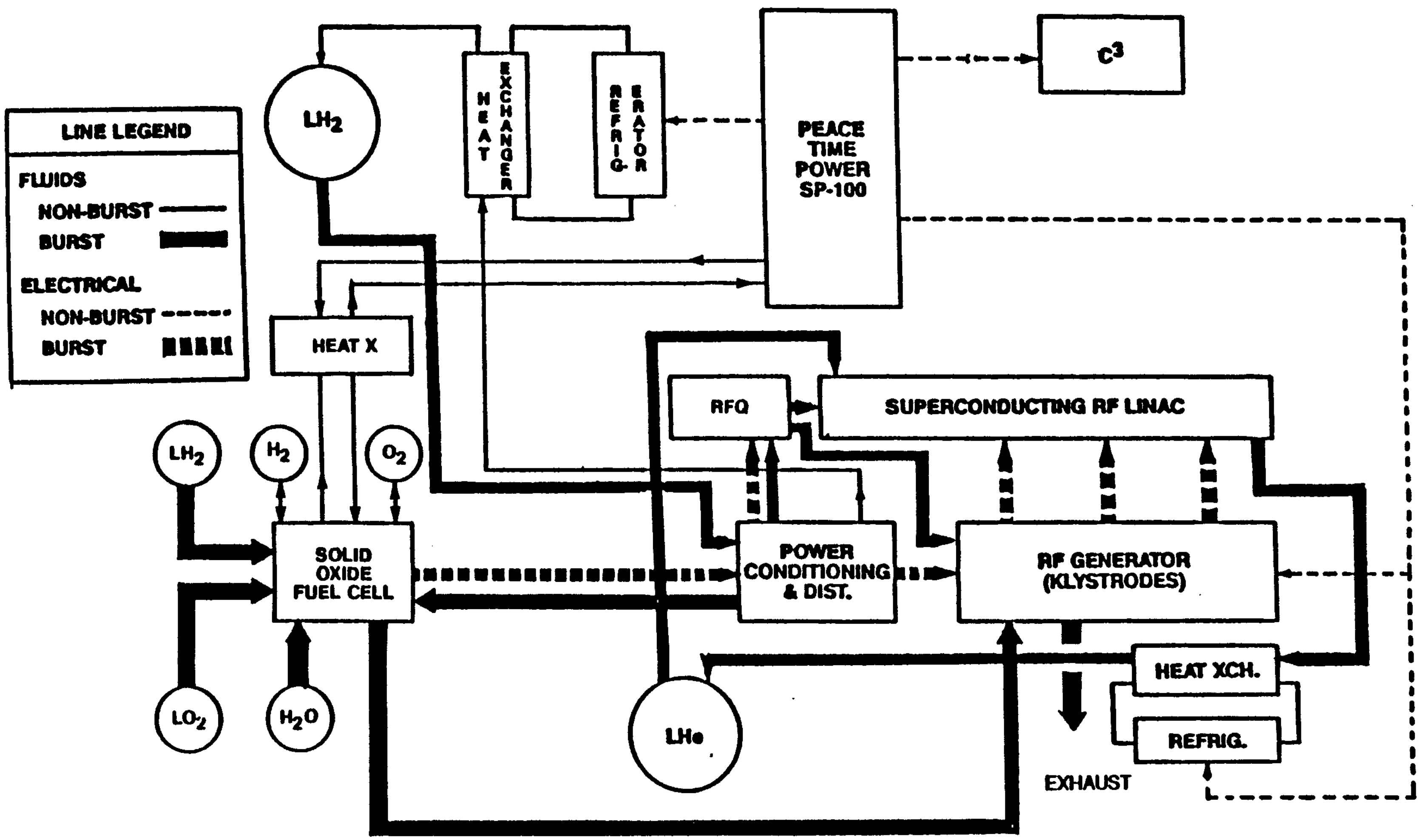
Solid Oxide Fuel Cell (G.E.)

G.E. identified the Argonne Monolithic solid oxide fuel cell as a candidate technology for energy storage, and proposed a regenerative system loosely based upon a regenerative design previously proposed by ANL in a classified report (Fee, et al, "Fuel Cell Development for SDI Applications"). Various implementations of this same basic system configuration were applied to the FEL, NPB, and RDS missions. All of the GE designs, both open and closed cycle, despite the variety of system integration options that were available as a result of the various applications and their requirements, employed exactly the same basic stack integration, inlet and outlet conditions and waste heat removal method; namely, using a recirculating loop on the oxygen side to cool the cell. This requires a high temperature gas flow loop and components--heat exchangers, ducting, pumps, impellers and radiators--that can handle pure oxygen at 1000 deg C. G.E. failed to identify fundamental feasibility issues associated with handling high temperaure oxygen, and failed to recognize the other integration options available with SOFC. There are several alternate methods of stack integration; most commonly the fuel gas stream is used to remove waste heat, by means of a recirculating loop similar to alkaline fuel cells. Since this stream maintains a reducing atmosphere, metal heat exchangers can be used. Where open cycle operation is allowed, stack integration can be greatly simplified. G.E. based their system energy storage requirements on the assumption that the entire stack would have to be heated instataneously from low temperature every time burst power was required. No investigation was made into electrical startup, or bootstrapping individual modules in sequence during the alert mode. Evidenced by their system designs, the mode of converter operation chosen; and by the development issues they raised, their understanding of SOFC technology appears so limited that their system designs, performance and mass estimates are questionable at best.

GENERAL ELECTRIC
Lockheed

NPB LMR-FC

SPACE POWER ARCHITECTURE STUDY
AFSTC



V. SYSTEM STUDIES

A. BURST SYSTEMS

2. OPEN SYSTEMS

d. ENERGY STORAGE SYSTEMS

Open Burst Systems--Energy Storage

These systems are characterized by a steady-state reactor power system (SP-100) used for housekeeping power, combined with a primary (not recharged) storage system for burst power. The primary storage system may or may not take advantage of weapon coolant as an energy source. In these systems the housekeeping power source is not used to recharge the energy storage; therefore burst power cannot be repeated.

1. All turboalternator systems (detailed discussion provided in Section V.A. 2a. of this report)
2. All MHD systems (detailed discussion provided in Section V.A.2b. of this report.
3. Open cycle fuel cell systems (HPD alkaline and SOFC, detailed discussion provided in Sectin V.A.1.c of this report)
4. Dynamic lithium/acid battery. The dynamic lithium/acid battery is discussed on the following pages.

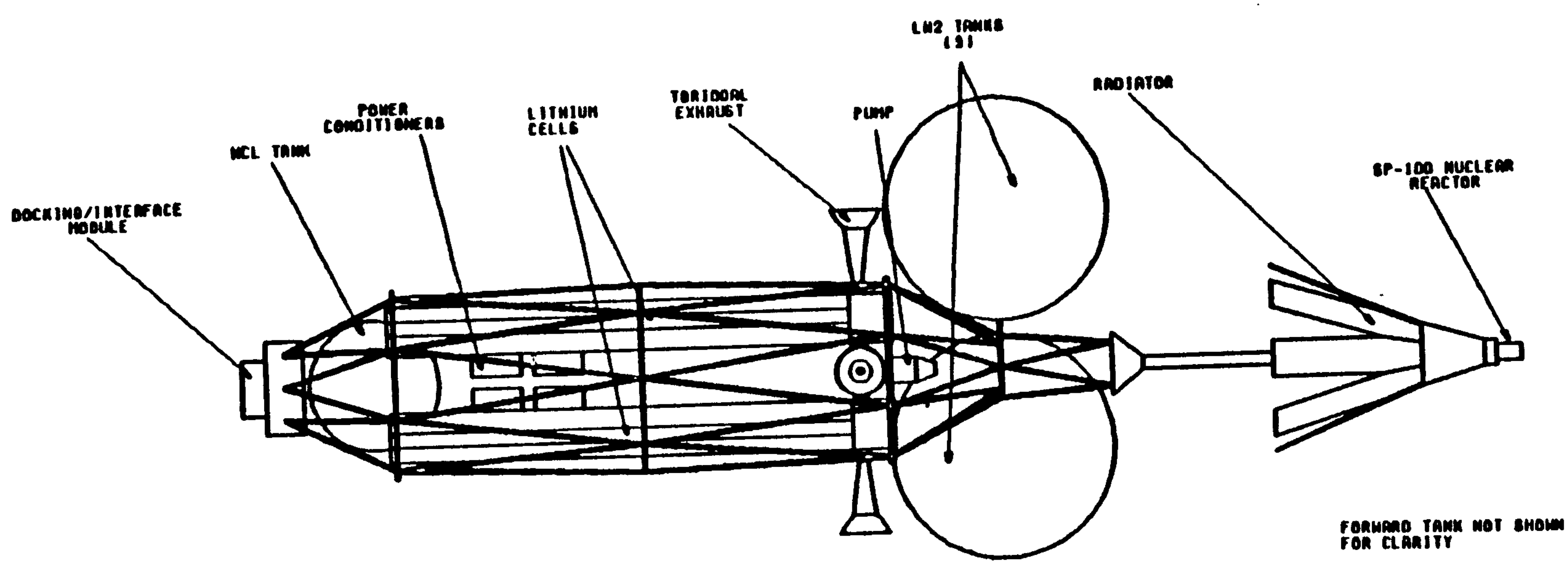
NEUTRAL PARTICLE BEAM
DYNAMIC LITHIUM/ACID BATTERY

GENERAL ELECTRIC

Lockheed

SPACE POWER ARCHITECTURE STUDY

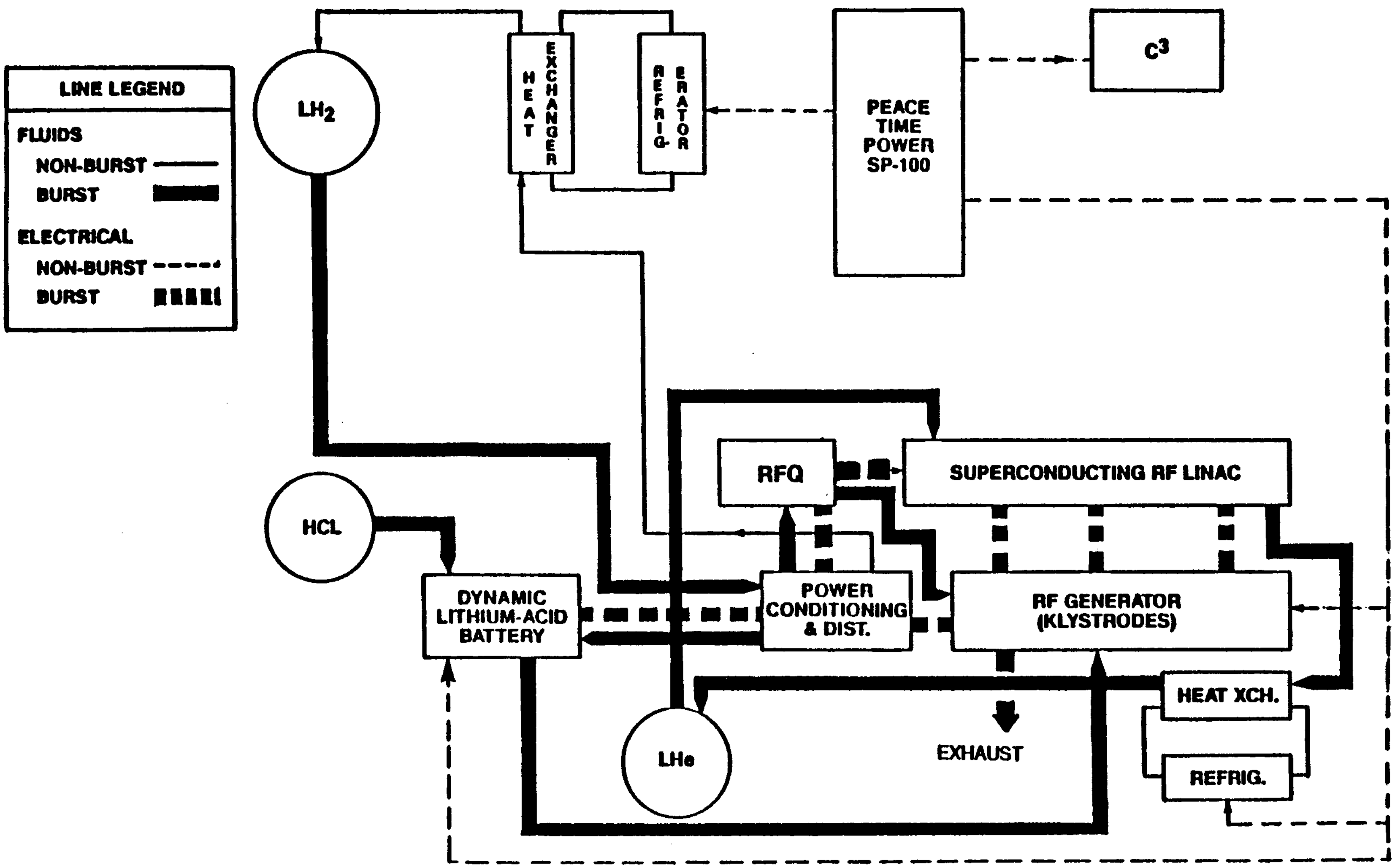
AFSTC



GE DYNAMIC LITHIUM/ACID BATTERY

A mechanical reserve primary battery for high power, short duration missions. Energy densities exceeding 400 W-hr/kg; power densities exceeding 35 Kwe/kg are claimed. The original patents were by LMSC, but are now under license to Gould. There was an experimental program supported by DARPA (F33615-83-C-2366) to establish cell voltage and current density for conceptual designs, but this program was terminated and there is no ongoing effort. This battery features a metallic Lithium anode with flowing hydrochloric acid electrolyte. Stack geometry is bipolar, operation is similar to torpedo batteries except that alternate bipolar plates in the stack rotate (mechanically similar to aircraft disc brake cluster); electrolyte flow, which carries off the gas bubbles evolved by the reaction and acts as a lubricant, is radially outward. The battery would be attractve for SDI applications because of energy and power density, indefinite storage time in orbit (would remain inert until electrolyte flows), and the potential to turn battery on and off (with additional system design features, flow can be controlled). Furthermore it is possible to reduce power conditioning requirements; plate design can be modified to provide pulsed power without switching (pulse frequency higher than plate rotation rate). G.E. claims they used data furnished by Gould to characterize the dynamic battery system they proposed. The energy storage system figure of merit they arrived at was 786 W-hr/kg.

NPB BS-3


LINE LEGEND
FLUIDS
NON-BURST
BURST
ELECTRICAL
NON-BURST
BURST
LH2
HEAT EXCHANGER
REFRIGERATOR
PEACE TIME POWER SP-100
C3
HCL
RFQ
SUPERCONDUCTING RF LINAC
DYNAMIC LITHIUM-ACID BATTERY
POWER CONDITIONING & DIST.
RF GENERATOR (KLYSTRODES)
HEAT XCH.
LHe
EXHAUST
REFRIG.

V. SYSTEM STUDIES

A. BURST SYSTEMS

3. CLOSED SYSTEMS

a. TURBOALTERNATOR SYSTEMS

TRW'S LITHIUM-HYDROGEN TURBOALTERNATOR SYSTEM ABSORBS PLATFORM EFFLUENTS

The facing chart gives the weight breakdown for TRW's 400 MW hydrogen-oxygen-lithium combustion, turboalternator system that operates for 1000 sec. It is closed because the oxygen in the water exhaust is absorbed by titanium in a reduction process, and the hydrogen exhaust is combined with lithium to form lithium-hydride which is stored as a liquid. Nothing is exhausted into space. This is the only system considered by any of the contractors that can close the entire platform since weapon cooling hydrogen is used as a fuel and then captured by the hydrogen-lithium reaction. A schematic for this system's process is shown in the chart following the one on the facing page.

The facing chart compares this system with TRW's hydrogen-oxygen combustion system that does not absorb hydrogen. The mass penalty for absorbing hydrogen is quite large. In fact, the Field Support Team believes that the penalty may be even greater than TRW estimates, because we estimate higher weights than TRW for the lithium combustion heat exchanger and for the radiator that removes waste heat from the lithium reactor.

The heat exchanger for the lithium chemical reactor will transfer heat from the hydrogen-lithium combustion process into the cold hydrogen coming from the weapon. Based on an assumed heat transfer coefficient, temperature difference, and heat exchanger wall thickness, the FST estimated 100 metric tons for the lithium reactor heat exchanger, and we think even this is probably an underestimate because there also has to be a heat exchanger that transfers heat into the excess radiator (see the description in the nest paragraph). There were no details on how TRW obtained their estimate, but their weight for the lithium chemical reactor's heat exchanger is only slightly higher that for their hydrogen preheater. We believe that it should be much more complicated and more massive.

The other big difference is for the excess heat removal radiator. The temperature of the hydrogen exiting the lithium chemical reactor must be limited to 945 K to keep the lithium-hydride in a liquid state. Because of this, more heat is being generated by the lithium-hydrogen combustion process than can be removed by the specified hydrogen flow rate. The excess heat must be removed by a radiator. The quantity of excess heat is found by subtracting the heat of fusion and the sensible heat between room temperature and melting temperature LiH from the net hydrogen enthalpy (which is positive) and the chemical energy of combustion.

TRW's Lithium-Hydrogen Turboalternator System Absorbs Platform Effluents

Fixed Weight in kg/kW	Without Hydrogen Absorbtion	With Hydrogen Absorbtion	FST Estimate Hydrogen Absorbtion
Power Conversion	.083	.083	.052
Radiator		.215	1 .358
Lithium Tank & HX	.052	.067	.250
	.135	.365	1 .660
Time Dependent Weights in kg/kWh			
Oxygen & Tank	.179	.179	.132
Titanium	.375	.314	.241
Lithium		2.439	2 .369
Hydrogen	.356	.356	.338
Hydrogen Tank	.154	.154	.250
	1.064	3 .442	3 .331

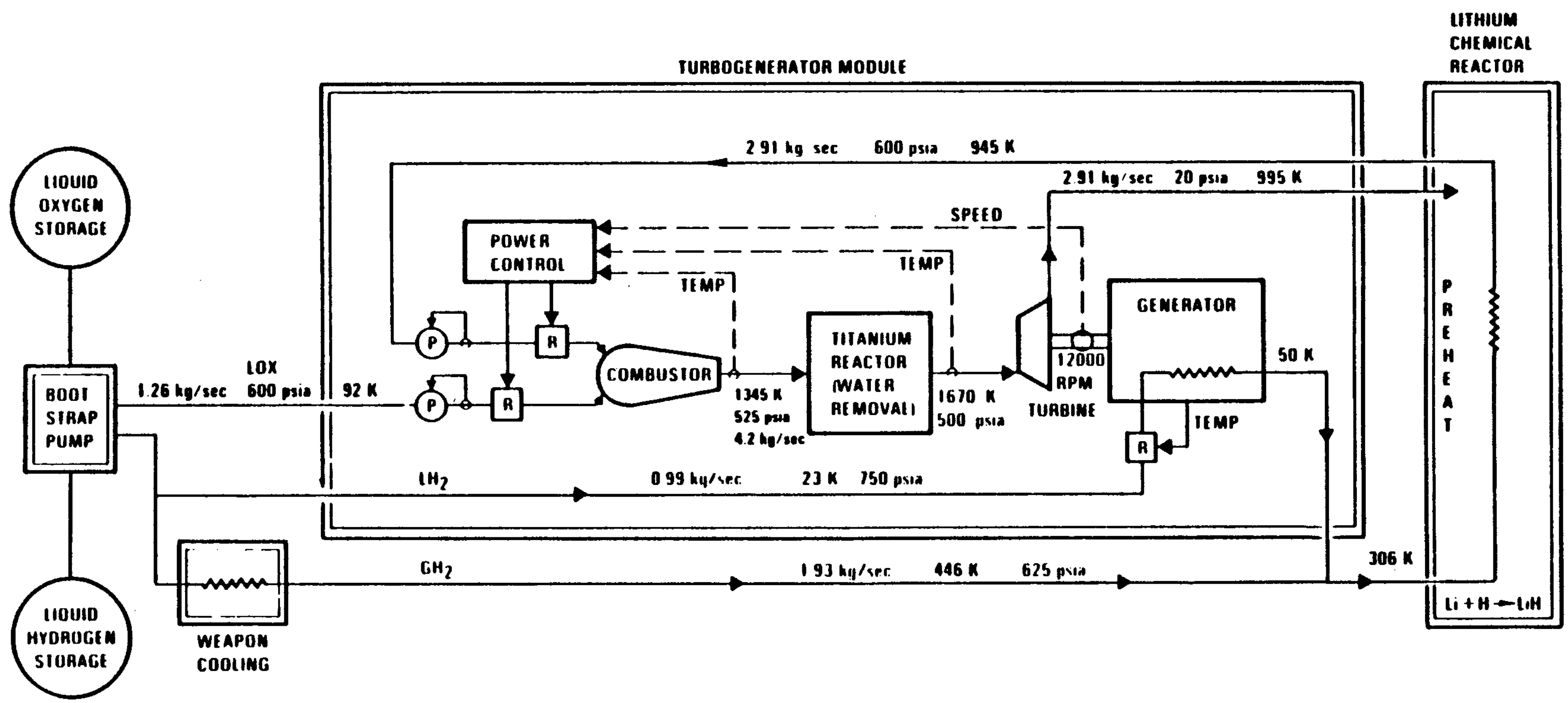
TRW'S LITHIUM-HYDROGEN TURBOALTERNATOR SYSTEM ABSORBS PLATFORM EFFLUENTS (cont.)

combustion energy	3430 MW
net hydrogen enthalpy	197
heat of fusion	-790
sensible heat	-1123
excess heat	1714 MW

A heatpipe radiator operating at 986 K and weighing 10 kg/m^2 (which is the radiator weight that the Field Support Team uses for temperatures between 650 K and 1000 K) needs an area of 36,200 m^2 and weighs 362 metric tons. Adding 25% for meteoroid losses and 20% for the evaporator heat exchanger, the total weight is 543 metric tons. We did not see TRW's weight calculation, but their weight appears to be too light even for an advanced, liquid droplet radiator.

(U) Generation Module Design (30 MW)

(U) Li + H/Turbogeneration



V. SYSTEM STUDIES

A. BURST SYSTEMS

3. CLOSED SYSTEMS

b. FUEL CELL SYSTEMS

CLOSED BURST SYSTEMS--FUEL CELL

Typically closed systems do not compete with other prime power sources for the electricaly driven weapons. That is because the weapon accelerator cavity, which must be maintained at cryogenic temperatures to operate, is normally cooled with liquid hydrogen using vaporization to control temperature. At multimegawatt power levels copious amounts are required. Usually the flow required to provide this cooling is so great that the weapon effectively cannot be made closed cycle; copious amounts of hydrogen will be vented overboard.

If the weapon accelerator cavity could be made superconducting, however, the amount of cooling required would drop sharply. Effluent from the weapon would be greatly reduced ; theoretically closed cycle operation would be possible. In this case a closed power source could be considered depending on the degree of effluent contamination that is allowed outside the spacecraft. G.E. assumed superconducting accelerator cavities.

If a closed cycle power source were in fact required, the fuel cell would provide the most attractive burst system in this case because it produces the least amount of waste heat per electrical megawatt delivered to the weapon. Fuel cell conversion efficiency is very high (60-70%) not Carnot limited) compared to other chemical systems (such as combustion) resulting in less waste heat to reject. The high temperature SOFC closed system requires a radiator greatly reduced in size compared to other closed cycle systems; but, for the range of burst times considered for SPAS, an ice bath heat sink gave even lower system weight than a radiator for the HPD alkaline fuel cell system.

Unlike turbine driven rotating machines the fuel cell is inherently a low voltage device. This imposes a power conditioning penalty unless low voltage solid state amplifiers are used to drive the accelerator cavity. However, individual cells can be stacked in series to yield outputs of up to hundreds of volts.

Two fuel cell technologies were considered for burst power: the high power density (HPD) alkaline fuel cell developed by United Technologies Corporation (UTC) and the high temperature monlithic solid oxide fuel cell (SOFC) developed by Argonne National Labs (ANL). Martin-Marietta and TRW were furnished alkaline fuel cell technology information and complete SDI burst power system designs (both open and closed cycle) by UTC. For SOFC, G.E. copied some system designs originally proposed by ANL for SDI application and used portions of this same design for their open cycle systems.

CLOSED BURST SYSTEMS--FUEL CELL

The Martin and TRW systems (fuel cell and design information furnished by UTC) used weapon coolant as fuel, and stored cryogenic oxygen for burst power, and separate gaseous reactant inventory for testing. The test fire reactant could be regenerated but there was no capability for full recharge after a burst. The SOFC system on the other hand did not use weapon coolant as a fuel but carried a separate inventory of reactant gases stored at high pressure. The SOFC system design is comprehensively described in an ANL document (Fee, et al: "Fuel Cell Development for SDI Applications") and apparently was the source for the GE design.

Martin-Marietta and TRW

1.) Closed cycle HPD alkaline (ice bath heat sink)

G.E.

2.) Closed cycle high temperature solid oxide RFC

Martin Fuel Cell System

Martin provided four (4) stored energy burst prime power systems designs for each of the weapon platforms (EML, FEL, and NPB), based on high performance advanced alkaline fuel cell technology.
The information and system designs were furnished by UTC (UTC acted as subcontractor to all three SPAS primes for fuel cell systems and technology): they provided five (5) different configurations to Martin:

1. open cycle
2. open cycle but condense the water
3. closed cycle, steam cooling, expandable bag radiator
4. closed cycle, steam cooling, ice heat sink
5. closed cycle, methanol vapor cooling, expandable bag radiator

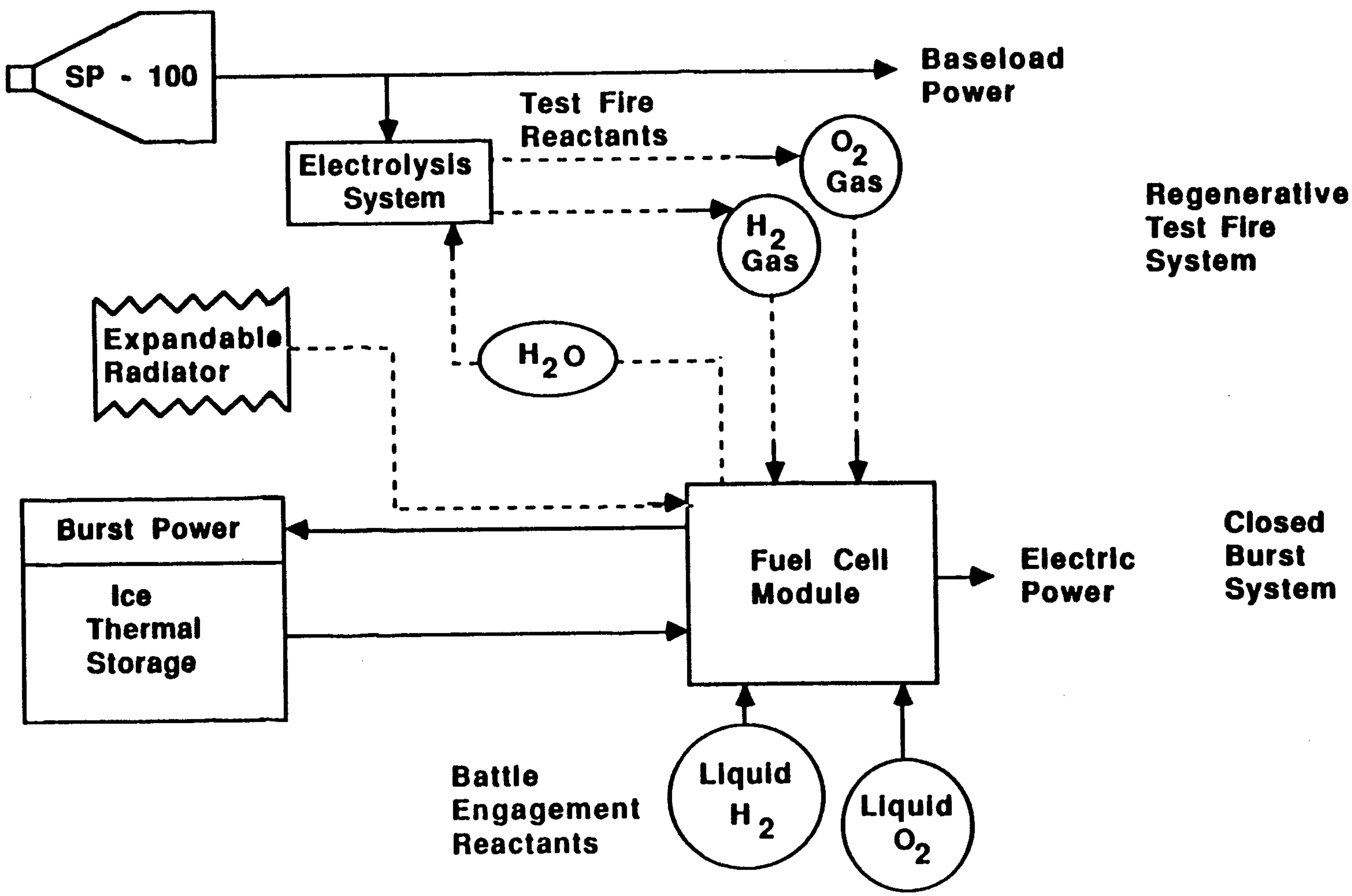
Martin Marietta originally presented them all in Task II, but the gov't downselected to options 2 and 4 only. At UTC's behest, Martin carried options 1 through 4 on through task 3 but presented only the downselected options in the task 3 report Appendix A summary.

Alkaline Fuel Cells Technology Issues

Performance, mass predictions for alkaline fuel cell systems are very optimistic.
Stack power densities are unprecedented; have not yet been demonstrated.
For example, they estimate their (Martin) open cycle stack (directly gas cooled by cryo hydrogen, oxygen streams) at 26 kWe/kg.
High power densities have been shown in individual cell tests (1975 Air Force program demonstrated cell operation over 5000 ASF in pulsed mode, 3000 ASF continuous) but not yet in an integrated stack test.
There is a stack test planned--the Air Force 50 kWe demonstrator program--goal is 0.3 lb/kWe (7.33 kWe/kg) -- stack only, excluding ancillary components -- by 1989.
UTC has run individual cells at high power density. But no one has ever built a stack that runs at these power densities.
High power density is more difficult to achieve in a stack due to reactant and coolant distribution, thermal management.

But they are claiming a five-fold increase over the HPD power density numbers derived from individual cell tests.

Fuel Cell Closed System - HO/FC/Rad



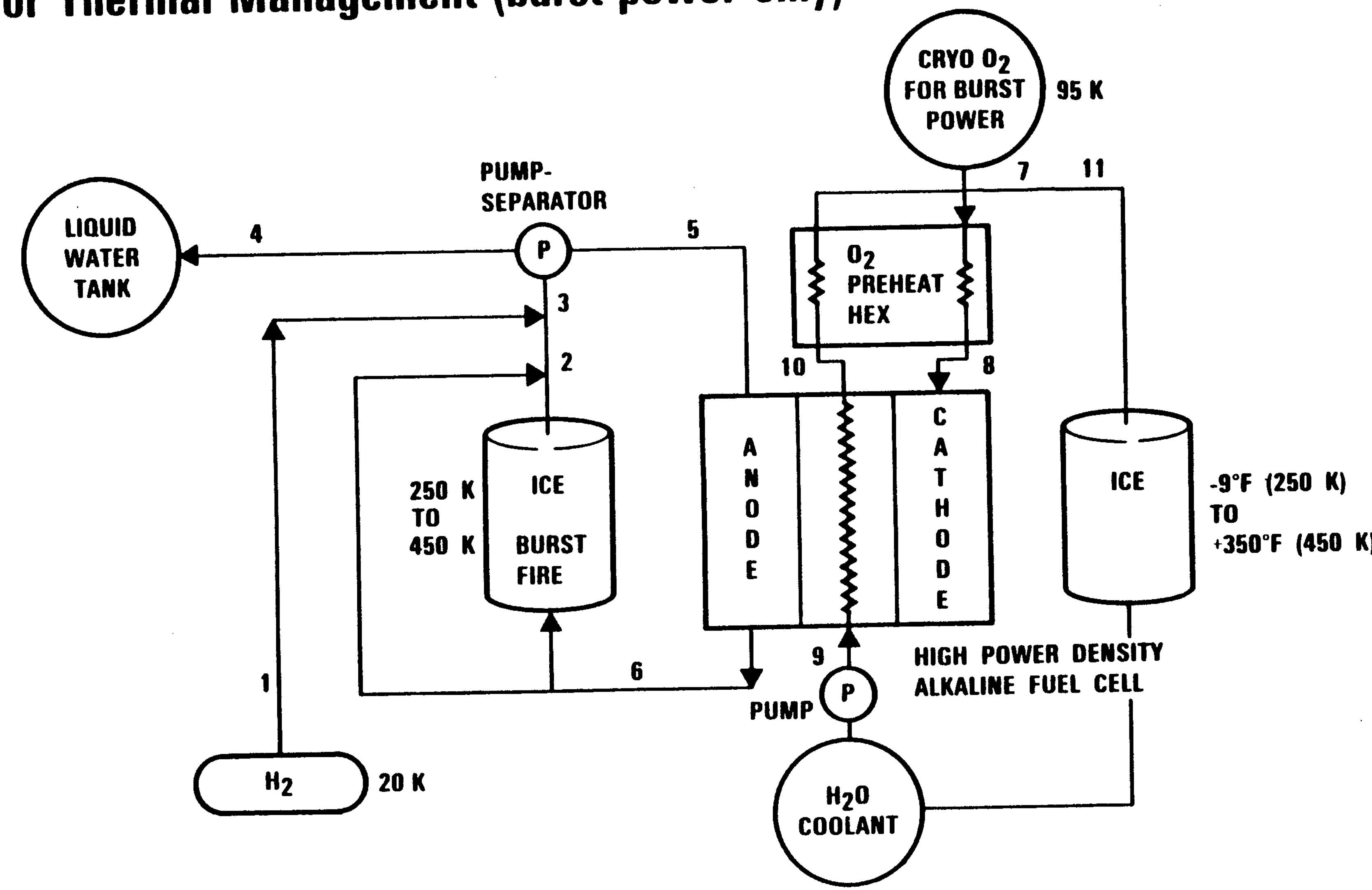
H+O FUEL CELL CLOSED CYCLE (TRW)

TRW presented closed cycle stored energy burst prime power systems for EML, FEL, NPB weapons based on an advanced alkaline fuel cell (steam cooling, ice heat sink) system. Basic fuel cell technology information and the system design was provided by UTC; TRW did the cycle calculation, performance and mass estimates. UTC provided TRW with five (5) different configurations.

1. open cycle
2. opencycle but condense the water
3. closed cycle, steam cooling, expandable bag radiator
4. closed cycle, steam cooling, ice heat sink
5. closed cycle, methanol vapor cooling, expandable bag radiator

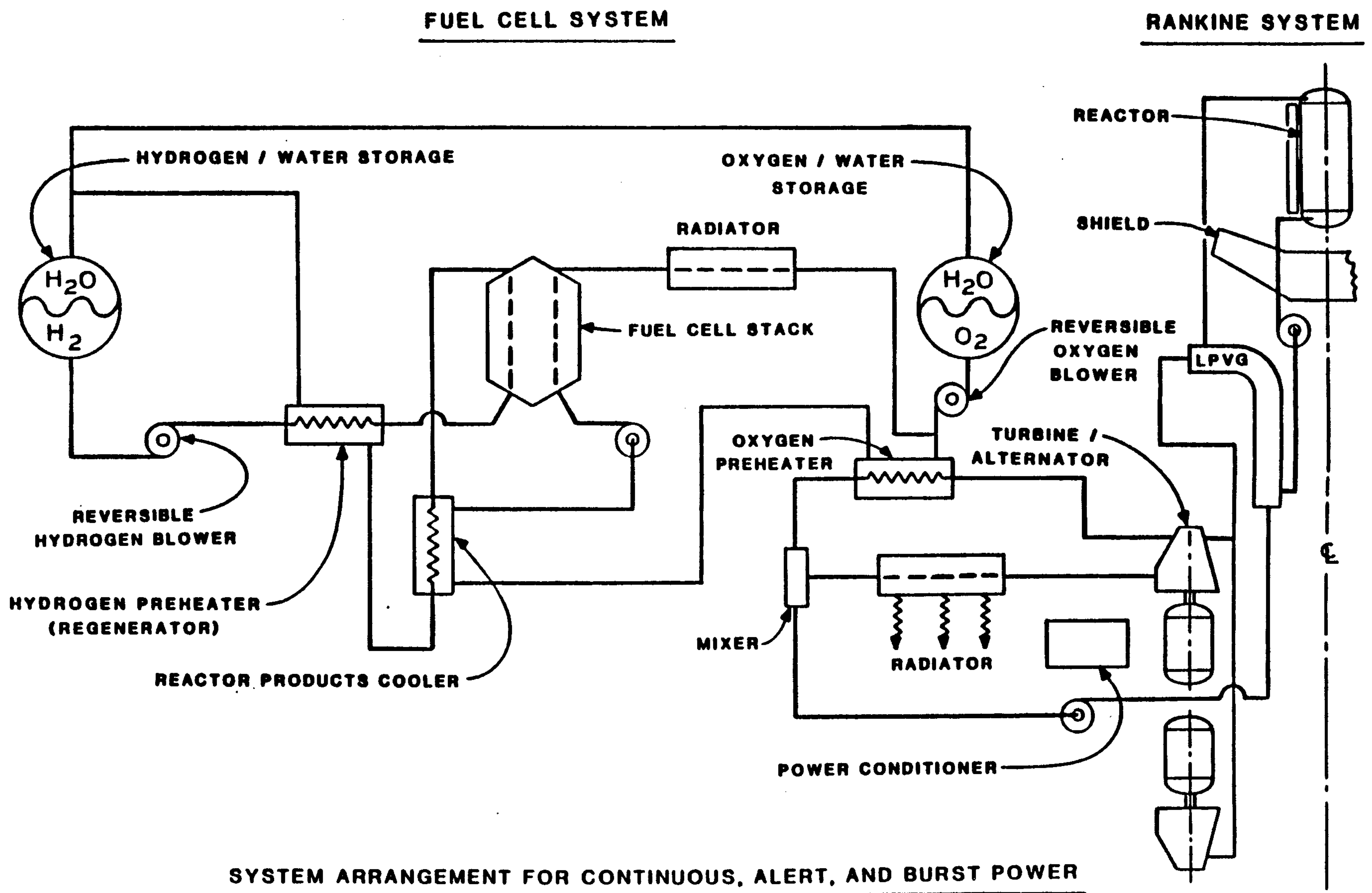
TRW took only one of these configurations (option 4, closed cycle, ice heat sink) as per direction by the government. TRW took UTC's data as given; as a result their system estimates are in good agreement with Martin-Marietta.

Closed Cycle HPI F/C System ICE Heat Sink for Thermal Management (burst power only)



Solid Oxide Fuel Cell (G.E.)

G.E. identified the Argonne Monolithic solid oxide fuel cell as a candidate technology for energy storage, and proposed a regenerative system loosely based upon a design previously proposed by ANL in a classified report (Fee, et al, "Fuel Cell Development for SDI Applications"). Various implementations of this same basic system configuration were applied to the FEL, NPB, and RDS missions. All of the GE designs, both open and closed cycle, despite the variety of system integration options that were available as a result of the various applications and their requirements, employed exactly the same basic stack integration, inlet and outlet conditions and waste heat removal method; namely, using a recirculating loop on the oxygen side to cool the cell. This requires a high temperature gas flow loop and components--heat exchangers, ducting, pumps, impellers and radiators--that can handle pure oxygen at 1000 deg C. G.E. failed to identify fundamental feasibility issues associated with handling high temperaure oxygen, and failed to recognize the other integration options available with SOFC. There are several alternate methods of stack integration; most commonly the fuel gas stream is used to remove waste heat, by means of a recirculating loop similar to alkaline fuel cells. Since this stream maintains a reducing atmosphere, metal heat exchangers can be used. Where open cycle operation is allowed, stack integration can be greatly simplified. G.E. based their system energy storage requirements on the assumption that the entire stack would have to be heated instataneously from low temperature every time burst power was required. No investigation was made into electrical startup, or bootstrapping individual modules in sequence during the alert mode. Evidenced by their system designs, the mode of converter operation chosen; and by the development issues they raised, their understanding of SOFC technology appears so limited that their system designs, performance and mass estimates are questionable at best.



SYSTEM ARRANGEMENT FOR CONTINUOUS, ALERT, AND BURST POWER

V. SYSTEM STUDIES

A. BURST SYSTEMS

3. CLOSED SYSTEMS

c. ENERGY STORAGE SYSTEM

CLOSED BURST SYSTEMS--ENERGY STORAGE

These systems are characterized by a steady-state reactor power system (SP-100) used for housekeeping power, combined with a storage system for burst power. The storage system may or may not take advantage of weapon coolant as an energy source; the housekeeping power source may or may not be used to recharge the energy storage.

Systems studied by SPAS which fall into this category were:

1. All closed cycle fuel cell systems (HPD alkaline and SOFC, discussed in section V.A.3.b of this report).

2. Flywheel systems (discussed in following pages)

3. Secondary battery systems (discussed in following pages)

   i GE -- lithium thionyl chloride secondary battery
   ii TRW -- lithium metal sulfide secondary battery

General Electric presented three (3) types of closed cycle stored energy burst prime power systems, based on the following supporting energy storage technologies:

a. composite flywheel (relatively near-term technology) for EML, FEL, and NPB weapons, and the RDS satellite.
b. lithium-thionyl chloride primary battery (near-term technology) for the FEL and NPB weapons, and the RDS satellite.
c. high temperature monolithic solid oxide fuel cells (very advanced, high risk technology) for the FEL and NPB weapons, and the RDS satellite.

TRW presented two closed cycle stored energy burst prime power systems for EML, FEL, and NPB weapons based upon the following technologies:

a. lithium-metal sulfide secondary battery
b. advanced alkaline fuel cell(closed burst system with steam cooling and ice heat sink)-- for this system, basic fuel cell technology information and the system design was provided by UTC, but TRW did the cycle calculation, performance and mass estimates independently.

TRW also presented additional energy storage technology information on:

a. composite flywheels
b. secondary batteries--
   i. bipolar Ni-H2
   ii. Ni-Cd
   iii. bipolar lead acid
   iv. high temperature sodium-sulfur for comparison against the storage technologies which were selected.

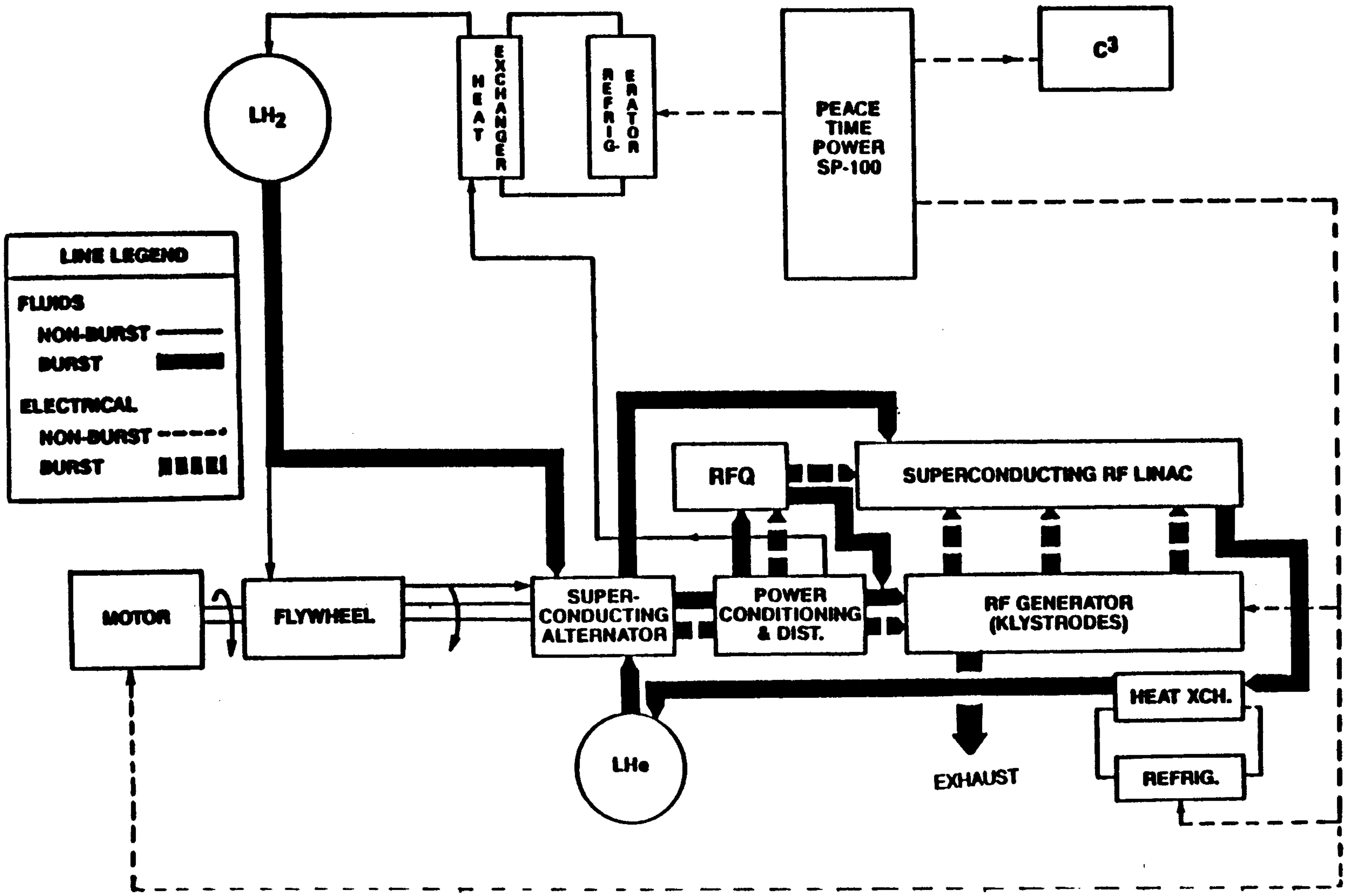
FLYWHEEL ENERGY STORAGE (G.E.)

G.E. considered flywheels as a means of energy storage for the EML, FEL, NPB weapons and RDS satellite. They assumed wound filament rotors, and a rotational kinetic energy density of 600-650kJ/kg. The SOA value using same materials is less than 400 kJ/kg. They assumed a speed ratio 2:1, which yields a 75 pct equivalent depth of discharge. They also assumed that most of the flywheel energy storage system mass resides in the rotor; for example, structure weight equal to 15 pct of rotor weight. However, other studies have shown that the rotor typically comprises less than 50 pct of the overall flywheel energy storage system mass. Their assumptions resulted in an overall system energy storage specific weight of 510 kJ/kg. G.E.'s analysis was detailed enough to indicate that the flywheel generator and power conditioning would have to be actively cooled during discharge. Despite the simplistic and favorable assumptions used, G.E.'s finding was that flywheel energy storage was not competitive with other storage means for the missions investigated.

GENERAL ELECTRIC
Lockheed

NPB FW-1

AFSTC
SPACE POWER ARCHITECTURE STUDY



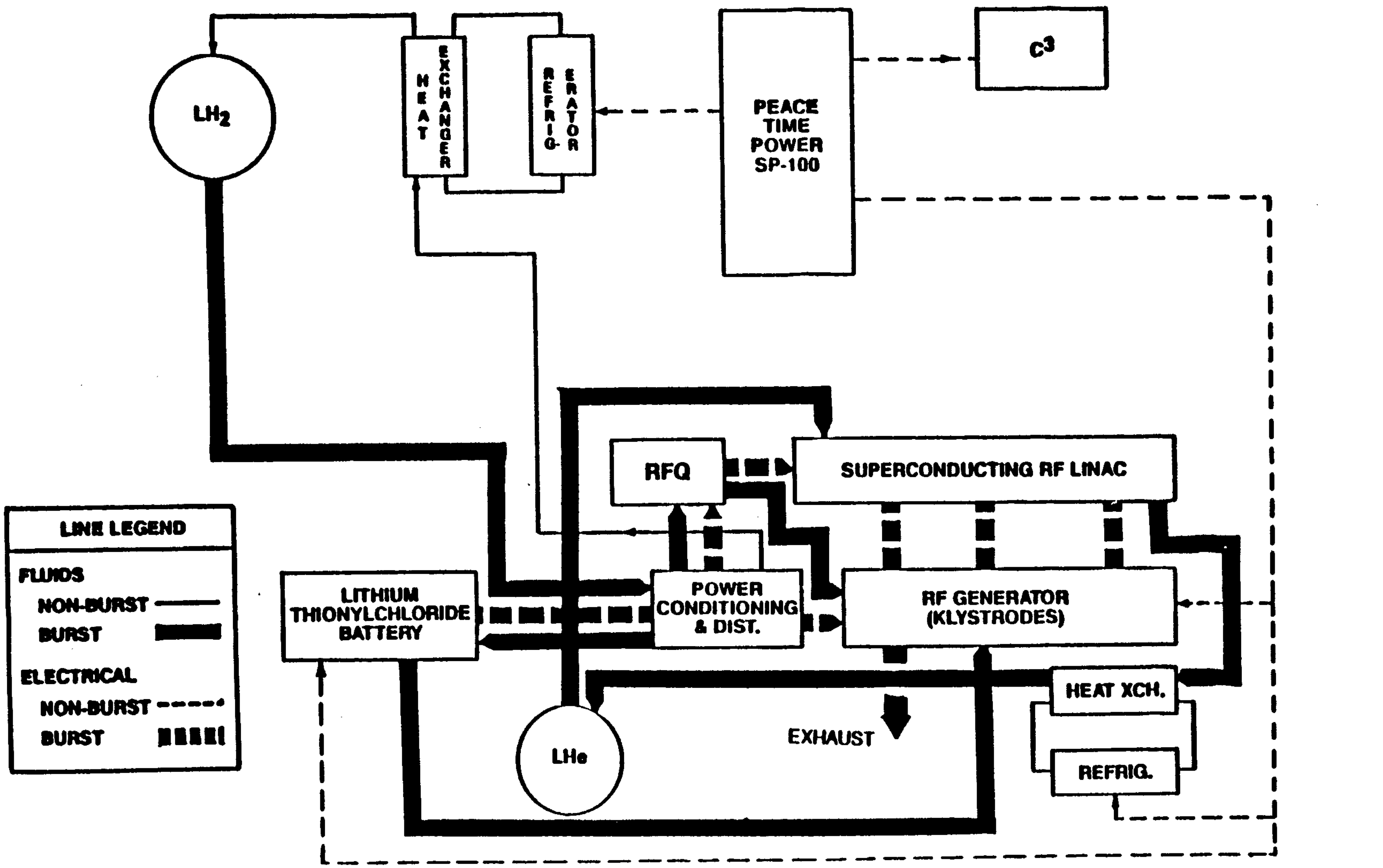
BATTERIES (G.E.)

Two battery technologies were considered by G.E.: a "near-term" technology (the Lithium Thionyl Chloride Battery) and an "advanced, high risk technology (the Lithium-Acid Dynamic Battery) for energy storage application to the FEL, NPB weapon and RDS satellite. The LiSOCl battery is an SOA high energy density system which can be operated as a primary battery or a secondary if discharge rates and number of cycles are limited. Operated as a primary battery, it has demonstrated 3-500 W-hr/kg energy density for individual sealed cells and 85 W-hr/lb (187 W-hr/kg) in a 2.5 kWe launch vehicle battery. It has a ten year life when active; but can also be configured as reserve battery for indefinite storage lifetime, safety. The technology has recently matured and gaining acceptance in Aerospace applications. Two manufacturers (GTE , Althus) are presently qualified to produce LiSOCl batteries for the Air Force. G.E. proposed operation as a primary battery for the missions. They assumed an overall battery energy storage system figure of about 170 W-hr/kg. Their data was taken directly from suppliers and developers (mainly from the JPL program) and the published literature, and used directly to characterize their system designs they proposed.

GENERAL ELECTRIC
Lockheed

NPB BS-1

AFSTC
SPACE POWER ARCHITECTURE STUDY



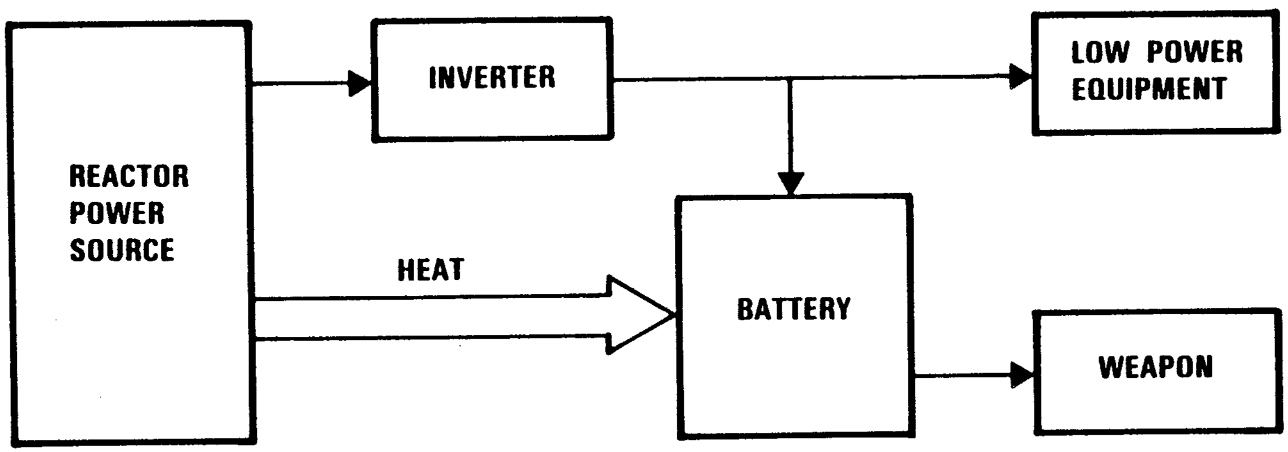
LMR/BATTERY POWER SYSTEM (TRW)

TRW presented closed cycle stored energy burst prime power systems for EML, FEL, NPB weapons based on Lithium-metal sulfide battery technology. This is a high temperature (450 deg C) secondary battery of moderately high energy density (values of 50-75 W-hr/kg are reported in the literature) and moderately high power is believed possible (100 W/kg peak) applicable for burst power. TRW assumed 6 times this figure for their system characterization. The lithium-metal sulfide battery would be advantageous in SDI application because it can be stored (cold) fully charged indefinetly, and will remain inert until activiated (heating to operating temperature). It can be cycled from the active to inert state repeatedly (hundreds of freeze/thaw cycles have been demonstrated). The most recent development effort for this technology took place under electric vehicle program of the 70's; small bipolar stacks have been demonstrated for few tens of charge/discharge cycles. It is believed that 90-W-hr/kg can be achieved (excess of 100 W-hr/kg has been demonstrated for NaS technology at similar stages of development), but life is limited at operating temperature.

TRW

Power Subsystem Concept

LMR/Battery



STAR-M REACTOR
LITHIUM-METAL-SULFIDE BATTERIES
ONE BATTERY MODULE PER KLYSTRODE

V. SYSTEM STUDIES

A. BURST SYSTEMS

3. CLOSED SYSTEMS

d. THERMODYNAMIC CYCLE SYSTEMS

MARTIN MARIETTA ESTIMATED WEIGHTS FOR RANKINE AND THERMIONIC BURST POWER SYSTEMS

Martin Marietta designed closed Rankine and thermionic burst power systems that use radiators to remove waste heat. These systems are heavier than open systems. The facing chart compares weights for these systems with those calculated by the Field Support Team (FST).

The FST used Martin Marietta's thermodynamic parameters to check individual component weights for the Rankine system. Based on this, we believe that their reactor and boiler are too heavy and that their radiator is too light. The overall agreement is quite good.

The FST used its reference system model to estimate thermionic system weights. Our weights were in close agreement with Martin Marietta's, but not for the right reasons. They used a system efficiency of 27%, and we used 11%. We cannot explain how we got the same reactor and radiator weights with such different efficiencies. An efficiency of 27% is beyond state-of-the-art, and requires a far greater technology advancement than the 17% efficiency used for the Rankine system.

Martin Marietta Estimated Weights for Rankine and Thermionic Burst Power Systems

kg/kW	MM Rankine	FST Rankine	MM Thermionic	FST Thermionic
Reactor	.24	.03	1.15	1.24
Boiler	.64	.30		
Turbine	.03	.05		
Generator	.30	.05		
Pumps	.03	.03		
Radiator	.97	1.43	1.12	1.09
Misc	.27	.21	.33	.23
	2.48	2.10	2.60	2.56

V. SYSTEM STUDIES

A. BURST SYSTEMS

3. CLOSED SYSTEMS

e. THOR

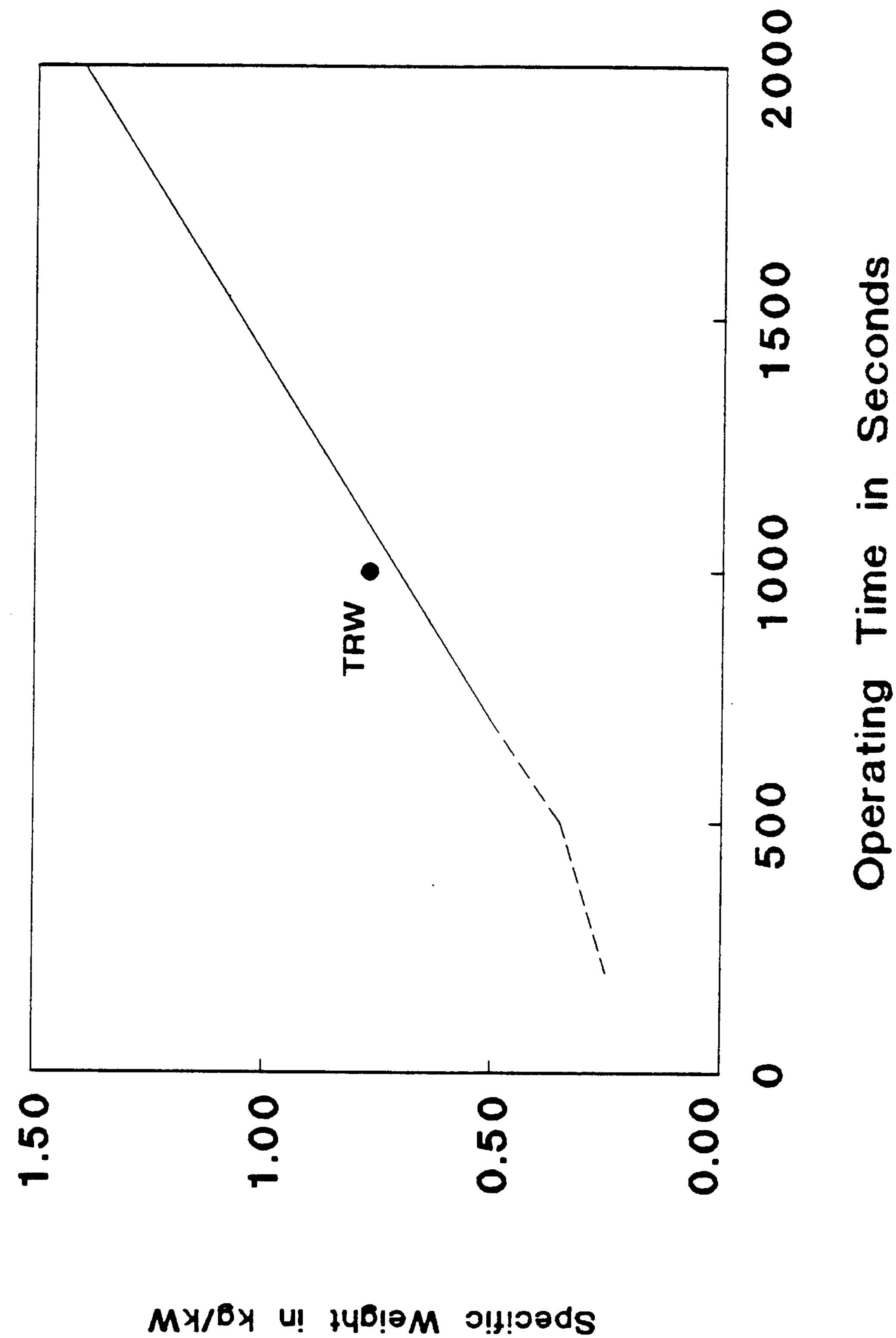
THOR REACTOR SPECIFIC WEIGHT ESTIMATES AS A FUNCTION OF OPERATING TIME

The Field Support Team developed a rough estimate of the specific weight for the THOR reactor system as a function of operating time since that information was not provided by TRW. The following procedure was used. An estimate of the THOR reactor mass was made by using the heat capacity of LiH (heat of fusion plus sensible heat) to estimate the moderator/heat sink mass and then using a multiplier on the moderator mass to obtain the total reactor mass. A multiplier of 2.2 was inferred from GA data. An examination of the THOR geometry indicated that a factor of 2.2 was a reasonable approximation. A plot of our estimated THOR reactor specific weight is presented in the figure along with the TRW specific weight. The good agreement with TRW is not surprising since GA data was used to obtain our multiplier.

At high power levels and long operating times, the reactor mass is determined by heat capacity considerations and is dominated by the LiH and structural masses. At very low power and short operating times, critical mass considerations will ultimately determine reactor sizes and the simple approximation just described will not be a good approximation. Furthermore, the amount of fuel required will depend on the amount of LiH present, the enrichment of Li, H and U and other factors. Consequently, the increased uncertainty in our estimate of the THOR reactor mass at low power and brief operating times is indicated by a dashed line in the figure.

Since the THOR reactor is a self contained power system the THOR reactor mass is the entire power system mass except for power conditioning. It should also be pointed out that 28% efficiency was assumed, corresponding to a 2600 K emitter temperature. Although some Soviet data exist in this range, thermionic operation at these emitter temperatures has not been demonstrated in the US.

THOR Reactor Specific Weight Estimate as a Function of Operating Time



V. SYSTEM STUDIES

A. BURST SYSTEMS

4. STEADY STATE WITH ENERGY STORAGE

Burst Systems -- Steady State with Energy Storage

These systems are characterized by a steady state reactor power system (SP-100) combined with a secondary (rechargeable) storage system for burst power. The steady state system is used to recharge the storage which allows burst power to be repeated after an indefinite period. Since reactants, products, and working fluid must be conserved for repeat operation; all of these systems are closed cycle (no effluents from the power system).

The systems fitting this category were:

G.E.

1. Closed cycle solid oxide regenerative fuel cell (RFC). This system, attributed to ANL, was discussed in section V.A.3.b (closed fuel cell systems).

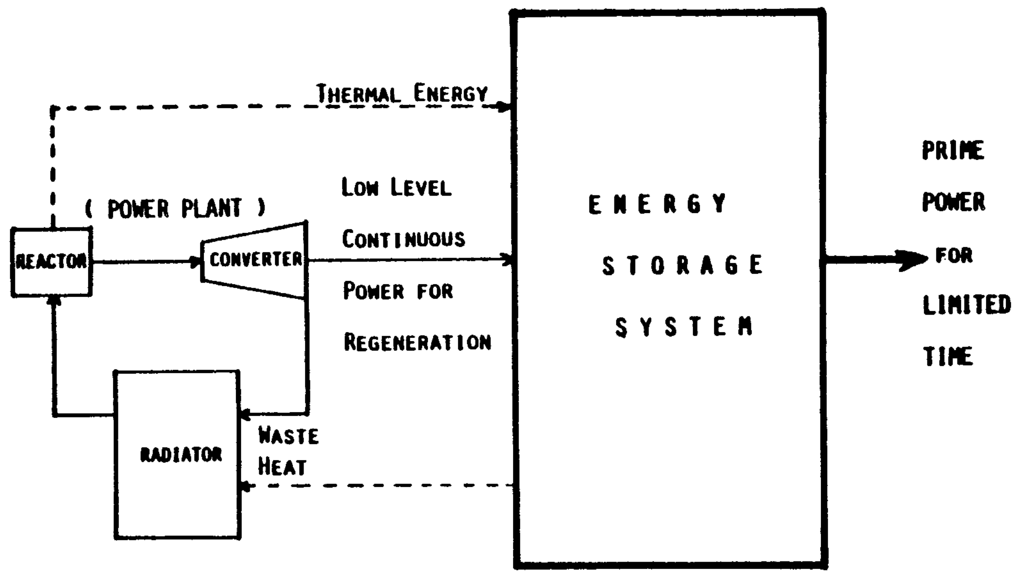
2. Flywheel. This system was discussed in section V.A.3.c. (closed cycle energy storage systems).

3. Lithium thionyl chloride primary battery. This system was discussed in section V.A.3.c (closed cycle energy storage systems).

TRW

4. Lithium metal sulfide secondary battery. This system was discussed in section V.A.3.c (closed cycle energy storage systems).

ENERGY STORAGE BURST PRIME POWER SYSTEM



- CLOSED CYCLE POWER SYSTEM -- NO EFFLUENTS ARE RELEASED
- DELIVERS CONTINUOUS PRIME POWER FOR LIMITED RUN TIME
- STORAGE SYSTEM MAY OR MAY NOT BE RECHARGEABLE
- POWER IS REGULATED BUT NOT PULSED

V. SYSTEM STUDIES

B. STEADY STATE SYSTEMS

THESE STEADY STATE SYSTEMS WERE CONSIDERED

GE and TRW both designed 5 MWe steady state power systems for an orbital transfer vehicle (OTV) application. Since these were the only common steady state systems studied, they were the only results that the Field Support Team could compare. Martin Marietta started to define Rankine, thermionic, and thermoelectric OTV systems during task two but did not follow through with these systems in task three. There is some information on a Rankine OTV system in their draft final report, but it is incomplete and is not included in the Field Support Team's evaluation.

GE developed Rankine cycle and HYTEC (a proprietary, advanced energy conversion process similar to AMTEC) concepts for OTV power. Their OTV used an arc-jet thruster with ammonia as a propellant. GE selected a specific impulse of 1000 s and a transfer time of 60 days but did not specify the payload mass and only vaguely specified the orbit change (from 280 km to between 500 and 2000 km).

TRW developed steady state thermionic and Brayton cycle OTV power concepts. They considered four different OTV thruster designs but selected a pulsed inductive thruster with ammonia as a propellant. TRW selected a specific impulse of 3000 s that will lift a 100 to 300 metric ton payload from a 160 nmi orbit to a 1000 nmi orbit in 1 to 3 weeks.

TRW also provided power system concepts for free electron maser and transmitter-receiver surveillance platforms. GE developed concepts for space surveillance platforms, but chose short run-time burst rather than steady state systems. These systems will not be discussed further in this report since, because of the different applications, the two contractors' results cannot be compared.

These Steady State Systems Were Considered

	TRW	*GE*	*MM*
Nerva Derivative Reactor--Brayton	X		
Liquid Metal Reactor--HYTEC		X	
Liquid Metal Reactor--Rankine		X	Y
Liquid Metal Reactor--Thermionic	X		

A VARIETY OF ASSUMPTIONS WERE MADE FOR 5 MW STEADY STATE ORBITAL TRANSFER VEHICLE POWER SYSTEMS

This table shows parameter values and component mass breakdowns for four, five megawatt orbital transfer vehicle systems.

TRW Thermionic--The efficiency for this system is a little beyond current technology but is not unreasonable, as an advanced value, for the temperature specified. The voltage is somewhat below the voltage (15 kV) needed by the load; thus, power conditioning weight is significant. However, the weight they use, 1.15 kg/kW, is somewhat heavier than they used for similar burst mode power conditioning units, 0.4 kg/kW, that convert low voltage dc to high voltage dc. We do not understand why the weights are different since TRW's schematics show them to have the same function. We believe that their reactor (which includes a shield) is a little heavy, based on an analysis using reactor and shield weight estimating algorithms developed by the Field Support Team, but that their radiator is light. Their radiator area is just adequate to dissipate the specified waste heat if the whole radiator operates at its inlet temperature. Thus, there is no extra area to account for meteoroid losses nor does it account for the temperature drop in the coolant as it traverses the radiator. Furthermore, the 5.2 kg/m^2 that TRW uses may be a little too low, even for an advanced TiBe material, to offer adequate meteoroid protection.

TRW Brayton--We tried to verify TRW's Brayton cycle efficiency and calculated 17.6 instead of 20 %. We also found a much more efficient cycle that requires dissipating half as much waste heat in the radiator. This cycle is shown on the chart following chart on the facing page. Their cycle has apparently not been optimized. We believe that the radiator is a little light for the same reasons stated in the paragraph above. We also notice that the power conditioning weight for the Brayton system is the same as for the thermionic system. This doesn't seem reasonable because the alternator in this system should generate a voltage (8.7 kV) higher than the converter's output voltage (7.5 kV), avoiding the need for a heavy transformer that was needed for the thermionic system converter. The two power conditioning weights should not be the same. It should be noted that power conversion weights for the Brayton system include redundant turbines and generators.

GE Rankine--GE's radiator weight may be a little light. They selected a SiC ceramic composite radiator--an advanced design that allowed for 10% meteoroid loss. They used

A Variety of Assumptions were Made for 5 MW Steady State Orbital Transfer Vehicle Power Systems

	TRW Thermionic	TRW Brayton	GE Rankine	GE HYTEC
Efficiency	.15	.20	.24	.23
Voltage	50dc	8700ac	3425ac	1000dc
High temperature (K)	1900	1700	1420	1300
Radiator temperature	1100	1006-612	933-832	850-750
(kg/kW)				
Reactor	3.43	1.77	1.63	1.64
Power conversion	.50	.94	3.65	2.81
Radiator	.48	1.22	.55	.83
PC	1.15	1.15	.39	.57
PC Radiator	.35	.24	.15	.04
	5.91	5.32	6.37	5.89

A VARIETY OF ASSUMPTIONS WERE MADE FOR 5 MW STEADY STATE ORBITAL TRANSFER VEHICLE POWER SYSTEMS (cont.)

around 5 kg/m^2 for a radiator specific mass. We believe that 5 kg/m^2 is marginal for meteoroid protection even for SiC. It will not withstand space debris.

GE HYTEC--HYTEC is a proprietary conversion process similar to AMTEC. GE gave us minimum information that was insufficient for a cycle evaluation.

We believe that the inconsistencies in mass among these systems are greater than real mass differences, and we recommend that the systems not be ranked according to mass based on these values.

A Variety of Assumptions were Made for 5 MW Steady State Orbital Transfer Vehicle Power Systems

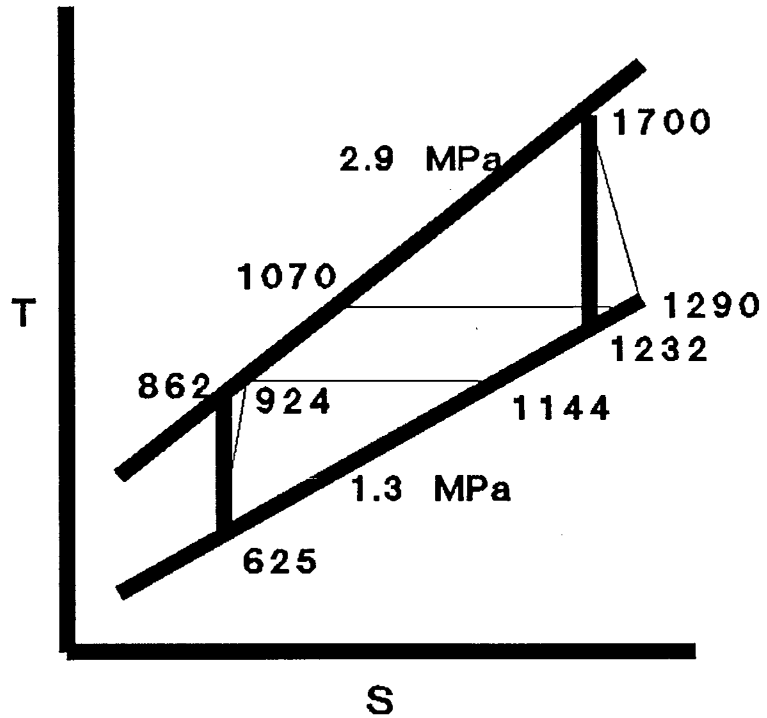
	TRW Thermionic	TRW Brayton	GE Rankine	GE HYTEC
Efficiency	.15	.20	.24	.23
Voltage	50dc	8700ac	3425ac	1000dc
High temperature (K)	1900	1700	1420	1300
Radiator temperature	1100	1006-612	933-832	850-750
(kg/kW)				
Reactor	3.43	1.77	1.63	1.64
Power conversion	.50	.94	3.65	2.81
Radiator	.48	1.22	.55	.83
PC	1.15	1.15	.39	.57
PC Radiator	.35	.24	.15	.04
	5.91	5.32	6.37	5.89

TRW'S BRAYTON CYCLE IS NOT OPTIMUM

We compared TRW's recuperated Brayton cycle to a nonrecuperated cycle generated by our optimization process using the same upper temperature and pressure. The optimized, nonrecuperated cycle has a higher efficiency and a lower radiator heat rejection rate than TRW's recuperated cycle. This does not mean that nonrecuperated cycles in general are better than recuperated ones, but it does say that TRW's cycle did not use optimum parameter values. It doesn't look like they did an optimization study. An optimization study would lead to either a nonrecuperated cycle similar to ours or to a recuperated cycle somewhat better than TRW's.

On this chart, temperatures are given in degrees K.

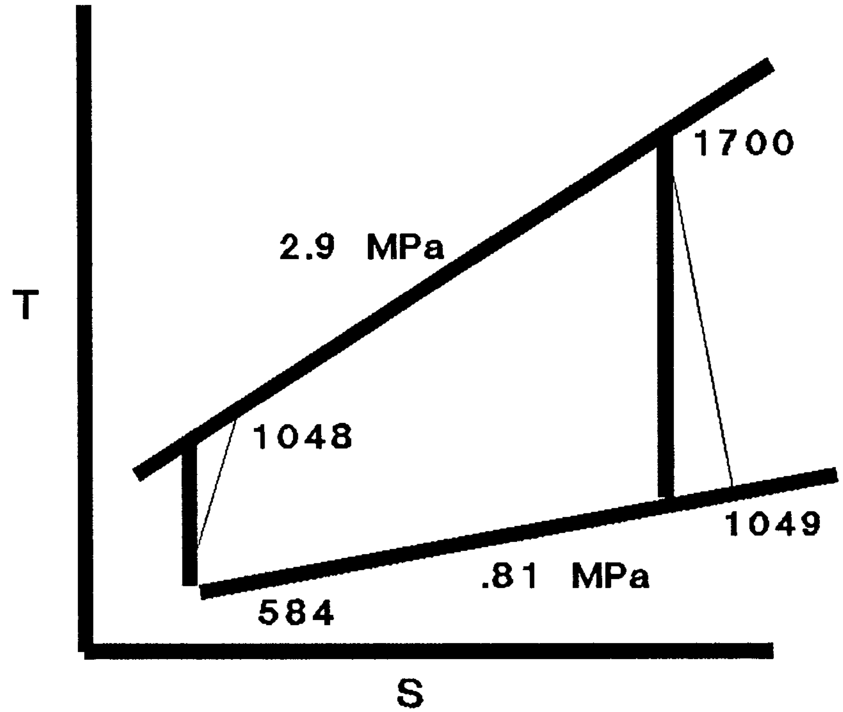
TRW's Brayton Cycle is not Optimum



TRW's Regenerated Cycle

Efficiency = 17.6%

$Q_{radiator}$ = 23.4 MW



A More Optimum Cycle

Efficiency = 29%

$Q_{radiator}$ = 12.2 MW

STEADY STATE RESULTS ARE INADEQUATE FOR DOWN SELECTION

As stated earlier, assumptions were too inconsistent to rank the steady power systems. Also, none of the contractors designed the same system so we could not compare results for similar systems.

GE did not give us enough information on HYTEC to evaluate it.

Steady State Results are Inadequate for Down Selection.

1. Errors and inconsistencies in calculating weights are greater than the real weight differences between systems.

2. TRW's Brayton cycle needs optimization.

3. Radiator weights are too light.
   * Low specific weight
   * Some meteoroid but no debris protection
   * Little or no redundancy

4. PC weights are inconsistent.

5. There was not enough cross reference between contractors.

VI. SYSTEM ISSUES AND INTERFACES

A. EFFLUENTS

THESE ISSUES HAVE BEEN RAISED REGARDING POWER SYSTEM EFFLUENTS:

A number of issues associated with power system effluents have been raised. The major ones address collisional stripping of neutral particle beams. (Stripping the neutral beam leaves a charged beam, which is then deflected by the geomagnetic field.) The effluent cloud may affect IR and visible sensors since signals traversing the cloud are subject to scattering and absorption. Water vapor effluent is an additional concern if it leads to condensation on sensor surfaces. The effluent cloud will be ionized by natural sources as well as from nuclear ASATs. The primary concern here is the plasma cutoff frequency, the frequency below which RF cannot propagate. Radar and communications operating frequencies must then operate above this frequency, given approximately by 9 kHz times the square root of the plasma electron density in number/cm^3. All contractors anticipated the need for nozzles to direct the effluent away from the platform without aggravating the concerns listed here. The nozzle itself then becomes a source of thrust and vibration with possible adverse impacts on the platform mission. The platform itself will be immersed in the effluent/plasma cloud. Characterization of the interaction between the platform and the effluent cloud is needed.

These issues have been raised regarding power system effluents:

1. NPBW stripping
2. IR and visible sensor attenuation
3. RF (radar) interference
4. Nozzle thrust and vibration
5. Platform/plasma interactions

CONTRACTOR'S SUMMARY ASSESSMENT OF EFFLUENTS

The contractors' responses regarding these issues varied. In some cases, they expected the effluent cloud to be tolerable, or tolerable given the measures suggested, such as the use of directional nozzles and baffles. In other cases the issue was not addressed or was left for follow-on work.

Contractor's Summary Assessment of Effluents:

	GE		TRW				MM		
Effect\Effluent	H2	H2O	H2	H2O	Cs	R	H2	H2O	Cs
1. Optical									
condense	OK	OK*	OK	OK	C	OK	OK	C	C
scat/abs	OK	OK	OK	C	?	OK	OK	?	?
2. Beam									
EML	OK	OK	OK	OK	OK	OK	OK	OK	OK
NPB	OK	OK	OK	OK	OK	OK	OK	OK	?
FEL	OK	OK	?	?	?	?	OK	OK	?
3. Plasma									
RF prop.	OK*	OK*	?	?	?	?			
Electric								?	
breakdown	OK*	OK*	OK*	OK*	?	?			
power loss	OK	OK	?	?	?	?			
CONCLUSION:	OK*	OK*	OK	C	C	?	?	?	?

OK = NO PROBLEM IDENTIFIED
C = CONCERNED

OK* = OK WITH MEASURES TAKEN
? = NO CONCLUSION

THE CONTRACTORS HAD THE ESSENTIAL INGREDIENTS TO DO AN EFFLUENT STUDY:

All SPAS contractors had the analytical capability to estimate the effluent density around the platform. Each had assumed a number of opposing nozzles, each directing thrust through the platform center-of-mass to provide thrust balance. Martin Marietta used a modified version of a code obtained from the Air Force Rocket Propulsion Lab and applied it to their continuous annular nozzle. The effluents were known for each of the power systems they were assigned. The power source key is as follows: 1) GCR+TG: gas cooled reactor with turbine and generator; 2) H2O2 comb + TG: hydrogen-oxygen combustor with turbine and generator; 3) H2O2 MHD: hydrogen-oxygen combustor with MHD conversion; 4) H2O2 FC: hydrogen-oxygen fuel cell; 5) GCR MHD: gas cooled reactor with MHD conversion; 6) GEL MHD: inhibited red fuming nitric acid (gel) + Be (also in a gel) with MHD conversion. The GEL MHD produces a number of effluents in addition to the primary effluents, H_2 and water.

The Contractors had the essential ingredients to do an effluent study:

	GE	TRW	MM
Model:	Contam 3.2	BLIST 2DNOZEL	RPL(mod)
# Nozzles	6	4	slot
Power/effluent sources			
1. GCR + TG	H_2	H_2	H_2
2. H_2O_2 comb	H_2+H_2O	H_2	H_2
+TG			H_2+H_2O
3. H_2O_2 MHD			$H_2+H_2O+CsOH$
4. H_2O_2 FC			H_2, H_2+H_2O
5. GCR MHD	H_2+Cs	H_2+Cs	
6. GEL MHD		H_2+H_2O + stuff	

THE CONTRACTORS ALL AGREE THAT H2 COLUMN DENSITIES FOR THE GCR-NPBW SYSTEM ARE TOLERABLE WHEN NOZZLES ARE USED

All contractors calculated column densities in the direction of the beam, a quantity relevant to estimating the effect of the cloud on neutral particle beams. All concluded that, for systems producing only an H_2 effluent, the beam would not be seriously degraded. This finding is in good agreement with estimates made by Space Power Inc. SPI tried to duplicate the SPAS contractors' results. They were quite close for General Electric and TRW but differed by three orders of magnitude for Martin Marietta. The difference was probably because Martin Marietta used a slot nozzle and SPI tried to duplicate it using several small conical nozzles.

The Contractors All Agree That H2 Column Densities For The GCR-NPBW System Are Tolerable When Nozzles Are Used

Column Densities in gm/cm^2

	Contractor	SPI
MM	5.3 E-8	$.003 \times 10^{-8}$
GE	8 E-10	30×10^{-10}
TRW	3.2 E-9	$.7 \times 10^{-9}$

These neutral column densities attenuate NPB << 1%, have no significant effect on IR, visible, or radar sensors.

EVEN WATER-EVOLVERS, WITH NOZZLES, SHOULD NOT SERIOUSLY DEGRADE THE NPBW

The water column densities in the direction of the beam were also estimated or could be inferred from the contractors' results. These were also estimated with the simple spherical model by the Field Support Team. Again, the nozzle is good for a two to three order of magnitude reduction relative to the spherical model. Although not as effective as the high Mach number nozzles, even the MHD duct effectively reduced the column density by a factor of forty relative to the spherical model. It should be noted that, on a mass basis, water is not as effective a stripper as hydrogen. This fact has not been included in this comparison.

Even water-evolvers, with nozzles, should not seriously degrade the NPBW

	g/cm2	
	SPAS	spherical
Comb. MHD (MM)	2 E-7	8 E-6
Comb. TG (GE)	2 E-9	3 E-6
Open FC (MM)	9 E-8	9 E-6

THE CALCULATIONS ARE ALONG THE LOWEST DENSITY LINE, BUT...

The column density calculations on the previous charts were made along the line of lowest effluent density which is along the long axis of an NPB platform since the effluent nozzles are arranged to expel effluent perpendicular to this axis. The calculations were made for this direction because that is the direction in which the beam is propagated. TRW also did calculations for a turning platform that could theoretically cause the beam to pass through a denser region of the cloud, but they concluded that the cloud disperses faster than the platform can turn. GE calculated that less than 1% of the beam will be lost if fired within 60 degrees of the lowest density line. Thus, both contractors conclude that turning and firing will not cause the beam to be seriously attenuated. However, there is some concern that wide angle sensing and communications may be a problem at some angles near lines of highest effluent density.

The Calculations are Along the Lowest Density Line, But...

TRW calculates that the cloud will disperse faster than the platform can slew, so turning into the cloud and firing will not seriously attenuate a NPB.

GE calculates that column densities are below the NPB 1% attenuation level within 60° of the lowest density line.

IONIZATION OF THE HYDROGEN CLOUD BY A NUCLEAR BURST MAY CAUSE TEMPORARY SENSOR INTERFERENCE

If the effluent cloud surrounding a platform is highly ionized by a nuclear burst it may interfere with sensors and communications. TRW and GE both calculated that the effect should be transient, lasting about one second, because the ionized cloud will decay and because it will be swept away by the neutral effluent replacing it. However, there is concern that nuclear burst generated electrons trapped in the Earth's magnetic field may be a more persistent source of ionization. There is also concern that magnetic fields from turning and steering magnets in the weapon may trap ions and not allow them to dissipate. These effects are not well quantified and should be investigated further. There may also be ways to minimize the effect of trapped ions.

Ionization Of The Hydrogen Cloud By A Nuclear Burst May Cause Temporary Sensor interference.

TRW and GE have calculated that the effect should last for around 1 second.

- The plasma decays
- The cloud disperses
- But, ions may be trapped by magnetic fields

EXHAUST NOZZLE THRUST IMBALANCE AND VIBRATION:

The three contractors made different assumptions on how to balance thrusts from their exhaust nozzles. TRW used small, thrust cancellation nozzles, GE assumed that thrust imbalances can be cancelled by fluidically balancing the quantity of exhaust going to each nozzle, and Martin Marietta used a ring nozzle that was assumed to need no thrust cancellation. TRW was the only contractor that characterized the exhaust nozzles as a vibration source. They suggested that a combination of active and passive vibration control can provide the vibration reduction necessary for weapon performance. The vibration mitigation necessary was five orders of magnitude. This will be a challenging technical problem and deserves further attention.

Exhaust Nozzle Thrust Imbalance and Vibration:

TRW uses small, thrust imbalance cancelling nozzles.

GE uses nozzle fluid control.

MM uses a ring nozzle.

For nozzle vibration control, TRW proposes a combination of active and passive isolation.

EFFLUENT CLOUD SUMMARY

This chart summarizes the SPAS contractors' conclusions on effluents with some comments by the Field Support Team.

While their results indicate that neutral and naturally ionized hydrogen effluent will not interfere with beams or sensors when high mach number exhaust nozzles are used, they were based on analytical models that are reasonable but have not been experimentally verified. Plans for experimental verification should be made. The Field Support Team feels that these results should be presented to sensor designers for further analysis.

TRW and GE calculations indicated that ionization of the cloud by a nuclear burst could disrupt sensors and communications for around one second, but they did not consider longer term ionization sources such as nuclear burst electrons trapped in the Earth's magnetic field or ionized particles trapped in the fields of weapon magnets. Studies on these need to be conducted.

The contractors agreed that insulation and shielding are necessary to prevent arcing and sparking particularly when the cloud surrounding the platform is ionized.

Effluent Cloud Summary

Beams and Sensors can Tolerate Neutral of Naturally Ionized Hydrogen.

- Requires the Use of High Mach Number Nozzles
- Conclusion is Based on Analysis, Not Experiment

Ionization of the Cloud by a Nuclear Burst May Cause Temporary (Around 1 sec) Sensor Interference.

- Unless Ions are Trapped by Magnetic Fields

Electrical Insulation and Shielding are Necessary to Prevent Arcing and Sparking.

EFFLUENT CLOUD SUMMARY, CONT.

Based on the SPAS results, we believe that nozzle vibration mitigation will be the most challenging effluent issue to overcome. Several orders of magnitude reduction will be required.

If Hydrogen effluent is tolerable and the nozzle vibration problem can be solved, then open systems should be selected to power weapon platforms unless total engagement plus test time exceeds 2000 to 3000 seconds. The required total operation time at full power is presently unknown. This issue along with the practicality of refueling to replace test consumables (GE proposes refueling every 40 months.) must be resolved before closed systems that do not use consumables are ruled out.

Based on designs by TRW and by Sundstrand for Martin Marietta, water can be removed from the exhaust of a hydrogen - oxygen combustion system with little mass penalty. Thus, hydrogen - oxygen combustion systems should be acceptable if hydrogen is tolerable. It is not clear yet that water is either tolerable or not tolerable. It will not seriously degrade a neutral particle beam but, its effect on sensors depends on their location and type. The effects of other effluents have not been adequately addressed.

Effluent Cloud Summary, Cont.

Effluent Nozzle Vibrations can Cause Beam Pointing Problems

- Vibration Isolation May be Possible, But Challenging

If Hydrogen Effluent is OK and the Nozzle Vibration Problems Can be Solved, Then Open Power Systems Can Be Used

- If Water is a Problem, It can Probably be Removed, so Combustion Systems are OK Even if Water isn't
- Water issues Include Sensor Type and Placement
- Issues with Other Effluents are Not Resolved

VI. SYSTEM ISSUES AND INTERFACES

B. PLATFORM DYNAMICS

Dynamic Disturbances (TRW)

TRW dynamically modelled a generalized DEW platform, treating it as a five mass element distribution connected by elastic beams. System disturbances on the model were assumed to come from the "worst case" power systems:

a.) combustion turbogenerator
b.) MHD

which were characterized by their power spectral densities. A random vibration analysis was then performed to determine the resulting dynamic response. From these analyses, TRW concluded that the platform designs will perform within the required pointing error/jitter specification providing that appropriate vibration mitigation techniques are used. TRW presented survey information on dynamics/vibration control technologies they were cognizant of, showing how much disturbance reduction could be obtained from each. They proposed to apply various combinations of these techniques to obtain the necessary attenuation which would allow their platform designs to meet the applicable pointing error/jitter requirements. Considering the preliminary nature of their platform designs, the precursory level of the analyses performed was appropriate. One can only expect the contractor to demonstrate their ability to dynamically analyse these platforms, identify performance problems that may be encountered, and determine whether or not these problems are solvable. They did not, nor could they be expected to, produce final results or definitive conclusions.

Dynamic Disturbances (TRW)

TRW Corp. Inc.	The Spec. from Task I report	Performance Believed Achievable	Disturbance Sources Considered	Analytical Methods Used	Mitigation Techniques Required
NPB platform jitter	(classified)	not given	exhaust noz- zle thrust inbalance;	uniform beam model, random	multiple levels of active vibration control; momentum cancellation;
NPB beam pointing jitter	(classified)	11-14 n rad	flow disturbances /turbulence;	vibrations; transfer function;	magnetic isolation
FEL platform stability between mirrors	(classified)	not given	turbogen. unbalance;	disturbance PSD's	multiple levels of active vibration control; momentum cancellation;
FEL beam stability	(classified)	5-7 n rad	turbopumps vibration; combustion		magnetic isolation
EML platform stability	(classified)	not analysed			

Dynamics Assessment (Martin-Marietta)

Martin-Marietta dynamically assessed both the NPB and FEL platforms. A uniform beam with a circular cross-section was used to model the platforms. System disturbances on the model consisted of the MHD and laser cooling system. Both the MHD and the laser cooling system were characterized by their respective power spectral densities. A random vibration analysis was then performed to determine the resulting dynamic response. From these analyses, Martin-Marietta concluded that the NPB design will perform in the most severe environment, while the FEL design requires some optimization to be able to perform in the MHD environment. Although the preliminary FEL design does not meet jitter requirements, there is confidence that the FEL response may be improved by relocating the source of excitation, passive damping, use of graphite epoxy material, active control, and reducing source disturbance. Considering the preliminary nature of their platform designs, the precursory level of the analyses performed was appropriate. One can only expect the contractor to demonstrate their ability to dynamically analyse these platforms, identify performance problems that may be encountered, and determine whether or not these problems are solvable. They did not, nor could they be expected to, produce final results or definitive conclusions.

Dynamics Assessment (Martin-Marietta)

Martin Marietta Corp.	The Spec. from Task I report	Performance Believed Achievable	Disturbance Sources Considered	Analytical Methods Used	Mitigation Techniques Required
NPB platform jitter	(classified)	74 u rad	MHD comb-	uniform	platform natural response
			ustion and	beam model,	
FEL platform jitter	(classified)	less than	flow; laser	random	passive damping;
		172 u rad	coolant flow;	vibrations;	relocate power system
			turboalt.	transfer	
EML platform jitter	(classified)	not analysed	vibrations	function;	
				disturbance	
				PSD's	

Dynamics and Control (G.E.)

G.E. dynamically analysed the FEL, NPB, EML, RDS and OTV space platforms. Finite element models were used. System disturbances, characterized by forcing functions generated by counterrotating turbine generator, counterrotating flywheel, effluent exhaust, and gravity gradient, were considered in the analyses. Finite element analyses were then conducted on the platforms, with system disturbances applied to appropriate structural nodes, in order to determine their respective dynamic responses. G.E. concluded that the disturbances generated by low frequency sources fell within the respective tolerances of each platform and that, in general, the dynamic impact from rotating machinery was manageable. Considering the preliminary nature of their platform designs, the precursory level of the analyses performed was appropriate. One can only expect the contractor to demonstrate their ability to dynamically analyse these platforms, identify performance problems that may be encountered, and determine whether or not these problems are solvable. They did not, nor could they be expected to, produce final results, or definitive conclusions.

Dynamics and Control (G.E.)

G.E. Space Div.	The Spec. from Task I report	Performance Believed Achievable	Disturbance Sources Considered	Analytical Methods Used	Mitigation Techniques Required
NPB platform jitter	(classified)	not given; claimed to be wtihin spec.	exh. thrust inbalance; turboalt. inbalance;	finite element models; force vs time disturbance	S/C attitude control system, active control of effluent exhaust, CMG's
FEL platform jitter	(classified)	not given; claimed to be wtihin spec.	flywheel inbalance; coolant flow turbulence; gravity gradi.		S/C attitude control system, active control of effluent exhaust, CMG's
EML platform jitter (fire control not attached)	(classified)	170 mrad			S/C attitude control system, active control of effluent exhaust, CMG's
(if fire control attached)	(classified)	1.t.1 mrad			

VI. SYSTEM ISSUES AND INTERFACES

C. POWER CONDITIONING

POWER CONDITIONING DESIGNS WERE TOP LEVEL

In our assessment of the power conditioning information contained in the SPAS draft final reports and task briefings, we found the information supplied to be rather top level. Only major items in top-level power processing subsystems were identified. Circuit protection, fault isolation, fast shutdown, methods for shielding, insulation, and control issues are examples of areas not adequately addressed. TRW did however, provide schematics for a high voltage rectifier assembly and a converter in their report with weight estimates for components within these circuits.

As shown on the following pages, mass estimates for power conditioning varied widely among the contractors. These mass estimates, we believe, represent the weights of the power conditioning subsystems identified in the top level block diagrams presented and did not include the weights of items such as protection, enclosures, electrical insulation, shielding and thermal management equipment in the GE and Martin Marietta concepts.

All three contractors identified high voltage power conditioning with a klystrode RF source as the system of choice, although Martin Marietta considered low voltage, solid state RF generation as an option. The klystrode is a tube device requiring an anode voltage on the order of 80 to 140 kVdc. Klystrodes, we assume, were chosen to minimize conductor size, switching concerns and mass penalties associated with low voltage, high current power conditioning options. However, the issue of high voltage in space was not addressed in detail nor did we see detailed tradeoffs between high voltage tube-type and low voltage, solid state RF power conditioning options. The selection of high voltage, tube type RF generators favors high voltage sources (alternators with voltages above 74 kV), which do not require heavy step-up transformers as part of their power conditioning package, over low voltage sources such as fuel cells and MHD. Favoring high voltage sources may be justified for an NPB weapon which requires high frequency RF power, but it may not be justified for FEL weapons that can use lower frequency, low voltage, solid state RF generators.

Tube-type RF sources are currently the most viable contender for the second and third stages of the LANL funneled NPB concept. This concept requires RF power at frequencies of 425, 850 and 1700 MHz. The RF free electron laser requires RF at a frequency of 433 MHz. At this frequency, very efficient (75-80%) RF sources in either

Power Conditioning Designs were Top Level

There was Little Detail

Power Conditioning Mass Estimates Varied Widely Between Contractors

Only Martin Marietta Considered Solid State RF Generators, but Only as an Option. Does this Discriminate Against Low Voltage Devices? Does it Apply to the FEL?

Power Conditioning Mass may be a Discriminator, But:

- GE Assumed Very Light, Cryocooled PC Components
- MM and TRW Assumed High Voltage Alternators Requiring Light Power Conditioning

Thus, Conclusions and Discrimination Depend on Unsubstantiated Technologies tube or solid state technology appear feasible. Projections of technology advances for tube and solid state RF modules show tube technologies to have higher operating efficiencies than solid state modules especially at the higher frequencies. Development efforts are in progress to increase power levels and operating efficiencies and to lower the specific weight for both klystrode and solid state modules.

The weights presented for low voltage verses high voltage power conditioning subsystems indicate that power conditioning mass may be a discriminator for selecting one prime power source over another. From the power conditioning data contained in the contractor reports, we can not draw valid conclusions regarding the impact of the power conditioning subsystem on the selection of the prime power source. This is due to the fact that we were not given sufficient detail to adequately assess the technology employed in the power conditioning subsystem concepts proposed.

Power Conditioning Designs were Top Level

There was Little Detail

Power Conditioning Mass Estimates Varied Widely Between Contractors

Only Martin Marietta Considered Solid State RF Generators, but Only as an Option. Does this Discriminate Against Low Voltage Devices? Does it Apply to the FEL?

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Thus, Conclusions and Discrimination Depend on Unsubstantiated Technologies

PC MASS COMPARISONS FOR THE NPB
(kg/kW)

This figure summarizes the weights projected by the three contractors for power conditioning subsystems to support NPB RF sources.

Power conditioning for turboalternators consists of rectifier stacks operating at about 100 kV in the Martin Marietta and TRW concepts and a transformer-rectifier combination to increase generator output voltage from 50 kVac to 142 kVdc in the GE concept. The difference between the TRW and Martin Marietta weights for high voltage turboalternator power conditioning appears to be related to near-term verses far-term technology as well as, the mass associated with packaging the power conditioning subsystem in the TRW case. The mass for the transformer-rectifier power conditioning in the GE concept is about half the mass given for the Martin Marietta rectifier stack alone. The major reason for GE's lightweight power conditioning subsystem is a cryo-cooled transformer which is projected to be an order of magnitude lighter than present transformer weight projections. That transformer is projected to weigh on the order of 0.013 kg/kW.

Power conditioning for fuel cells, thermionics and MHD sources are dc-dc converters in the GE and Martin Marietta concepts and an inverter and rectifier at separate platform locations in the TRW concept. Because the power sources all produce low voltage dc, transformers are required as part of the converter package to increase the input voltage to the 100 kV level. The weights of the GE power conditioning subsystems are about a factor of 30 lighter than the TRW and Martin Marietta projections. As stated above, this is mainly due to the lightweight cryo-cooled transformer in the dc-dc converter.

PC Mass Comparisons for the NPB (kg/kW)

	GE	MM	TRW
Turboalternator	.014	.022	.12
Fuel Cell	.015	.41	.41
Thermionic	.015	.41	.46
MHD	.015	.41	.46

NPB-TURBOALTERNATOR POWER CONDITIONING COMPARISON/ NPB-THERMIONIC POWER CONDITIONING COMPARISON

NPB power conditioning weight comparisons between contractors are shown for high voltage ac and low voltage dc power source options. Specific examples of sources shown are alternator and thermionic sources. The alternator sources will be discussed in the appendix on alternators. Alternator electrical frequencies range between 1 and 2 kHz with output voltages in the range of 50-100kV. The TRW and Martin Marietta power conditioning concepts have rectifier outputs of about 100 kVdc to power 1 MW klystrodes and the GE concept shows an output of 142 kV to power 2.5 MW klystrodes.

The thermionic source power conditioning dc outputs are the same as identified for the turboalternator concepts described above. Inputs to power conditioning are in the 100-500 volt range (Martin and GE) and 1500 volts (TRW). All three contractor concepts used dc-dc converters. TRW split the converter into an inverter and a rectifier. In the TRW concept, medium voltage ac is transmitted and is rectified at the load. TRW and Martin Marietta low voltage dc to high voltage dc power conditioning masses are comparable. The mass of GE's power conditioning concept is about a factor of 5 lighter due to an assumed lightweight cryo-cooled transformer.

Sandia NASA

NPB-Turboalternator Power Conditioning Comparison

	TRW	MARTIN	GE
Device	Alternator	Alternator	Alternator
Voltage Out (kVac)	105	74	50
Frequency (kHz)	1.0	1.657	1.1
Specific Mass (kg/kw)	.06	.27	.05
Device	Rectifier	Rectifier/Filter	Xfmr/Rectifier
Voltage Out (kVdc)	105	100	142
Specific Mass (kg/kw)	.12	.022-.060	.014
Total Specific Mass (kg/kw)	.18	.292-.330	.064

NPB-Thermionic Power Conditioning Comparison

Device	Inverter	DC-DC Converter	DC-DC Converter
Voltage In (kVdc)	1.5	.1-.5	.1-.3
Frequency (kHz)	4.0	-----	-----
Specific Mass (kg/kw)	.34	.41	.015
Device	Rectifier	|	|
Voltage In (kVac)	105	|	|
Specific Mass (kg/kw)	.12	|	|
Total Specific Mass (kg/kw)	.46	.41	.015

POWER CONDITIONING COMPONENT WEIGHT COMPARISON (kg/kw)

This figure gives weight comparisons of major elements in space platform power conditioning subsystems for burst mode and continuous mode applications. The specific weights (kg/kW) for continuous power applications are a fairly consistent order of magnitude higher than those for burst mode application. Both Martin Marietta and GE show similar weights for advanced technology high voltage conductors. Comments regarding other entries on the adjoining page have been previously discussed.

Power Conditioning Component Weight Comparison (kg/kw)

Weapon	TRW	Martin	GE
Transformer	---	---	.013 ☆
Alternator	.06 □	.27 ○	.05 □
Rectifier	.12 ○	.022 □	.001 ☆
Inverter DC-AC	.34 △	---	---
Converter DC-DC	.41 △	.41 △	.015 ☆
Cryo Conductors	---	.004-.009 △	.0075 △

OTV	TRW	Martin	GE
Rectifier	1.06 ○	.27 ○	.09 △
Converter DC-DC	1.06 △	---	---

Legend

□ State of the Art

○ Old Technology

△ Advanced Technology

☆ Optimistic

OTV-TURBOALTERNATOR POWER CONDITIONING COMPARISON/ OTV-THERMIONIC POWER CONDITIONING COMPARISON

Weight comparisons for OTV continuous operation missions are shown for high voltage ac and low voltage dc power source options. Specific examples used are turboalternator and thermionic sources. GE and TRW masses reflect near-term superconducting or cryo-cooled alternator technology. As in the NPB example, the Martin Marietta concept includes a Lundell-Rice alternator. Alternator electrical frequencies range between 1 and 2 kHz with output voltages in the range of 3.4 to 74 kV. The GE concept has a 200 volt rectified output to the thruster load while the TRW concept has a 15 kVdc output to a thruster pulser module. Power conditioning specific masses for OTV turboalternator concepts ranged from 0.48 to 1.33 kg/kW.

The Martin Marietta power conditioning concept for the turboalternator power source includes only a rectifier stage. The GE concept has a transformer/rectifier power conditioning configuration, and the TRW concept has a transformer/rectifier configuration with a pulser interface to the thruster.

The power conditioning output for the TRW thermionic power source example is the same as described above. The TRW power conditioning concept employees a dc-dc converter with a $\pm$ 50 Vdc input producing 15 kVdc which is fed into a pulser which produces 15 kV pulses at 1.5 kHz. TRW shows the specific masses for the turboalternator and thermionic power conditioning to be the same, even though the input voltages are significantly different.

OTV-Turboalternator Power Conditioning Comparison

	TRW	MARTIN	GE
Device	Alternator	Alternator	Alternator
Voltage Out (kVac)	8.7	74	3.425
Frequency (kHz)	1.0	1.657	1.0
Specific Mass (kg/kw)	.10	.27	.09
Device	Xfmr/Rectifier	Rectifier	Xfmr/Rectifier
Voltage Out (kVdc)	15	?	.2
Specific Mass (kg/kw)	1.06	.59	.39
Device	Pulser	—	—
Voltage Out (kVdc)(pulsed)	15	—	—
Pulse Frequency (kHz)	1.5	—	—
Specific Mass (kg/kw)	.17 (nom)		
Total Specific Mass (kg/kw)	1.33	.86	.48

OTV-Thermionic Power Conditioning Comparison

Device	DC-DC Converter	None	N/A
Voltage In (Vdc)	± 50	—	—
Frequency (kHz)	4.0	—	—
Specific Mass (kg/kw)	1.06	—	—
Device	Pulser	—	—
Voltage Out (kVac)(pulsed)	15	—	—
Operating Frequency	1.5	—	—
Pulse Frequency (kHz)	1.5	—	—
Specific Mass (kg/kw)	.17 (nom)	—	—
Total Specific Mass (kg/kw)	1.33	—	—

OTHER AREAS WHERE POWER CONDITIONING INFORMATION LACKED SUFFICIENT DEPTH TO CONDUCT MEANINGFUL ASSESSMENT OF CONTRACTOR EFFORTS

In addition to the general comments regarding our assessment of the power conditioning information contained in the SPAS documentation covered in figure PWC-1, there were other issues which we believe lacked sufficient detail to adequately assess contractor power conditioning concepts. The adjoining figure summarizes some of the topical areas which deserve further study.

Other Areas Where Power Conditioning Information Lacked Sufficient Depth to Conduct Meaningful Assessment of Contractor Efforts

Sandia NASA

Analyses were based on point designs - full extent of ranges were not considered
- Lacked details of tradeoff studies showing one power conditioning approach better than another

Focus on new technologies without comparing to fallback positions

Did not show effects of platform/power system dynamics on PC hardware

Did not identify hardness requirements for PC components, weak points, mitigation techniques

Did not perform trade study to show the relationship between turbine optimization vs alternator frequency

SPAS CONTRACTORS CONDUCTED SOME USEFUL PC ANALYSES

During our review of the SPAS power conditioning efforts, we identified areas where we felt the contractors conducted analysis work which we believe to be useful in conducting assessments of power conditioning options. The topical areas are summarized on the adjoining figure.

General Electric showed the scaling relationship for their superconducting alternator over a power range of 8 to 100 MW and an output voltage range of 20 to 80 kV. In evaluating platform transmission and distribution technology, GE identified space environment interaction concerns relating to long life at continuous high voltage stresses on cable insulating materials as well as, conductor connectors and high temperature/low temperature transmission line interface issues.

Martin Marietta assessed aluminum and copper conductor materials, four conductor configurations (solid, hollow, imbedded phase change material and Litz wire). Other areas evaluated were passive cooling and active cooling as well as, the effects of initial conductor temperature on transmission line mass. For high voltage switching, Martin Marietta identified crossatrons as an alternative to high voltage semiconductor switches for rectification and phase control regulation noting their inherent radiation hardness, switching frequency compatibility, improved power conditioning reliability and reduced system mass due to a significant reduction in parts count over semiconductor switch technology.

TRW identified specific circuit topologies, components within those topologies and mass breakdowns for the high voltage rectifier and low voltage inverter/converter configurations proposed. Addressing graceful degradation issues, TRW proposed modular, distributed power conditioning modules sized to handle one klystrode per module rather than a centralized power processing approach. TRW was the only contractor to identify the necessity for control system interfaces and sensors. For the OTV application, TRW provided a detailed schematic design for the pulser needed to drive the thrusters and information on an active cooling concept for transmission line conductors. The space environmental effects such as plasma interactions, radiation, debris, high voltage breakdown and their effects on power conditioning components were assessed. Mitigating schemes were then factored into the design concepts.

SPAS Contractors Conducted Some Useful PC Analyses

Sandia NASA

General Electric

- Generator mass vs power output scaling
- Cable insulation vs space environment interactions

Martin Marietta

- Conductor configuration, passive cooling schemes, skin depth, and start-up temperature effects
- Alternative high voltage switching schemes
- Inverter/converter reliability vs parts count
- Radiation, weight, tech dvt & risk tradeoffs
  - Solid State vs Tube Switches

TRW

- Identified components, weights, & schematics for inverters/converters
- Proposed distributed PC for RF generation (graceful degradation)
- Gave some thought to control system interfaces
- Detailed OTV pulser design & conductor cooling details
- Identified some environmental effects on PC system design & operation

COMPONENT AREAS NEEDING FURTHER INVESTIGATION

In reviewing the SPAS summary documents, there were important power conditioning integration issues that we felt were not adequately covered or not covered at all. Some of those issues are identified for cables, switches, alternators and inverters/converters.

Cable insulation is an issue that was identified. However, insulating system approaches, choices of materials and their relationship to specific environmental exposure concerns needs to be documented. The tradeoffs between an enclosed system and an insulated/shielded system need to be identified. Transmission line conductor concepts were discussed; however, there was no information as to how these conductors would be fabricated. The subject of transmission line connectors was covered briefly by Martin Marietta. We feel that conductor-connector joining methods, cable terminations, feed-throughs and interfaces such as cryo/ambient temperature joints needs to be critically addressed.

The packaging and modularization of high current, mechanical and solid state switches for bus switching, distribution disconnects, and fault protection requires further investigation. Although the need for these switches was identified, parameters such as packaging configuration, life expectancy, rep rate and their integration with the thermal management system, for example, are important details not discussed in the documentation. Higher power, higher voltage, faster switching devices merit further investigation and parameterization.

High voltage alternator concept block diagrams indicated classical power conditioning element configurations. It appears that a significant power conditioning weight reduction is possible by integrating the alternator and power conditioning circuits into one package. The impact on power system mass, attendant to integrating the alternator and power conditioning, requires further study. Redundant multibus power generation and transmission schemes were proposed for improved power system reliability. The mass impact and the effect on power conversion and power conditioning component sizing for each approach merits further investigation.

Low voltage dc power source concepts require inverters or converters to produce the high voltage output needed for RF tube loads. In order to thoroughly assess the mass impacts of low voltage power conditioning, detailed designs using real hardware and incorporating integrated thermal management techniques within the power conditioning module are needed.

Component Areas Needing Further Investigation

CABLE
- Insulation materials
- Space environment interactions
- Fabrication techniques for cooled high voltage lines
- Cryo conductors - joining, connectors
- Interfaces - cryo/ambient temperature joints
- Terminations, feedthroughs

SWITCHES
- High current mechanical and solid state switches
- Arc quenching, material loss
- Life, rep rate
- Higher dI/dt, voltage, power, faster switching
- Thermal management integration
- Low I*2 t losses during fault isolation
- Bus, distribution & load protection

ALTERNATORS
- Designs integrated with load input rqmts to minimize PC mass
- Trade study - integrated multibus, load separated, redundant design vs single bus approach

INVERTERS/CONVERTERS
- Detailed designs using real hardware & thermal management techniques

PC AREAS RECOMMENDED FOR FURTHER EFFORTS

Looking at the requirements for power conditioning subsystems from the operational standpoint, we identified some additional areas where we would like to obtain additional data and analyses to address integration and environment interaction issues. Three of the topics from the adjoining page require further explanation and are discussed below.

The contractors picked mission power levels and run times based on their review of architecture study documents and engineering judgement. General comments were made regarding the applicability of each power supply concept over a range of power levels and run times. It would be beneficial to evaluate the sensitivity of power conditioning mass, efficiency, modularity etc. to power level and run time. Further, it is also important to identify the power/run time regimes where one power system concept is more advantageous than others.

The power conditioning system of choice incorporated high voltage tube RF sources and high voltage transmission for reasons of lighter conductors, easier switching and lighter power conditioning subsystems. To adequately assess the high voltage tube verses low voltage solid state concepts, a critical analysis of packaged systems supporting each concept needs to be done; taking into account all the power requirements for the NPB and not just the klystrode anode voltage power requirements. When all the support system power needs are accounted for, it may be that the mass differences between the high voltage and low voltage systems will be significantly less than is projected by a cursory analysis.

The General Electric NPB power system concept showed that RF modules would be sized at 2.5 MW each. GE did not present data to support the premise that 2.5 MW RF injection into the accelerator structure is possible and that the maximum field tolerable within the accelerator is not exceeded.

PC Areas Recommended for Further Efforts

- Sensitivity of power level & run time to power system concept
- Detailed PC topologies showing the voltages to all the loads on the platform - not just the "power hogs"
- Better database on PC components
  - Define for each component a data sheet of input & output parameters:
    - Environments, EMI/RFI precautions, size, weight, constraints, & interfaces
- Tradeoffs high voltage tubes vs solid state
- Analysis to show that accelerator physics can handle 2-2.5 MW injection
- What are the real environments (temp, radiation) for electrical components given shielding and temperature mgt proposed
- What are dynamic environments (weapon & PS induced)
  - What can the components stand
  - What are the mitigation techniques (how implemented)
- What are electrical noise sources & characteristics of PC eqpt
  - What is the coupling into power distribution system
  - What are the mitigation techniques

VI. SYSTEM ISSUES AND INTERFACES

D. THERMAL MANAGEMENT

THERMAL MANAGEMENT: ALL CONTRACTORS CHOSE A DIFFERENT TYPE OF WEAPON COOLING
THESE ARE FOR NPB

This table shows the different types of cooling systems chosen by the three contractors for the different components of a neutral particle beam weapon. TRW chose to use a superconducting accelerator and magnets based on liquid hydrogen temperatures. That is, they are assuming the use of advanced superconductors that operate at higher temperatures than the current technology which uses liquid helium coolant. GE also chose superconducting accelerator and magnets but based on liquid helium temperatures. MM chose cryogenic cooling instead of superconducting. The assumptions made about the method of cooling can have a significant effect on the weapon power requirements and heat loads.

THERMAL MANAGEMENT:

ALL CONTRACTORS CHOSE A DIFFERENT TYPE OF WEAPON COOLING THESE ARE FOR NPB:

(SC - SUPERCONDUCTING, CRY - CRYOGENIC)

	ALT	ACC	MAG	RF GEN
TRW:	SC-H2	SC-H2 (30K)	SC-H2 (50K)	H2
MM:	?	CRY-H2	CRY-H2	H2
GE:	SC-HE (4K)	SC-HE (4K)	?	H2

NPB HEAT LOADS (MW)

The heat loads for the different components of a neutral particle beam weapon vary significantly among the three contractors. TRW's heat load for the accelerator is very low because it is superconducting. GE also assumes a superconducting accelerator which has a very small heat load, but the RFQ part of the accelerator and the high order mode dump for the accelerator are hydrogen cooled and are not superconducting. The heat load for these two parts is entered under the accelerator heat load in the table.

Notice also that Martin Marietta has a large stripper heat load. They were the only contractor to assume a laser stripper, and the laser stripper required a large fraction of the weapon's power and cooling needs.

Keep in mind that the weapons associated with these heat loads have different sizes. TRW's weapon uses an input power of 400 MW, while Martin Marietta's and GE's weapons use 200 MW.

NPB HEAT LOADS (MW)

	ACC	RF GEN	MAG	STRIPPER
TRW:	0.003	106	?	0
MM:	10.0	33.3	1.9	46.8
GE:	13.7*	47.2	?	0

* GE's accelerator is superconducting using helium as a coolant, but this number is for RFQ and high order mode dump using hydrogen coolant.

THERMAL MANAGEMENT COMMENTS

The assumption of supercooled weapons instead of cyrogenically cooled weapons results in very low hydrogen flow rates. The amount of hydrogen required by the platform is much lower for the supercooled weapons. As a result, hydrogen flow rates are governed by the power system for GE and TRW, while it is governed by the weapon cooling demands for MM.

THERMAL MANAGEMENT COMMENTS

- THE HYDROGEN FLOW RATE FOR MM's CRYOGENICALLY COOLED WEAPON WAS TWICE THAT FOR GE's AND TRW's SUPERCOOLED WEAPONS

  - MM's WAS DICTATED BY WEAPON COOLING

  - GE's AND TRW's WERE DICTATED BY POWER SYSTEM REQUIREMENTS

THERMAL MANAGEMENT COMMENTS (cont.)

A key point brought out by all three contractors is the need for careful weapon/power subsystem integration. However, none of the contractors identified the trade-offs associated with the use of superconducting and cryogenically cooled weapons. They also did not discuss how the choice of weapon cooling types impacts the overall platform design. Optimization of the weapon/power subsystem was not reported by any of the contractors. This is an important topic that needs to be addressed in more detail.

THERMAL MANAGEMENT COMMENTS

- ALL CONTRACTORS REPORTED THAT CAREFUL WEAPON/POWER SUBSYSTEM INTEGRATION IS NEEDED BUT THET DID NOT:

  - IDENTIFY TRADE-OFFS BETWEEN CRYOGENIC AND SUPERCONDUCTING WEAPON COOLING
  - DISCUSS HOW THE WEAPON COOLING SYSTEM IMPACTS PLATFORM DESIGN
    - DOCUMENT INTEGRATION APPROACH
  - IDENTIFY WHAT WEAPON/POWER SUBSYSTEM COMBINATIONS ARE BEST AND WHY
  - DO ANY COMBINED WEAPON/POWER SYSTEM OPTIMIZATIONS

THERMAL MANAGEMENT COMMENTS (cont.)

As determined by all three contractors, the hydrogen flow rates required to cool the weapon appear to be based only on an energy balance and not on heat transfer considerations such as the required heat transfer area. Satisfying heat transfer constraints may significantly affect platform design and should be addressed.

THERMAL MANAGEMENT COMMENTS

- NONE OF THE CONTRACTORS INVESTIGATED POSSIBLE HEAT TRANSFER CONSTRAINTS ASSOCIATED WITH HYDROGEN COOLING

ALL THREE CONTRACTORS AGREED THAT CONTINUOUS WEAPON COOLING IS NECESSARY

All three contractors concluded that steady-state continuous cryogenic cooling of the weapons was necessary due to the short startup times. However, only TRW provided specific weapon steady-state heat load information. Based on the results from all three contractors, the steady-state refrigeration power required to handle the platform cooling loads (weapon and cryogenic storage tanks) was less than 100 KW. Also, the refrigerator mass was not indicated to be a significant fraction of the overall platform mass.

ALL THREE CONTRACTORS AGREED THAT CONTINUOUS WEAPON COOLING IS NECESSARY

- Steady-state cryogenic cooling of the weapon and storage will require less than 100 kw steady-state power

- Refrigerator mass is not a significant fraction of the overall platform mass

COMPARATIVE STEADY-STATE COOLING REQUIREMENTS FOR NPB PLATFORM

This figure compares the three contractor estimates for steady-state cryogenic cooling requirements for a combustion powered NPB weapon system. The difference in hydrogen or oxygen storage masses was due to the assumed weapon power level, run time, and weapon cooling loads (during operation). As indicated in the figure, the proposed refrigerator power ranges from 17 to 60 KWe. Their cryogenic refrigerator COPs range from 0.008 to 0.011 when cooling liquid hydrogen at 20 K. All contractors estimated the cryogenic tankage heat gains (or cooling loads), but only TRW estimated the weapon steady-state cooling load.

TRW's weapon was assumed to be superconducting and cooled to liquid hydrogen temperatures (20 to 30 K) with a calculated heat gain of 92 watts. TRW's storage heat gain was indicated to be only 62 watts (52 watts for the liquid hydrogen storage tank and 10 watts for the liquid oxygen storage at 95 K). This storage tank heat gain was stated without an indication of the multi-layer insulation thickness or any trade-off study results. For this reason, the tank heat gain should be considered as an arbitrary (and perhaps unreasonably low) value. The TRW refrigeration system mass was based on two redundant refrigerators at 500 kg each and a single radiator. The radiator was assumed to radiate to deep space temperatures which would require orientation of the platform.

GE assumed a liquid helium cooled superconducting weapon at 4 K. Although GE did not estimate the resultant weapon cooling load, they did estimate the weapon refrigeration power at 15-25 KWe input. This weapon refrigeration power was included in GE's total refrigeration power of 60 KWe. GE's total storage heat gain of 410 watts (approximately 400 watts for the liquid hydrogen tank and 10 watts for the liquid oxygen tank) was derived from a system optimization based on multi-layer insulation mass (thickness), refrigerator mass, radiator mass, and input power requirements. Their cryogenic storage tank heat gains are also reasonable and should be considered the better estimate of the three contractors. Note that even their total refrigeration input power was less than 100 KWe.

MM estimated a total heat gain for the cryogenic storage tanks of 235 watts (216 watts for hydrogen storage and 19 watts for oxygen storage). Their assumed multi-layer insulation thickness was 10 cm for the hydrogen tank and 5 cm for their oxygen tank. Although no optimization was indicated, this hydrogen tank insulation thickness was near GE's optimized design. However, MM had only about half the

COMPARATIVE STEADY-STATE COOLING REQUIREMENTS FOR NPB PLATFORM

	H2 Mass (Mt)	O2 Mass (Mt)	HEAT GAIN		Total Refrig Power (kw)	H2 System COP	Refrig Mass (kg)
			Storage (Watts)	Weapon (Watts)			
MM	61	33	235	0✓	26.4	.008	----
GE	30	25	410	?	60*	.011	1000
TRW	39	22	62	92	17	.009	1600**

* Includes 25 kw LHe refrigeration power

** Includes redundant refrigerators

✓ MM did not account for steady-state weapon cooling

COMPARATIVE STEADY-STATE COOLING REQUIREMENTS FOR NPB PLATFORM (cont.)

hydrogen tank heat gain even though their hydrogen storage mass was nearly twice that proposed by GE. MM's much lower heat gain was due to an assumed much lower ideal multi-layer insulation thermal conductivity. No value or estimate was given for the cryogenic refrigerator and associated radiator mass.

COMPARATIVE STEADY-STATE COOLING REQUIREMENTS FOR NPB PLATFORM

	H2 Mass (Mt)	O2 Mass (Mt)	HEAT GAIN		Total Refrig Power (kw)	H2 System COP	Refrig Mass (kg)
			Storage (Watts)	Weapon (Watts)			
MM	61	33	235	0✓	26.4	.008	----
GE	30	25	410	?	60*	.011	1000
TRW	39	22	62	92	17	.009	1600**

* Includes 25 kw LHe refrigeration power

** Includes redundant refrigerators

✓ MM did not account for steady-state weapon cooling

CRYOGENIC COOLING - OBSERVATIONS

All three contractors proposed the Garrett reversed Brayton turbo-refrigerator units to cool at liquid hydrogen and liquid oxygen temperatures (20 K and 90 K respectively). The 20 K refrigerator would require Garrett's two stage expansion design. These refrigeration units should be considered conceptual designs only as none have been manufactured to date.

Only GE optimized the storage tank insulation, refrigerator, and incremental power system masses. The other contractors selected only arbitrary designs. Thus, TRW's and MM's lower heat gains for the hydrogen storage tank may be unreasonable. GE, however, was optimistic on the performance and/or heat gain of their proposed liquid helium (4 K) weapon cooling system and their power input for this refrigerator may also be unreasonably low.

The contractor refrigeration system studies did not address specific heat transfer design issues. Only overall energy balances were performed. Significant heat exchanger mass may be required to effectively utilize their refrigeration systems or to obtain their stated COP's.

The contractors did not include details in their draft final reports specifying how they calculated cryogen storage tank weights. GE and TRW's tank weights are a little lighter than those the Field Support Team calculates for the same size tanks. We believe this may be because meteoroid protection was underestimated. Martin Marietta's tank weights were very light, and we assume this is because they did not include any meteoroid protection. The FST uses aluminum meteoroid shield mass algorithms from Fraas (Protection of Spacecraft from Meteoroids and Orbital Debris, ORNL/TM-9904, February 1986) with a 0.99 survival probability over 7 years against meteoroid penetration. Space debris has not yet been considered by the FST nor has the use of bumpers for cryogen tank protection; thus, shield mass estimates are preliminary.

CRYOGENIC COOLING-OBSERVATIONS

- All contractors proposed Garrett reversed Brayton turbo-refrigerators
- Only GE optimized storage tank insulation based on mass
- TRW assumed unreasonably lower heat gains
- GE was optimistic on LHe refrigeration power
- No heat Transfer issues were addressed (only energy balances)
- GE and TRW tank weights were too light to have included proper meteoroid shields
- MM used no meteoroid shield at all

CRYOCOOLERS TECHNOLOGY DEVELOPMENT NEEDS

Space-based cryogenic refrigerators will operate continuously once placed in orbit to cool the stored cryogenic fluids (hydrogen and oxygen) and cold weapon components as required. Thus, the refrigerators must operate for the entire life of the platform (in excess of 7 years). The cryogenic refrigerators must also have high reliability because refrigerator failure would allow non-replenishable loss of stored cryogens and possibly intolerable temperature excursions within the weapon. This high reliability may only be possible with multiple refrigerators so individual refrigerator mass must be kept low. Finally, the full implication of low temperature heat transfer between cooled components and cryocooler working fluid with very low temperature differences should be determined on cryogenic refrigerator overall mass and performance.

Cryocoolers Technology Development Needs

- Long Operational Life (>7 yrs.)
- High Reliability With Minimal Mass Increase
- Investigation of Heat Transfer at Low Temperatures and Low Delta T's on Cryocooler Mass and Performance

VI. SYSTEM ISSUES AND INTERFACES

E. SURVIVABILITY

VI. SYSTEM ISSUES AND INTERFACES

E. SURVIVABILITY

Of the three contractors, TRW gives the most thorough treatment in the survivability area. There are, however, a number of issues which are not treated, or are inadequately treated by any of the contractors. The question of high voltage and high current operation in the space environment is avoided by TRW and inadequately or incorrectly treated by the others. The emission of effluent and the evolution of the effluent and its consequences are addressed by all three contractors with varying degrees of sophistication, but this issue should be examined more critically, because of the tremendous weight advantage of the open cycle systems and the large uncertainties in the accuracy of effluent dispersal models. Environmental effects need to be considered in the context of a local environment generated by the combination of the natural orbital environment and the changes to this environment induced by the presence and operation of a space system. This local environment is system and operations dependent, and requires a system perspective, including weapons and sensors as well as the power system.

Adequacy of Treatment
SPAS Contractor Task 4 Performance

GE

- Wide variety of effects treated
- Detailed treatment of nozzle geometry effects
- Inadequate treatment of HV interactions
- Assessment of HV breakdown problem probably not valid

MM

- Discussed EMI from the EML weapon system
- HV interaction problem not considered
- Least thorough treatment

TRW

- Most thorough treatment; included system specific analysis and mitigation strategies
- Wide variety of environment/effects treated: natural, self-induced & hostile
- Generally good treatment of effects considered
- Avoids most HV interactions issues by requiring complete insulation of electrical conductors; results in very heavy debris/meteoroid shielding requirements; complete long-term insulation probably not practical
- No treatment of high magnetic field effects around weapons
- Statement that H_2 effluent is benign to all systems too sweeping

Comments
SPAS Survivability Studies

Issues Not Addressed

- Breakdown of partially ionized gas (natural or system effluent) in presence of high voltage and/or magnetic fields
- Geometry/surface material property effects on arcing and plasma current collection
- Effects of strong magnetic fields associated with weapon operation
- Orbital motion effects (including ram/wake) on local environments and effluent cloud evolution
- Ramside glow effects on sensors

Issues Inadequately Addressed

- Ageing effects on high voltage insulation in orbital environments
- Floating potential of system only addressed in terms of S/C charging; effects of system voltages, effluent release, and weapon activation not addressed
- Ionization & evolution of effluent clouds
- Interactions between weapons and effluent clouds

General

- Tendency to treat effects independently rather than collectively
- Generalized system definition led to quantitative divergence in results

IMPACT ENVIRONMENT: METEOROIDS, DEBRIS, PELLETS

The next section covers the SPAS Contractor results concerning the effect of meteoroids, debris and pellet threats to the weapon/power platform.

Impact Environment
(meteoroids, debris, hostile)
SPAS Contractor Conclusions

GE

- Protection from micrometeoroids & debris required for cryogenic tankage (adds 10 kg/m2)
- Debris environment dominates shield design
- Debris shielding comparable to meteoroid shielding
- Defensive shields needed against KEW
- Pellet threat not treated

MM

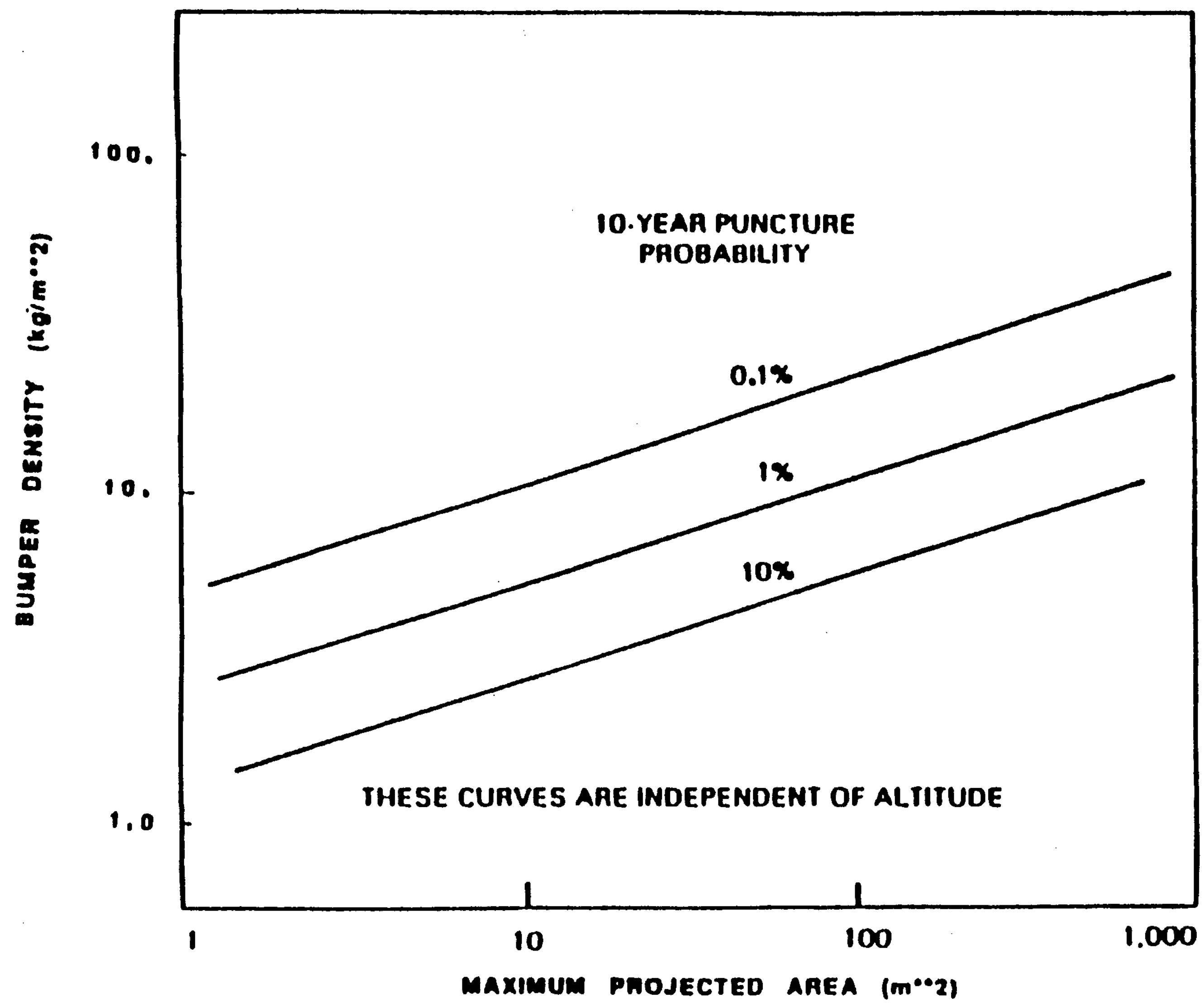
- Shield against debris & pellets

TRW

- Meteoroids & debris are dominant/limiting environment threats
- Debris dominates 700-1200 km, meteoroids higher
- Complete debris protection prohibitive (wt)
- 5-10% heat pipe redundancy needed
- Modularity for graceful degradation recommended
- Shield critical surfaces (laser/debris shield)
- Pellets ~ debris

GE- IMPACT ENVIRONMENT: METEOROIDS, DEBRIS, PELLETS

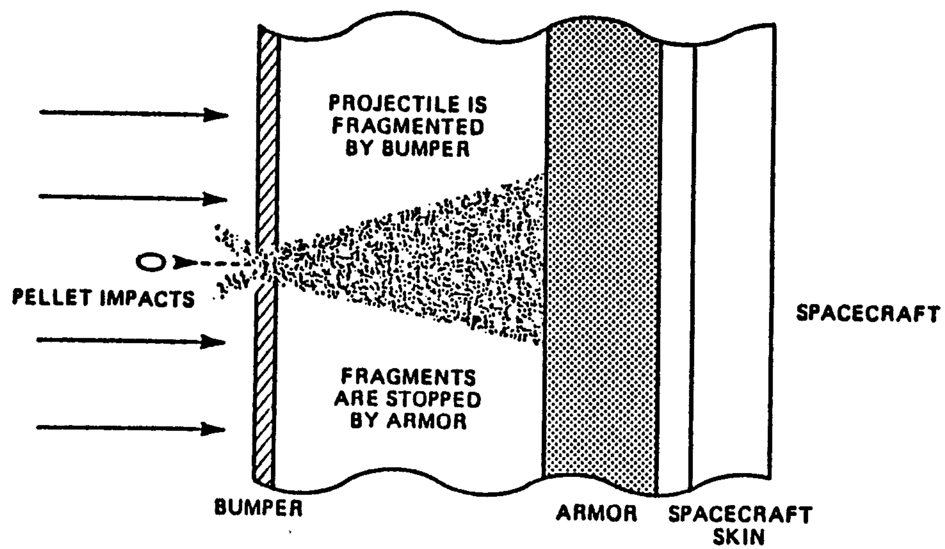
Meteoroid and debris environment was derived from NASA specification 8013. Meteoroid characteristics; 0.5 gm/cm^3, 20 km/sec. Debris characteristics; 2.7 gm/cm^3, 10 km/sec. Micrometeoroid flux is less than the debris flux for particles of mass greater than 10^{-5} gm. Therefore debris characteristics drive the design of shields but the results are comparable to shields for micrometeoroid survival. Thermal radiators and cryogenic tankage are the components most likely to suffer from meteoroid and debris encounters. Less than 1% probability of puncture in 10 yr requires ~10kg of shield/ m^2 of shielded cross section. Hostile pellet encounter could result in coolant and fuel loss as well as weakening of structure. The suggestion of shielding the entire platform seems prohibitive.



Aluminum Bumper Assessment - 10 Year Puncture Probability

Martin Marietta- Impact Environment

Martin Marietta discusses the debris/pellet environment but fails to mention the natural meteoroid environment. Their recommendations are to shun particle avoidance schemes due to the difficulty of the detection process, and to rely on passive shielding. They discuss a bumper/armor scheme which has proven effective against hypervelocity aluminum particles. They briefly mention that any shielding used will have a protective effect against a variety of environments and should be designed for the worst case.



<u>Typical Spacecraft Pellet Shield Concept</u>

TRW- IMPACT ENVIRONMENT: METEOROIDS, DEBRIS, PELLETS

TRW identifies the meteoroids/debris environment as the dominant environmental threat, with debris posing the major threat at low altitudes ($<$1000 km), and meteoroids at altitudes $>$2500 km. Complete protection against impact damage is found to be prohibitively heavy. Modular designs which can tolerate some degradation without catastrophic failure in conjunction with shielding and/or redundancy for critical elements are recommended. A shield for pellet/debris/laser threat is suggested.

The TRW design approach is to avoid high voltage-environment effects by requiring complete insulation of electrical conductors, particularly those carrying high voltages. This requirement for insulation results in the great need for impact protection, and is the driving force behind TRW's conclusion. It is not entirely clear what debris model is being used, although it is stated on page 2-37 that the effect of increase in debris with time and that of the launch and emplacement of SDI systems must be considered.

THREAT/ENVIRONMENT: IMPACT

PENETRATION FREQUENCY FOR POWER SYSTEM

TARGET CROSS-SECTION: $630M^2$

STRUCTURE THICKNESS	% SHIELDING WEIGHT	FREQUENCY, IMPACTS/YEAR
0.18CM	0	1279
0.9CM	17	34
2.0CM	34	5
4.5CM	55	1
11.0CM	76	.1

MITIGATION OF IMPACT FAILURES

- MODULAR DESIGN WHICH PERMITS PARTIAL LOSS OF FUNCTION (DEGRADATION) UPON PENETRATION RATHER THAN CATASTROPHIC FAILURE
- REDUCE WEIGHT INCREMENT BY SELECTIVE SHIELDING OF COMPONENTS RATHER THAN ENTIRE STRUCTURE

RADIATION ENVIRONMENT

The next section covers the SPAS Contractor results concerning the effect of the natural, platform-induced and hostile radiation environment upon the performance of the weapon/power platform performed.

Radiation Environment
(natural, P.S, W.S., hostile)
SPAS Contractor Conclusions

GE

- Total dose from fission gas effluent << natural
- Potentially significant gamma radiation from fissionable material in effluent cloud
- Low altitude (250 km) natural dose requires minimal shielding for .1 Mrad ~ 0.3 gm/sq cm
- Higher altitudes require 1-1.5 gm/sq cm

MM

- Weapon induced radiation < CARDS (?)
- Total dose is from reactor, natural & threat environments
- Prompt X-ray dose - 20 mil Ta shielding

TRW

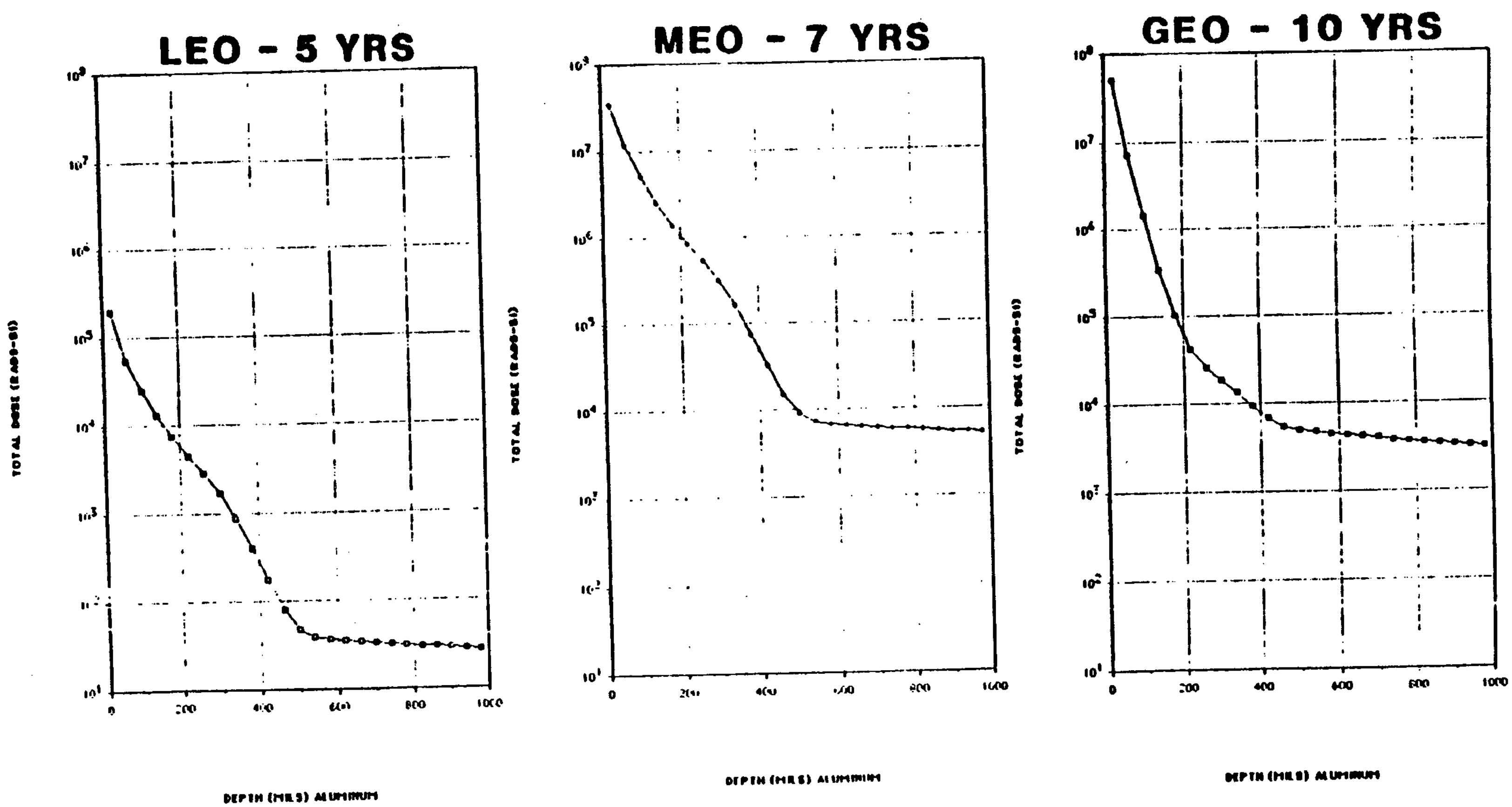
- Radiation shielding required, but not driver
- Total dose driver is natural environment, with contribution from on-board nuclear generator
- 0.9 cm Al gives 10E6 rads internal; commensurate with parts
- Add ~10 mils Ta for prompt dose effects
- Nuclear burst total dose << 10 yrs on orbit

TRW- RADIATION ENVIRONMENTS

TRW finds that, in terms of total radiation dose, the natural environment for a 7-year mission is the design driver. This assumes that an on-board reactor is separated by 25 meters from sensitive electronics. Shielding from radiation is required, but is not prohibitive. Because the natural environment is the design driver for radiation, this factor is not a real discriminator among systems. Additional shielding is found to be required for some switching devices to protect against prompt radiation effects under engagement conditions.

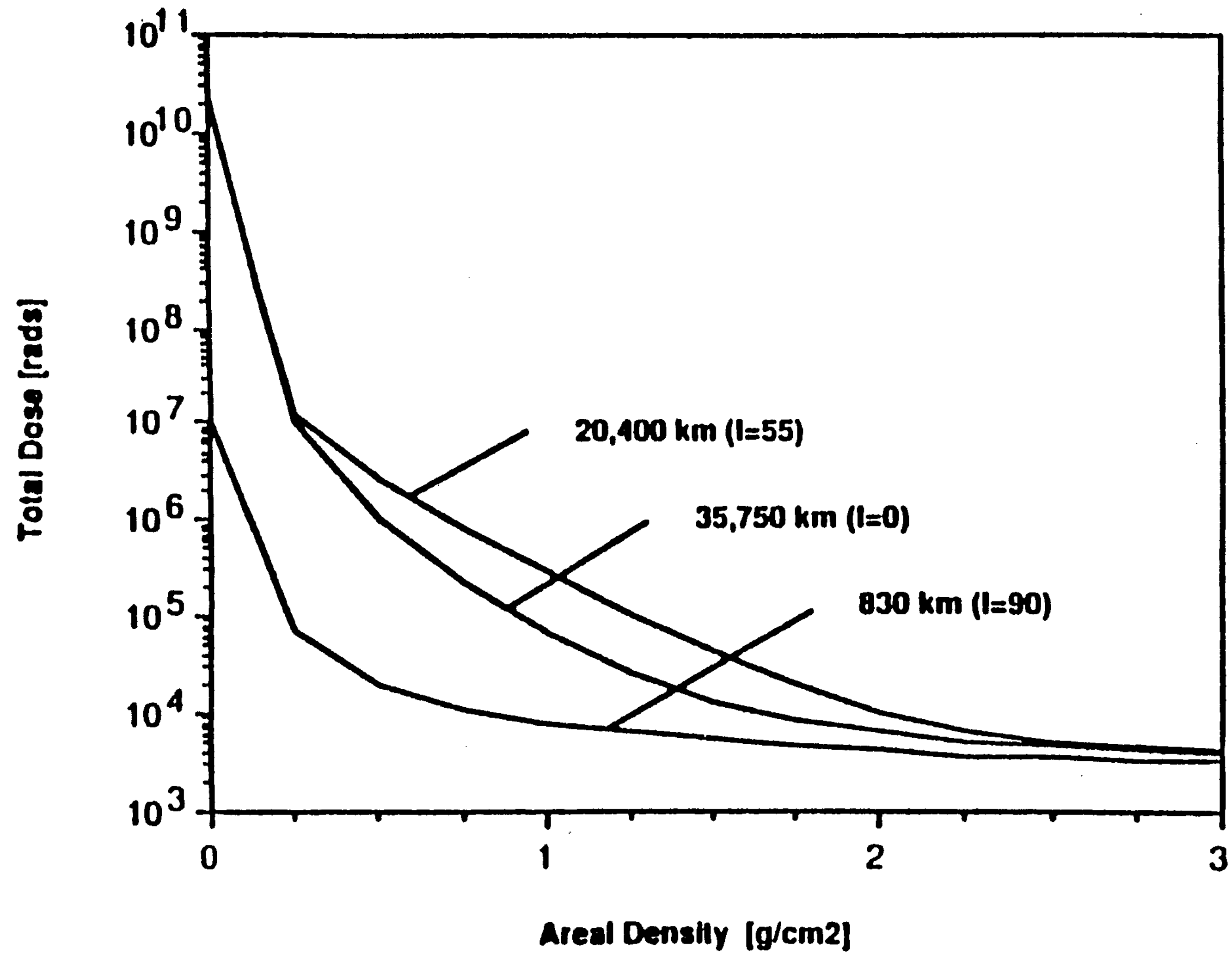
It is not stated precisely what environment models are being used, nor is "MEO" defined. However, given the conceptual nature of both systems and orbits for the SPAS effort, this is probably reasonable (assuming that the environment models used are the standard AE and AP models in general use for spacecraft design). Effects due to cosmic rays, e.g., single event upsets, are not addressed. These are device-dependent, so that again this is reasonable at this design stage.

THREAT/ENVIRONMENT: RADIATION
TOTAL DOSE - NATURAL RADIATION



GE- RADIATION ENVIRONMENTS

Sources considered were Van Allen Belts (NASA AE-8 for electrons and NASA AP-8 for protons), reactors, fissionable components in effluent gas, particle accelerators, and hostile weapons. Natural dose for altitudes below 850 km requires minimal shielding to get below 0.1 Mrad total dose (~0.3 gm/cm^2 shield areal density). Higher altitudes require 1 to 1.5 gm/cm^2. Shields will be needed for protection from reactor radiation. The calculated dose from fission components in the effluent cloud from a single effluent nozzle will be less than 0.1 rads. Details of radiation environment from particle accelerators and weapons are contained in classified appendices.



Natural Trapped Radiation Dose

Martin Marietta- Radiation Environment

Martin Marietta surveys a range of radiation environments. They conclude that the dominant concern is the total dose due to fission electrons from a nuclear burst. This is followed by the thermal response due to the prompt X-rays from a nuclear burst. Radiation from weapon operation is computed to be well below these levels. They assume 20 mil tantalum shielding against the natural environment. They also discuss the use of tungsten shielding against gamma radiation from the power system.

They feel that the use of SCR's is attractive, but their use will entail a combination of shielding, circuit hardening, and part development, since they will receive a substantial dose even through the tantalum shielding. They survey a variety of hardening options, including shielding, derating and thermal annealing.

Nuclear and Space Radiation Hardening Options

COMPONENT	TOTAL DOSE	PROMPT DOSE RATE	NEUTRON
Electrical Power & Control Electronics	Shielding-Al or Ta, Piecepart Selection, Piecepart Derating, Ckt Design Hardening, Subsys Power Down, Thermal Annealing, Limited Piecepart Development for High Volt/High Current Semiconductors, Tungsten Shielding or Increased Reactor Standoff for Most Sensitive Semiconductors	Shielding-Tantalum, Piecepart Selection, Ckt Design Hardening, Limited Piecepart Development for High Power Semiconductors, Tungsten Shielding to Reduce Weapon Gamma for Most Sensitive Semiconductors	Shielding , Piecepart Selection, Derating & Ckt Hardening for the Most Sensitive Devices (i.e. SCRs)
Materials In Power Control Subsystems	Hardening Not Req at These Radiation Levels	Low Atomic Number, High Strength & Temp Materials Selected For External Use	Hardening Not Req at These Radiation Levels

NEUTRAL ENVIRONMENT

The next section covers the SPAS Contractor results concerning the effect of the neutral environment caused by natural, self-induced and/or hostile mechanisms upon the weapon/power platform.

Neutral Environment
(natural; self-induced, hostile interactions)
SPAS Contractor Conclusions

GE

- Considered Paschen breakdown, condensation, reactivity, NPB interaction & optical interference of effluent cloud
- No HV breakdown for exposed kV power lines in effluent
- Water not a condensation problem except on cryogenic surfaces
- IR sensor not interfered with optically for most of range
- Effluent density order of mag below interference with NPB

MM

- Considered effluent contamination

TRW

- Effluent from open cycle systems (MHD, coolant) principal concern; contamination, NPB stripping (MHD)
- H_2 benign to all systems
- Other effluents could pose problems
- Weapons could excite cloud, effects transient (1–3 sec) ~ not a problem

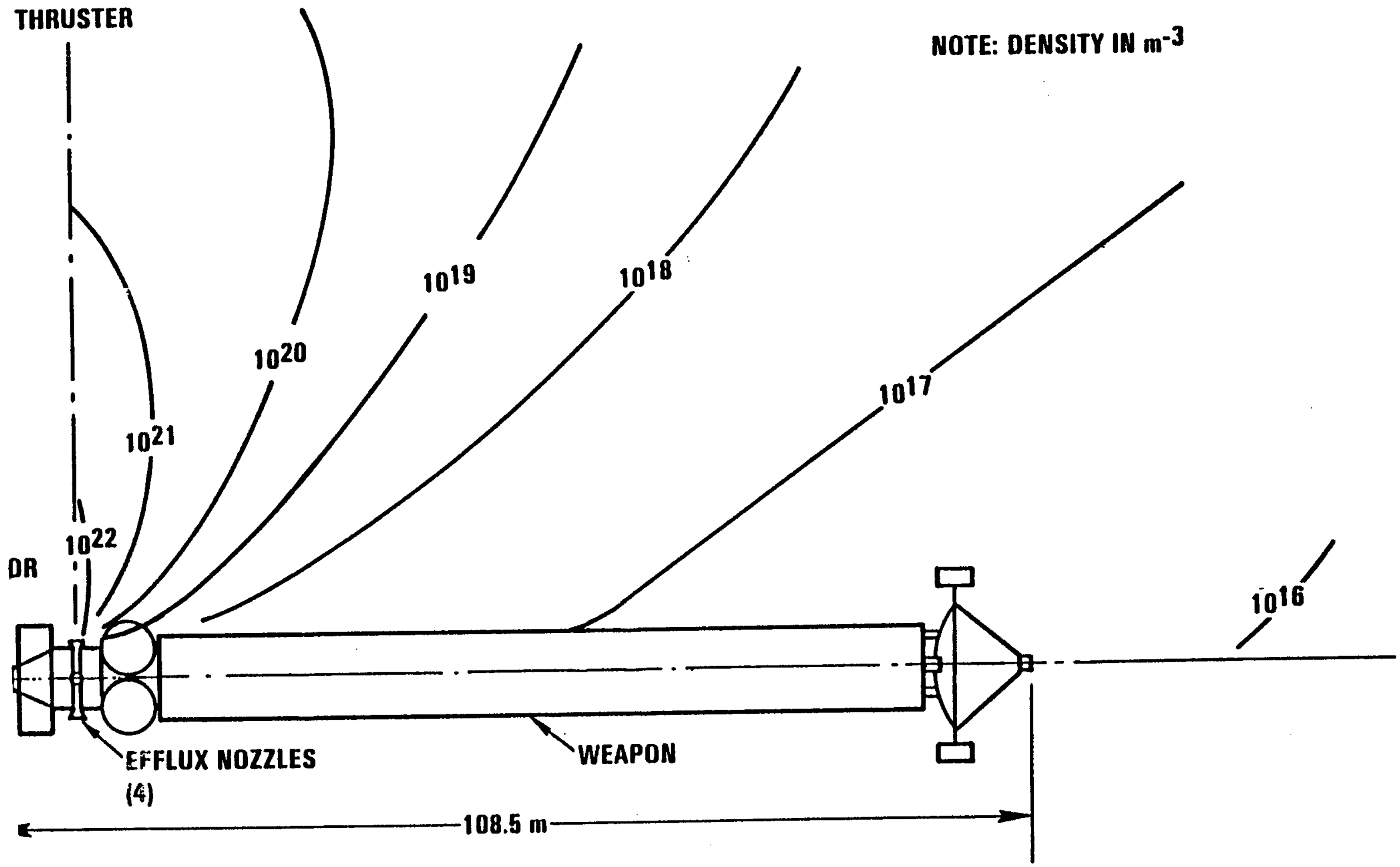
TRW-NEUTRAL ENVIRONMENT

The only neutral environment treated is the effluent from open cycle systems. This was treated as part of Task 3, and the write-up in Task 4 repeats that in Task 3. The analysis is based on an assumption of four nozzles arranged for thrust cancellation, and used a numerical nozzle core flow plus external plume methodology. A more detailed analysis at a later design stage is recommended. TRW found that the effluent effects were within acceptable limits for the DEW and sensors considered, at least for the turbine generator system. The removal of H_2O is recommended for the GEL/MHD system. It is noted that the TRW design has constrained the high voltages to be within the spacecraft body, which in turn reduces the severity of the interactions of the effluent cloud with the system.

It is not possible to assess the validity of the neutral density calculations from the information given, nor to check the conclusions. On page 3.10-7, a column density of $1 \times 10^{-5} g/cm^2$ is quoted, and on page 3.10-24 it is stated that NPB attenuation is .2-.3% for the turbine system and 2-3% for GEL/MHD. I have seen $10^{-6} g/cm^2$ quoted as sufficient for NPB stripping, which does not seem consistent with TRW's conclusion. Effects due to the natural neutral environment are not considered at all. These should be addressed, at least for the LEO systems.

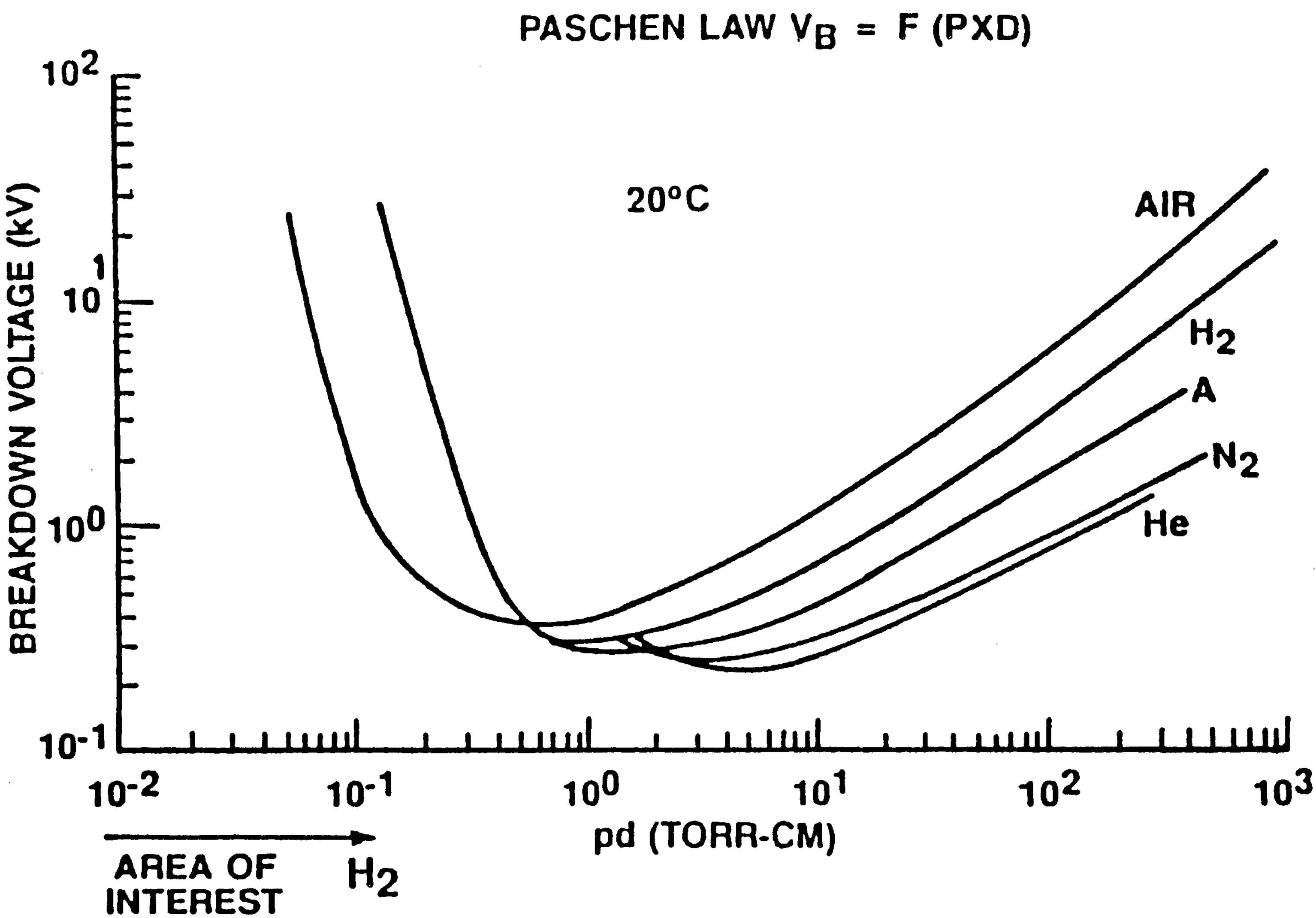
utral Hydrogen Number Density — Turbine
ıerator System

ıent from One Nozzle Only

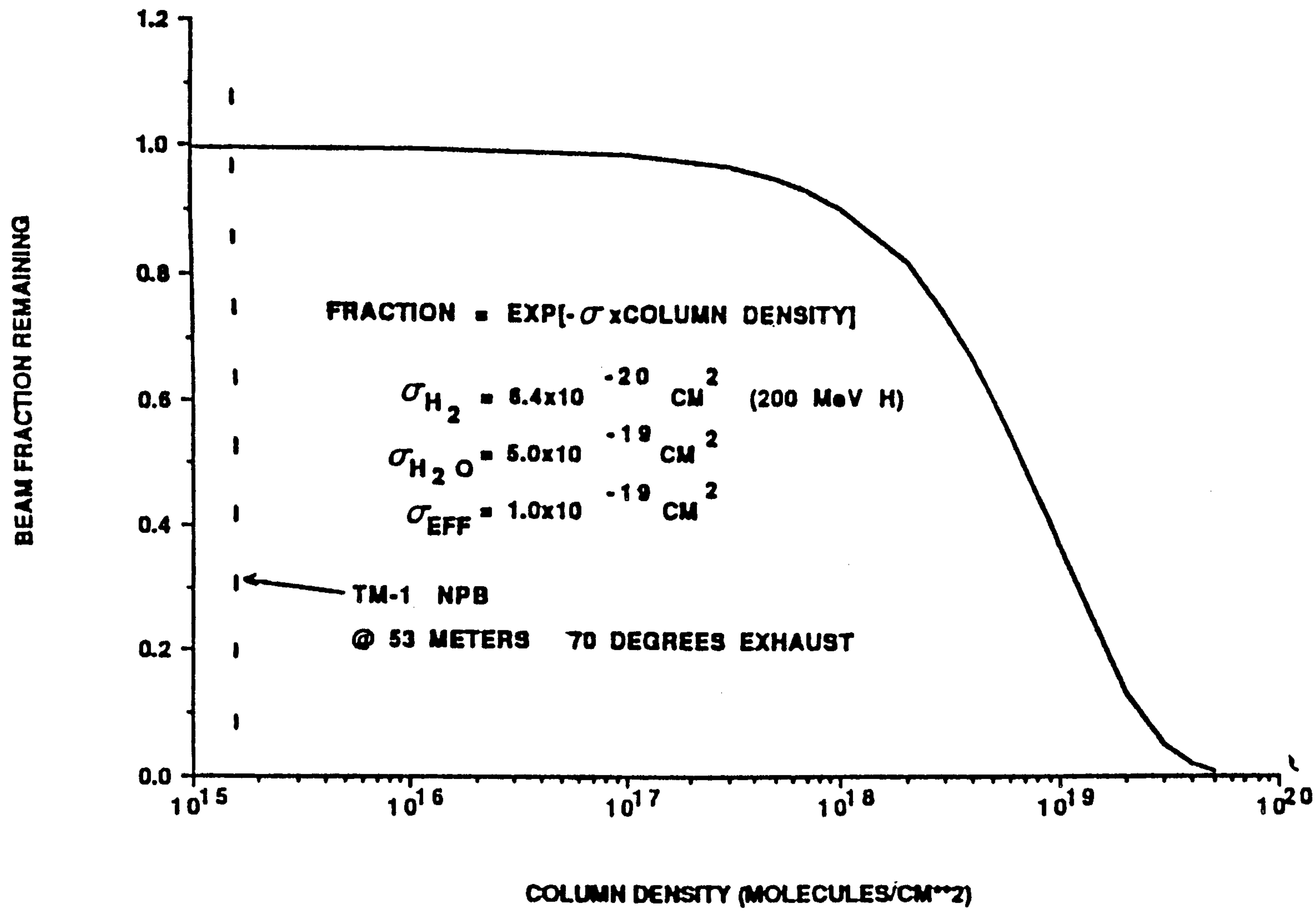


GE- NEUTRAL ENVIRONMENT

Paschen breakdown is not considered a problem for the self-induced H_2 and H_2O densities anticipated. It is not mentioned till later that the effluent is not likely to remain un-ionized. H_2O condensation on IR detectors is not considered a problem because of the detector design characteristics and the detectors' probable location and orientation relative to H_2O sources. H_2, H_2O, and ionic Cs are not considered a chemical reactivity problem because of their stability, but test data is needed for ionic Cs to quantify its chemical reactivity with proposed spacecraft materials. IR detectors are not subject to optical interference from H and H_2 effluent because there is no absorption in the 3 to 11 micron range and little attenuation (<1%) is expected from H_2O effluent due to low number density. Interference with NPB will be minimal for the effluent column densities expected, below $\sim 5*10^{17}/cm^2$.



High Voltage Breakdown Threshold for H_2



NPB Attenuation through Effluent

Martin Marietta- Neutral Environment

Martin Marietta analyzes, in some detail, the neutral effluent environment from a slot nozzle arrangement for various combinations of power systems and weapon systems. Several of the cases would result in deposition of water vapor on surfaces at right angles to the direction of the venting. They also discuss the problem of condensation within the plume and consequent interference with sensor operation. They mention the problem of infrared emission and absorption with the water effluent and conclude that the use of the CHARM computer code will be required for analysis. They cite several unresolved technical issues, including a mention of ionization, plasma and charging effects.

In their conclusions, they rank the effluents from pure hydrogen (best) to water plus hydrogen plus cesium (worst). They decline to rule out any effluent at the present time.

Effluent Temperatures, Pressures, and Flow Rates Assumed

Effluent Flow Rates (kg/s), Initial Temperatures (K), and Initial Pressures (atm)

		FEL		NPB		EML	
	Pres.	Temp.	Flow	Temp.	Flow	Temp.	Flow
Nuclear Brayton	1.0	586	52	416	44	855	44
Nuclear Rankine	----	----	----	----	----	----	----
Liquid Metal Reactor	----	----	----	----	----	----	----
Combustion Brayton	1.0	570	89	407	70	818	70
Combustion Brayton, Water Collected	1.0	639	48	447	41	996	41
Combustion-Driven MHD	1.5	3000	178	3000	122	3000	122
Fuel Cell	1.0	450	81.7	450	61.8	450	61.8
Fuel Cell , Radiator Cooled	----	----	----	----	----	----	----
Fuel Cell, Water Collected	1.0	450	48.3	450	41.8	450	41.8

PLASMA ENVIRONMENT

The next section covers the spas contractor results concerning the effect of the plasma environment naturally occurring and as the result of ionized effluent as it effects the weapon/power platform.

Plasma Environment
(natural, ionized effluent)
SPAS Contractor Conclusions

GE

- Effluent ionized by hostile action recombines in seconds ??
- Parasitic power loss < 100 W/m of exposed power line
- No significant RF signal attenuation by plasma

MM

- Acknowledge possible ionization of pure hydrogen effluent

TRW

- Insulate HV; pinholes could be problem
- Charging in auroral environment a concern
- Internal plasma from gas breakdown a concern (therefore insulate)

TRW-PLASMA ENVIRONMENT

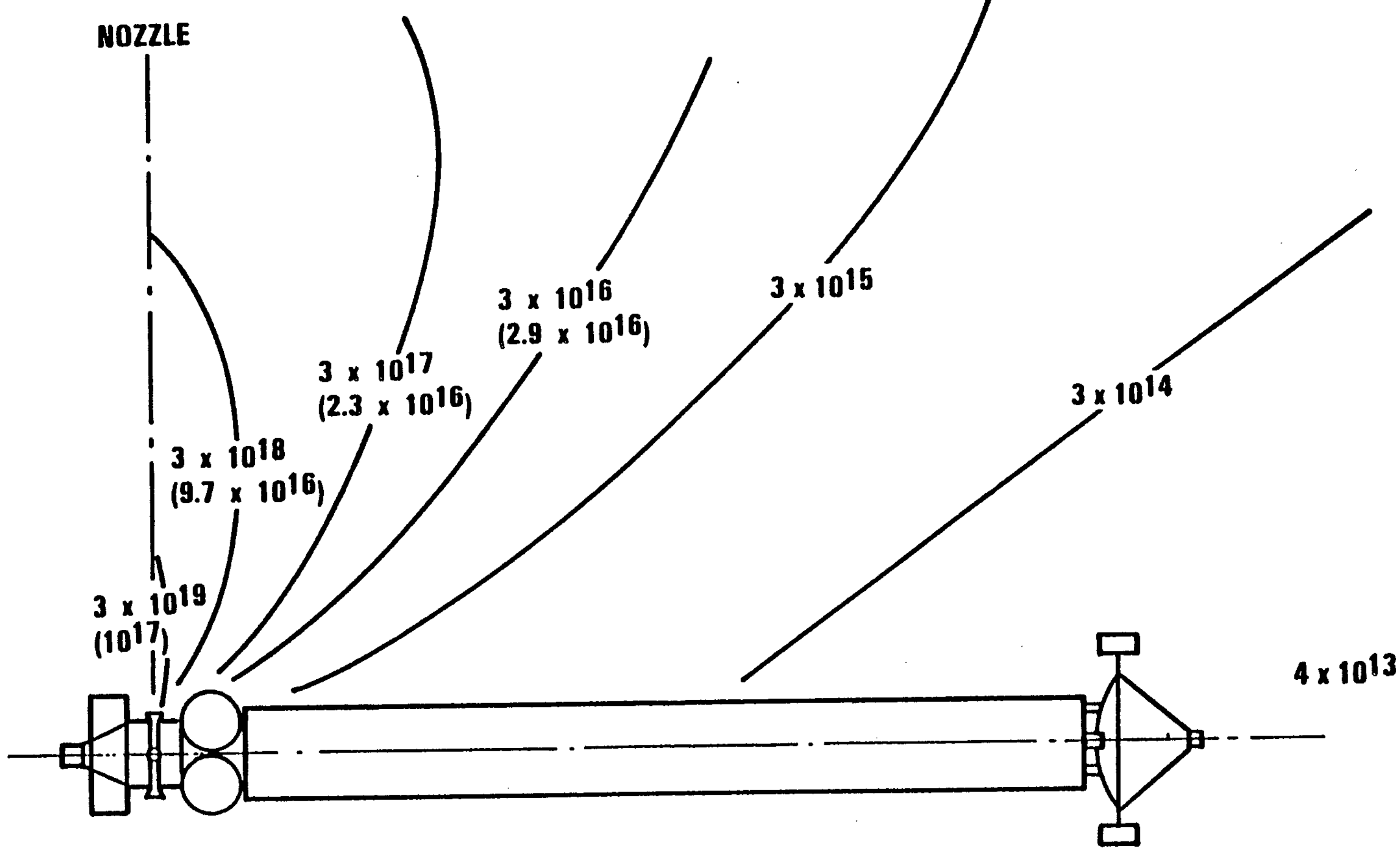
The final report does not address plasma issues in a separate section. Plasma due to ionization of effluents and directly emitted from the MHD system are treated as part of the "effluent" discussion. It is noted on Page 3.10-29 that the design assumption is that high voltage is fully shielded from external plasma, which obviates the need for treatment of plasma-high voltage issues. The geomagnetic substorm environment is noted on page 2-109, and conducting external surfaces, grounding and shielding are recommended. The possibility of arcing due to internally generated plasmas is noted on page 2-110. The importance of maintaining the integrity of the high voltage insulation is noted in several places.

The treatment of ionization of the effluent cloud seems reasonably complete. The design assumption of insulation of high voltage conductors allows TRW to ignore most plasma issues.

Plasma Density Distribution — Turbine Generator Systems

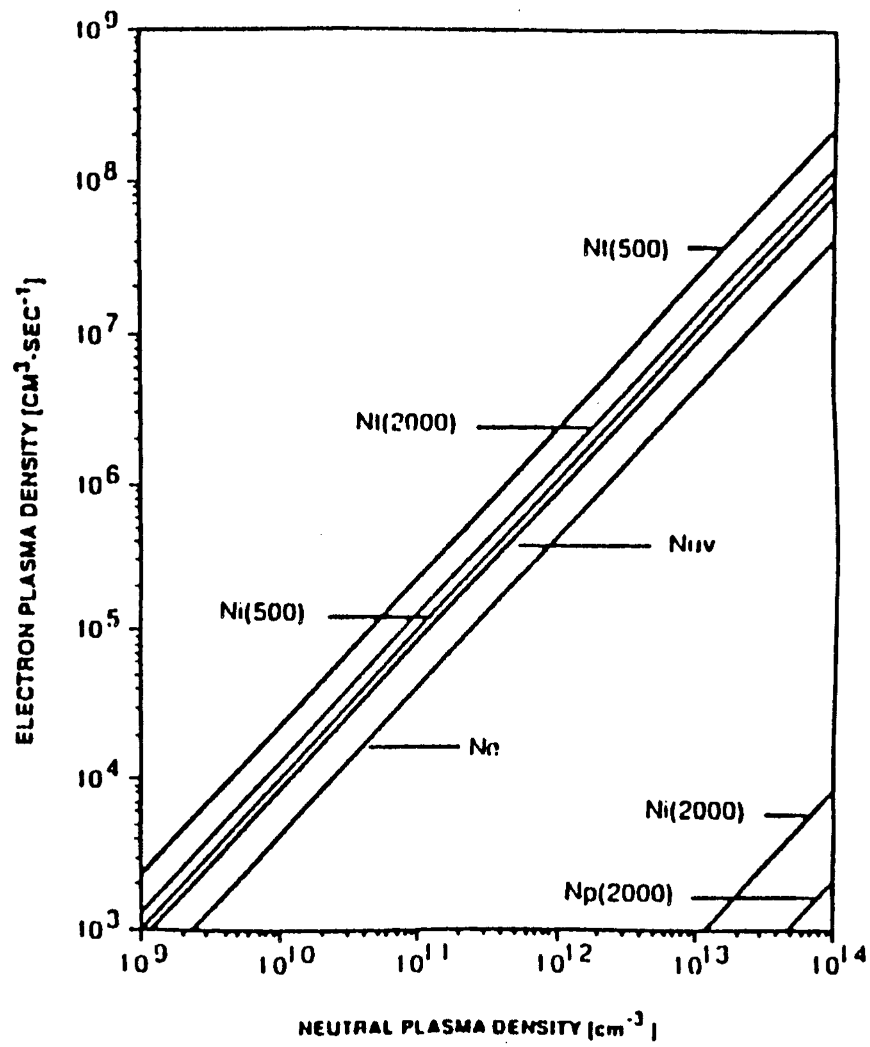
Density in m^{-3}

NOTE: NUMBERS IN PARENTHESIS INCLUDE RECOMBINATION ON A PER SECOND BASIS



GE- PLASMA ENVIRONMENT

Interactions with natural plasma and ionized effluent plasma environments were considered for their effects on high voltage systems and their interference with RF communications. Analysis focused on hydrogen because of its dominant mole fraction in all effluents considered. Ionization by solar UV was found to dominate plasma production from effluent. Photoionization by hostile X-ray threat was found to be significant but extremely short lived. Parasitic power loss from kilovolt level exposed power lines was found to be less than 100 watts/meter. Insulation of high voltage lines is necessary.



Effluent Ionization from Natural Environment Interactions

Martin Marietta- Plasma Environment

Martin Marietta lists ionization of the effluent cloud, plasma and charging effects as unresolved technical issues. They state that these are the only problem areas for a pure hydrogen effluent.

ELECTROMAGNETIC FIELDS ENVIRONMENT

The next section covers the SPAS Contractor results concerning the effect of the EM fields upon the weapon/power platform.

Fields Environment (EMP; magnetic) SPAS Contractor Conclusions

GE

- Only consider interaction of charged particles with magnetic field of MHD generator

MM

- EMP (long structures ~ EMP/SGEMP antenna)
- Magnetic field from EM launcher

TRW

- DEMP: protect with electrical conduit, fiberoptics for communications, tlm
- S/C charging in auroral zones (use conducting skin, filter sensitive circuits)
- Internal breakdown (insulate HV conductors)

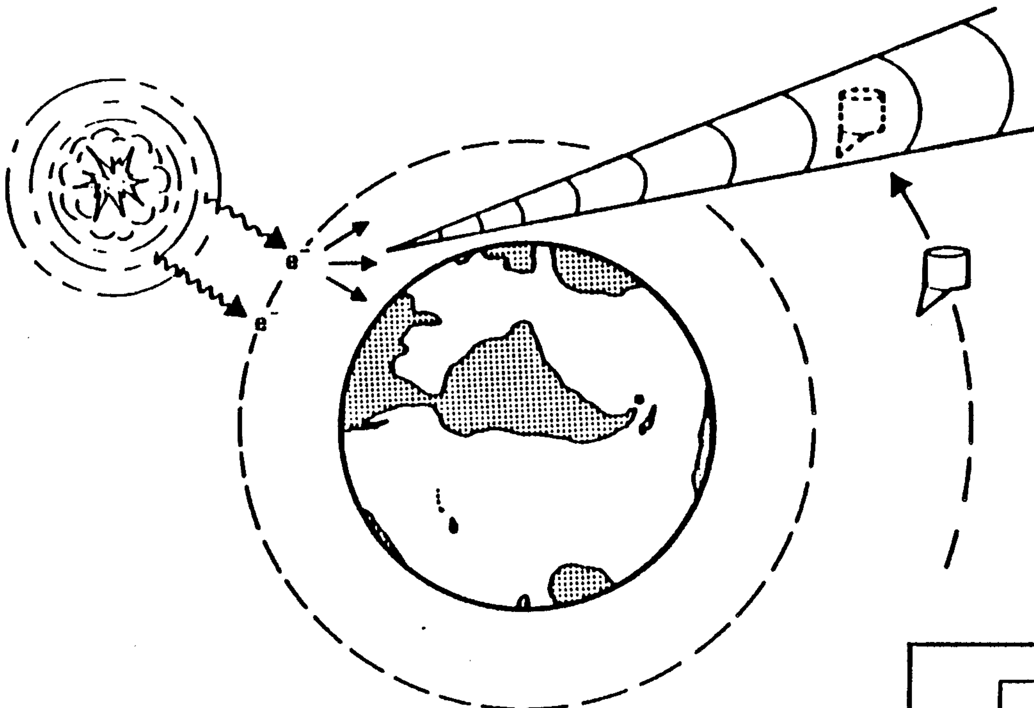
TRW-FIELD ENVIRONMENTS

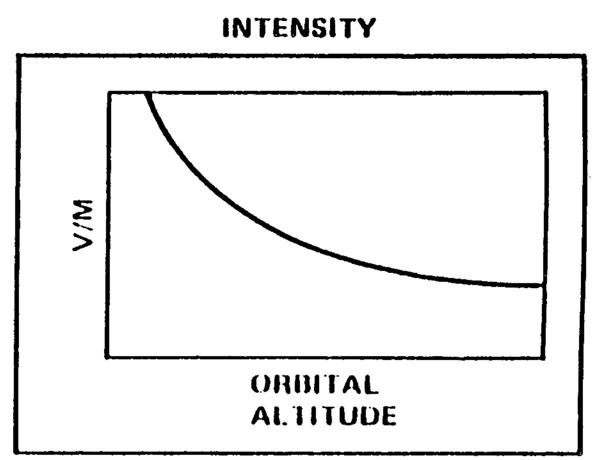
Electromagnetic field effects considered are dispersed EMP (DEMP) and electrostatic discharge due to spacecraft charging and internal high voltage breakdown. These are considered "conventional". Enclosure of cables in grounded conduits and use of fiberoptics are recommended to mitigate DEMP effects; grounding and circuit protection are recommended to minimize charging effects; and enclosing high voltage conductors in hermetically sealed environments is suggested to control internal arcing.

Treatment seems rather cursory. Again, the design approach of total high voltage insulation is invoked . Internal breakdown is noted as the most serious threat on page 2-111, and open cycle systems seen as more vulnerable to this threat. No consideration is given to other EMP effects; effects due to magnetic fields, e.g., for MHD systems or weapons are not considered.

THREATS/ENVIRONMENTS: FIELDS

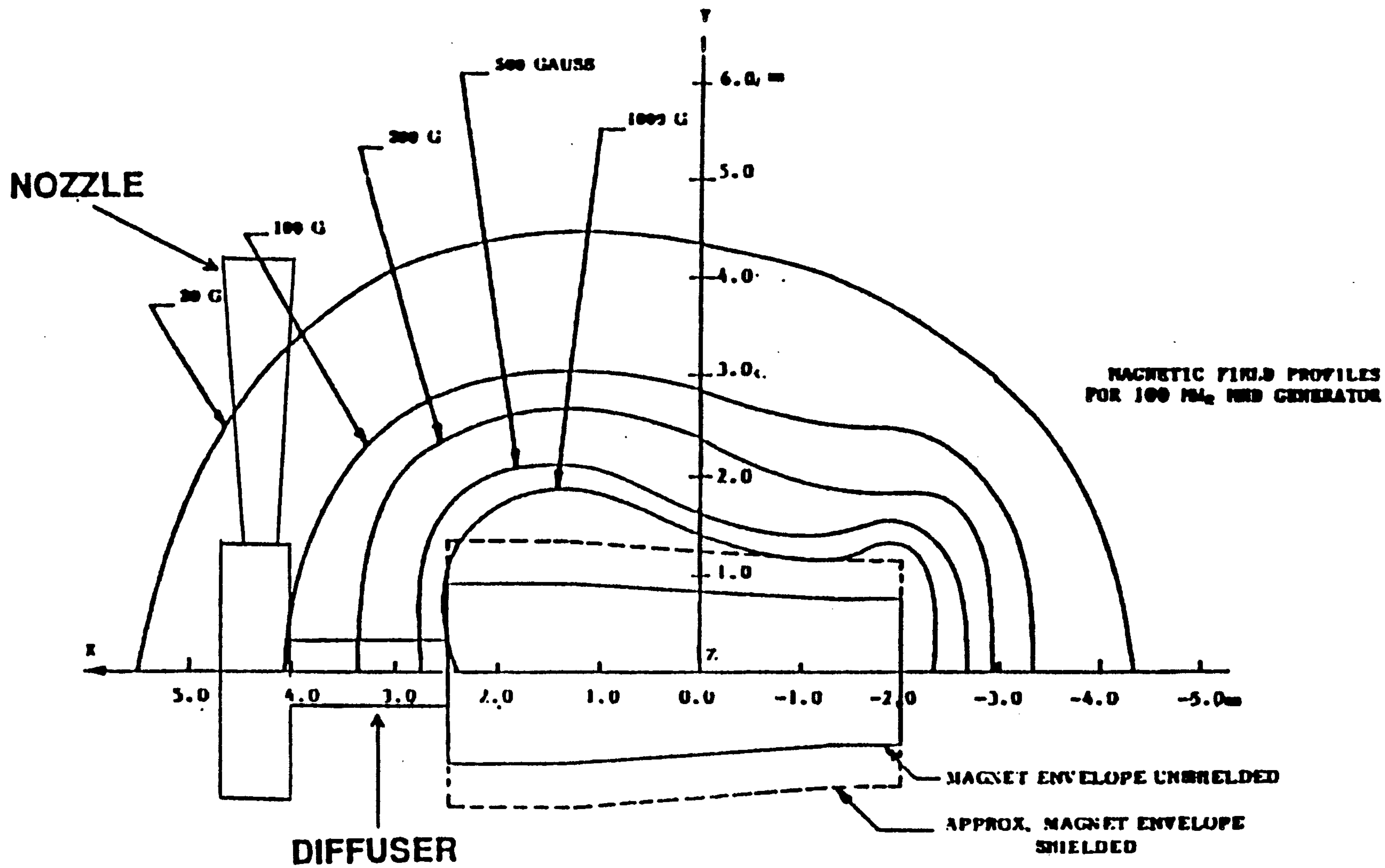
THE DEMP MECHANISM





GE- FIELD ENVIRONMENTS

Consideration was given only to the interaction of charged particles with the strong magnetic field of an MHD generator. Must be about 10 meters distant before the field strength drops to below 1 gauss. The Larmor radii for electrons and protons in fields greater than 1 gauss are well below 10 meters with the result that they will be trapped by MHD generator systems and produce locally higher than normal plasma densities. Increased RF propagation losses and parasitic power losses are possible in the region.



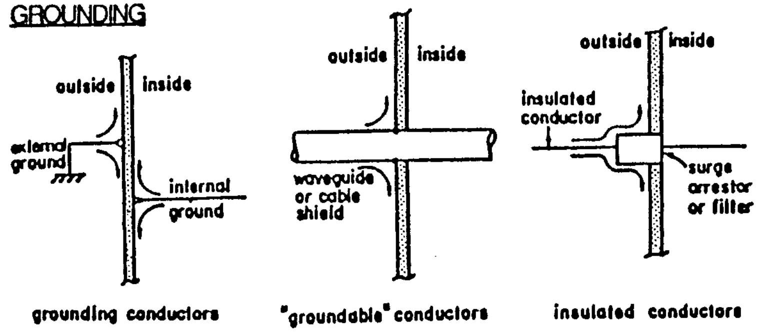
MHD Magnetic Field Profile

Martin Marietta- Field Environment

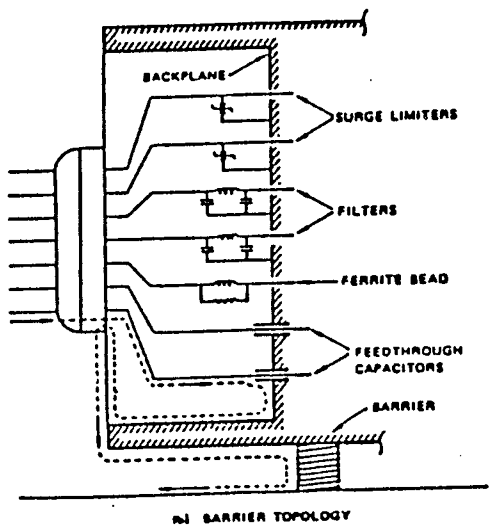
Martin Marietta discusses both DEMP and SGEMP. Their conclusion is that SGEMP is the driver. They propose to follow the hardening techniques recommended by DNA, which involve system topology, terminal protective devices, low impedance coatings, surge arrestors, filters, and grounding techniques.

Martin Marietta states that magnetic coupling with the electromagnetic launcher (EML) system will be the most significant effect and that separation distances of 40-400 inches may be required. The high voltage power bus poses a lesser problem which should be manageable with separation distances of 10-40 inches. They mention the possibility of magnetic shielding for the EML and stress the importance of the grounding system.

GROUNDING



EQUIPMENT - LEVEL BARRIER



EMP/SGEMP Mitigation Technique

THERMAL ENVIRONMENT

The following section discusses the effect upon weapon/power platform of thermal environment resulting from hostile laser attack.

Thermal Environment (lasers) SPAS Contractor Conclusions

GE

- Acknowledge hardening of cryo tankage, cryo radiators, transmission lines

MM

- Laser thermal threat is thermal shielding driver

TRW

- Laser thermal threat imposes operational constraints/shielding requirements
- Shield from, rotate S/C, shootback

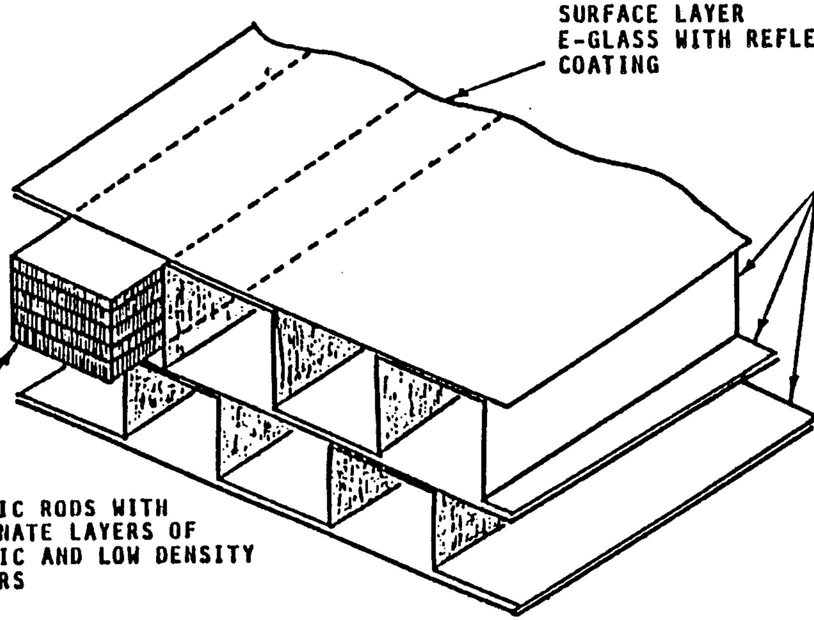
TRW-THERMAL ENVIRONMENT

The thermal environment considered is that due to lasers, either space or ground based. These are viewed as imposing operational constraints and/or shielding requirements. Shoot back is recommended for weapon platforms, a combined laser/pellet shield for OTV and surveillance platforms.

Again the treatment seems rather cursory. The questions of self-induced heat and solar heat input are not addressed.

TRW

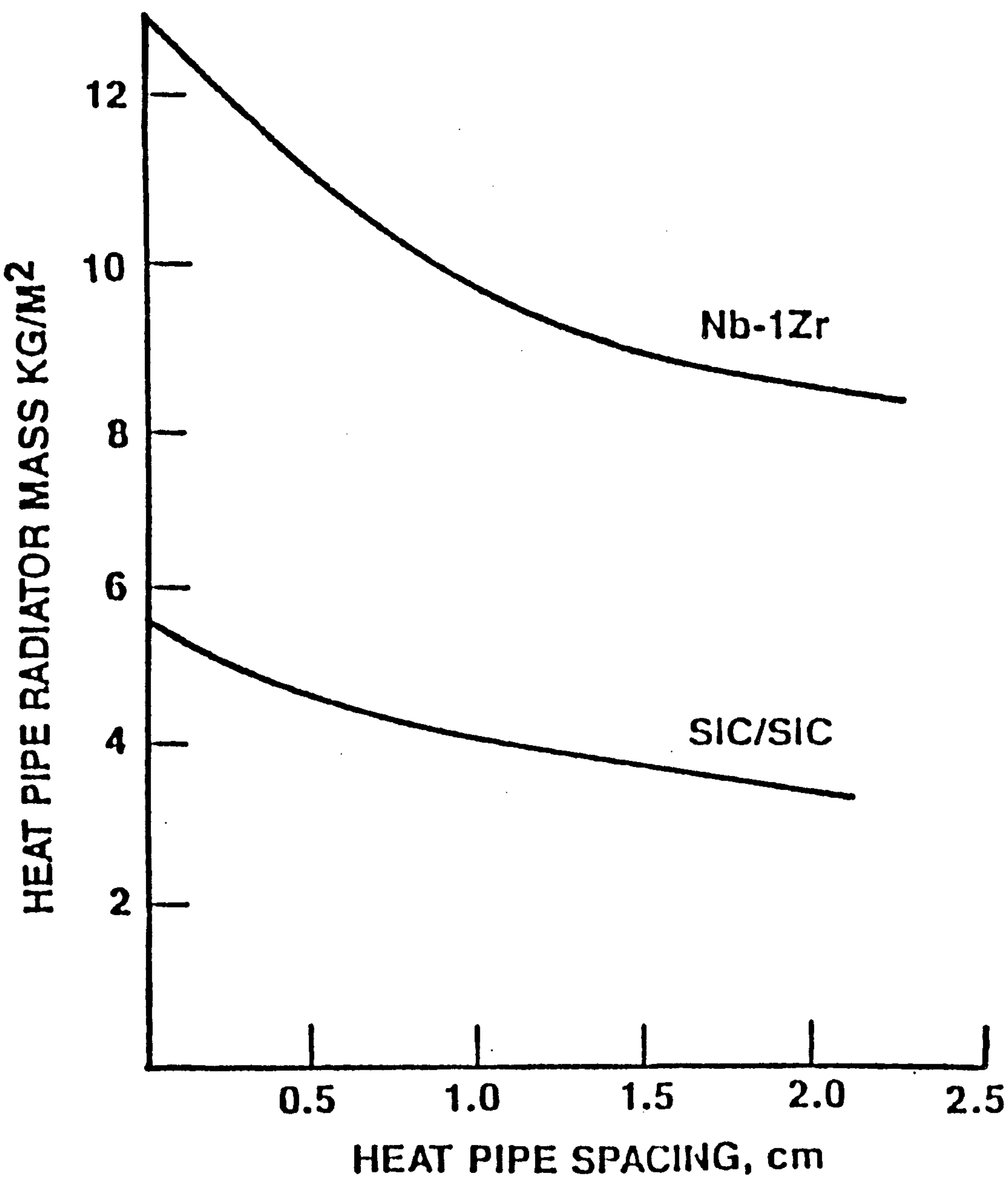
THREAT/ENVIRONMENT: THERMAL
COMBINED LASER/PELLET SHIELD



- TOP SURFACE E-GLASS WITH REFLECTIVE/ABLATIVE COATING FOR LASER THREAT
- CERAMIC RODS COMPOSED OF CERAMIC PLATES AND FOAMED METAL SPACERS
  - CERAMIC PLATES TO BREAK UP PROJECTILE
  - FOAMED METAL SPACER FOR SHOCK (MOMENTUM) TRAP
- 3-D WOVEN KEVLAR/MATRIX TO
  - MAINTAIN CONFIGURATION
  - CONTAIN CERAMIC DEBRIS FRAGMENTS
  - ADD STRENGTH TO SHIELD

GE- THERMAL ENVIRONMENT

Radiators and cryogenic systems are vulnerable to laser attack. The environment and hardening approaches are contained in classified appendix. One hardening approach is the use of new, high temperature materials such as Nb-1Zr and silicon carbide/silicon carbide with refractory metal liners for radiators.



Advanced Heat Pipe Radiator Mass

Martin Marietta- Thermal Environment

Martin Marietta discusses the thermal heating effect of laser and X-ray threat environments. Lasers produce surface heating, X-rays produce bulk heating. The laser threat is more severe. They mention a variety of possible shields for laser protection and conclude that many are adequate. However, some component hardening will be required.

Applicable SMATH Hardening Technology

	LEVEL
INSULATORS	
Refractory Fabric Blankets	
Astro Quartz	*
Boron Nitride	*
Metal Foil MLI	
Titanium/Moly/Zirconia Outer Layer	*
Hardened Rigid Insulation	
SiO_2 Fibrous Insulation	*
RADIATORS	
Passive	
BeO/Fused Silica	*
Si_3N_4	*
Active	
Diode Heatpipe (NH_4)	*
Deployable Shields	
Hardened Louvers	*
Window Shades	*

* (See Classified Appendix p. A-39)

SOLAR UV ENVIRONMENT

This section discusses the SPAS Contractor results concerning the effects of solar UV upon the weapon/power platform.

Solar UV Environment
SPAS Contractor Conclusions

GE

- Mechanism for effluent ionization

MM

- Not considered

TRW

- Changes emittance of thermal radiating surfaces; negligible effect
- Dominant mechanism for effluent ionization

GE- SOLAR UV ENVIRONMENT

Photoionization by solar UV is the dominant mechanism for ionization of effluents with ionization by energetic natural ions significant only at the lower altitudes in the 500 to 2000 km altitude range considered.

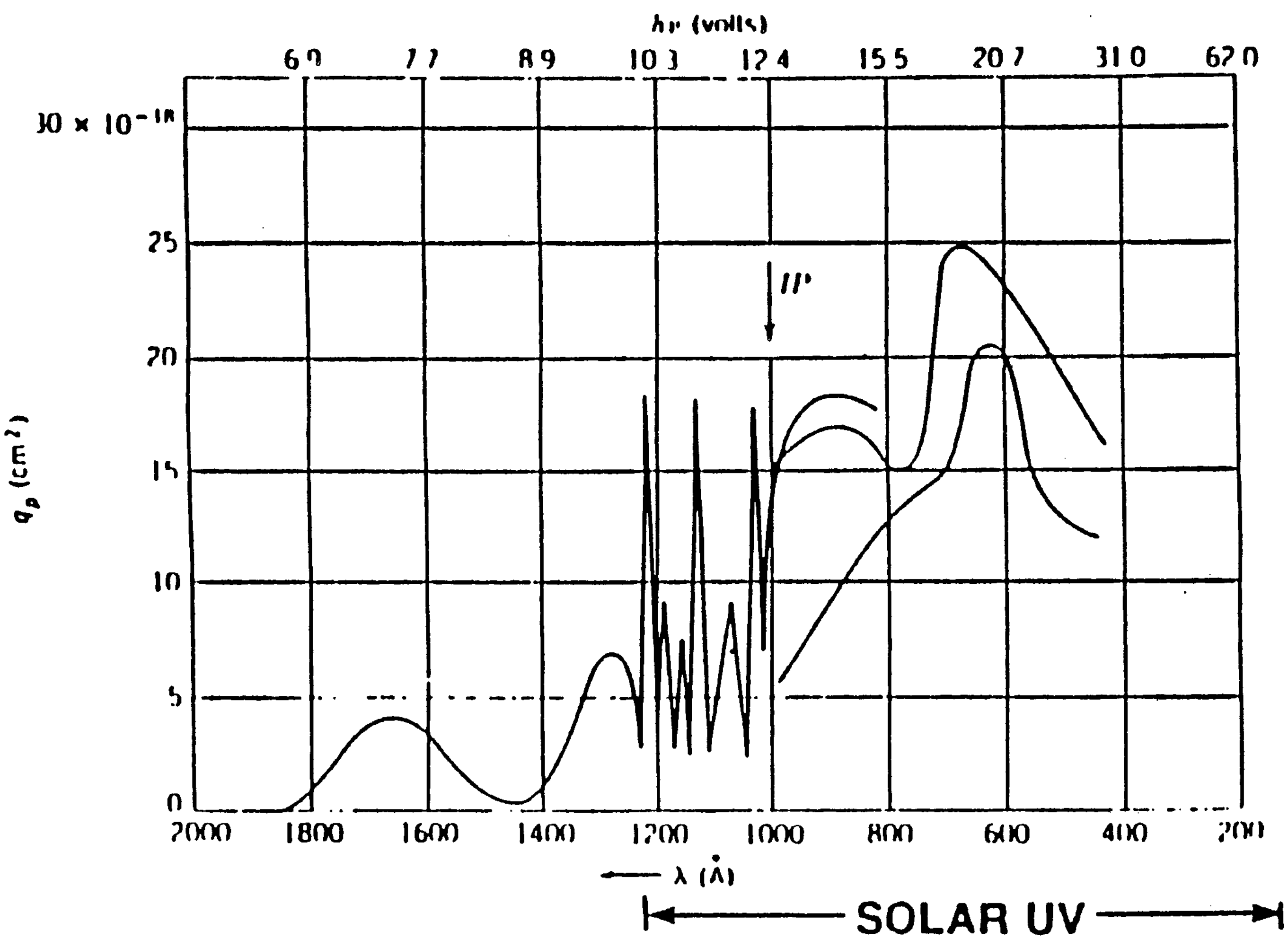


Photo Ionization Cross-Section for $\dot{H_2O}$

TRW-SOLAR UV ENVIRONMENT

Effects due to solar UV are treated in the text only in the effluent sections, in which photoionization of effluent is found to be the dominant mechanism for plasma generation in the effluent cloud. on page 2-122, changes in emittance of thermal radiating surfaces are noted. It is concluded that this will be a negligible effect.

THREAT/ENVIRONMENT: ULTRAVIOLET

TRW

I. SOURCE

- SUNLIGHT

II. EFFECT

- CHANGES IN THE EMITTANCE OF THERMAL RADIATING SURFACES:

  Q = RADIATED ENERGY

  $= A\sigma\epsilon T^4$, WHERE A = RADIATOR AREA

  σ = STEFAN-BOLTZMANN CONSTANT

  ϵ = EMITTANCE

  T = TEMPERATURE

III. MITIGATION

- RADIATED ENERGY FOR BURST POWER SYSTEMS IS DRIVEN BY TEMPERATURE. ANTICIPATED EMITTANCE CHANGE WILL HAVE NEGLIGIBLE EFFECT

Martin Marietta- Solar UV Environment

Martin Marietta does not mention long-term deleterious effect of solar ultraviolet radiation on spacecraft materials which may already be highly stressed due to extreme operating conditions. Neither do they mention its role as an ionizing agent for the effluent and outgassing clouds.

SUMMARY, CONCLUSIONS & COMMENTS

SURVIVABILITY

- o Debris/meteoroid and radiation shielding are design drivers; analytical tools/mitigation strategies are available
- o Natural plasma and plasma/neutral interactions with high voltage and large magnetic fields inadequately addressed
  - -- TRW design avoids HV issue by requiring full insulation; results in very heavy debris/meteoroid shielding requirements
  - -- Plasma/neutral breakdown not addressed
  - -- Weapon-generated fields inadequately addressed
- o Effluent cloud impact not fully addressed; better understanding of cloud expansion/ionization/dispersion and consequences needed
  - -- May require flight experiments
- o Need improved understanding of strategies for high voltage and strong field system operation in space environments to enable design of lighter weight power distribution/conditioning systems
- o Need more complete designs and more interaction with weapon/sensor users

CONCLUSIONS

SPAS SURVIVABILITY STUDIES

Further Effort Required

- Quantify effluent cloud ionization and evolution -- theory, ground test, flight experiment
- Quantify breakdown/arcing and current collection effects in partially ionized gases. Use to develop strategies for high voltage and high field systems to operate in space environments and to resolve open/closed cycle issues
- Examine effects of weapon-generated magnetic fields operating in plasma environments
- Examine interactions between weapons and effluent clouds
- Develop more complete platform and system designs
- Define and conduct focussed flight experiments; instrument weapons/sensors flight experiments to assess survivability aspects

Platform Perspective Required for Survivability Assessments

- Need strong interactions with weapon/sensor users to enable accurate evaluation of effects on realistic systems
- Definition of platform orbits needed for accurate assessment

VI. SYSTEM ISSUES AND INTERFACES

F. MAJOR TECHNOLOGY NEEDS

THE SPAS EFFORT IDENTIFIED SOME KEY TECHNOLOGY NEEDS

Based on the work the SPAS contractors did, the Field Support Team has selected some <u>key</u> technology needs for space power. Each of these needs is enabling to at least some type of power system.

Vibration isolation will be needed by open, burst power systems to attenuate the severe vibrations caused by high mach number, effluent exhaust nozzles. TRW was the only contractor to examine this issue, and, based on their results, this will be a challenging problem.

High voltage alternators remove the need for heavy transformers in power conditioning systems. The voltages proposed for these machines are considerably higher than present alternators. The penalties associated with constructing a high voltage alternator have not been quantified, but the potential benefits are significant. If very lightweight power conditioning transformers can be developed, then the need for high voltage alternators is diminished. But, such development is anything but certain, and high voltage alternators should be pursued. At the same time, high power space turbines do not exist and must be developed.

Lightweight power conditioning units with transformers are particularly important to low voltage sources such as fuel cells and MHD. And they will be important to turboalternator systems if high voltage alternators prove infeasible.

Nearly all of the open power systems and all of the weapon cooling systems required the use of large quantities of stored cryogens, mostly hydrogen but also oxygen for fuel cell and combustion systems and helium for superconducting accelerators. All three contractors used cryorefrigerators to maintain storage temperatures. The only option is a boil-off system that appears to be somewhat heavier than life and be reliable, characteristics for which they are not presently noted.

High performance fuel cells are an attractive open system option and the most attractive closed system option considered. They will be particularly attractive if little hydrogen is available from the weapon because they use little hydrogen and if low voltage RF generators are used because fuel cells produce low voltage and are modular.

Nuclear, multimegawatt, continuously operating power systems were used in SPAS to power surveillance platforms and orbital transfer vehicles, which the present SDI architecture does not call for. However, if they do become necessary, nuclear, multimegawatt, continuous power systems should be developed.

The SPAS Effort Identified Some Key Technology Needs

1. Vibration Isolation

2. High Voltage Alternators (and Turbines to Drive Them)

3. Lightweight Power Conditioning

4. Long Life Cryo-Refrigerators

5. High Performance Fuel Cells
   - Particularly if Closed Power Systems are Required
   - Little Hydrogen is Available from the Weapon
   - Low Voltage, Solid State, RF Generators are used

6. Nuclear, Multimegawatt, Steady State Power Systems
   - Particularly if Orbital Transfer Vehicles are needed

OTHER TECHNOLOGIES THAT MERIT ATTENTION

These have not been listed as key technology needs; nevertheless, they require development. In some cases, technology development programs are already in progress.

Lightweight radiators will be needed by all platforms to remove waste heat from station keeping power systems, refrigeration systems that maintain cryogens, and from generators and power conditioning units. These radiators should withstand natural, nuclear burst, pellet and laser threats.

Hydrogen turbines (and turbines that operate on a mixture of hydrogen and steam) have not been developed. A substantial turbine technology base exists, but not for space applications that use hydrogen or hydrogen mixtures as a working fluid.

All three contractors considered NERVA derivative reactors for open, turboalternator applications and cited previous NERVA development. Although reactor powered turboalternator systems will have a higher development cost than combustion powered turboalternator systems, they are somewhat lighter and may be worth the extra development cost.

There is a large technology base for exhaust nozzles, but high mach number, hydrogen nozzles with small boundary layers to reduce exhaust back-flow and with reduced vibration to relieve vibration isolation requirements need to be developed.

Stringent platform orientation and high power demands may result in much more thrust and at the same time require more accurate thrust balancing systems than have been developed for other space applications.

Now may not be the time to develop specific control systems since platform designs and requirements are still only concepts. But, a preliminary effort to define control philosophy, strategy, and concepts is needed.

A detailed reliability study is premature, but identifying components with reliability problems, identifying key reliability issues, and formulating a strategy for dealing with reliability are timely and need to be started.

A document that specifies safety requirements will help future system designers address the appropriate safety issues. Such a document should take care not to over-specify requirements, and it should not make requirements unless they are clearly necessary.

Other Technologies That Merit Attention

Lightweight Radiators

Hydrogen Turbines

Nerva Derivative Reactors

Exhaust Nozzles

Thrust Control Systems

Control Systems

Identification of Reliability Problems

Documentation of Safety Requirements

VII. CONCLUSIONS AND RECOMMENDATIONS

THESE ARE THE SPAS CONTRACTOR BURST POWER SYSTEM RANKINGS FOR TUBE RF POWERED NPB AND FEL WEAPONS

This chart shows how the contractors ranked their power systems for the neutral particle beam and free electron laser weapons. The ranking considered things besides weight and were reached with the assistance of figure-of-merit computer programs (except for TRW who didn't get their program running in time and used the expert judgement of Charles Sollo). Besides weight, the contractors considered such things as development, volume, cost, risk, operations, survivability, reliability, life, safety, maintenance, assembly, and environmental effects.

While the ranking did generally follow weight, there were several instances where other factors caused heavier systems to be ranked above lighter ones. For example, GE ranked the reactor powered turboalternator, the lightest system, higher than their combustion turboalternator system while Martin Marietta and TRW ranked it below their combustion turboalternator systems. Martin Marietta believed that operational, safety, serviceability, and assembly considerations overcame the reactor-turboalternator's weight advantage. TRW believed that the near-term, low development, nonnuclear advantages of the combustion turboalternator system overcame the disadvantages of its higher weight. GE believed that the reactor systems must be made safe in a development program and that their largest disadvantage is technology development. This risk factor was not large enough, however, to overcome its weight advantage.

The three contractors generally ranked open systems highest, but an important exception was TRW's second place ranking of the closed hydrogen - oxygen fuel cell. They ranked the fuel cell second because it is closed and because it is static -- no major moving parts except for pumps. It is important to remember, however, that it only closes the power system. It does not capture the weapon coolant which is exhausted to space. The only concept that closes both power system and weapon is TRW's combustion turboalternator system which uses titanium to capture oxygen and lithium to absorb hydrogen. Martin Marietta ranked the closed fuel cell somewhat lower than TRW probably because they considered a different group of systems but also because they estimated a higher weight for their closed fuel cell system than did TRW. As stated earlier, the Field Support Team believes that TRW's fuel cell weight estimates are a factor of 2 to 3 too low.

MHD got a fairly high rank from TRW (#4) and GE (#3 for NPB, #4 for FEL). TRW's #3 ranking was for their Gel MHD,

These are the SPAS Contractor Burst Power System Rankings for Tube RF Powered NPB and FEL Weapons

	TRW		GE		MM	
	NPB	FEL	NPB	FEL	NPB	FEL
NDR reactor-turboalternator H effluent	3	3	1	1	3	3
H-O Combst-turboalternator H+W effluent			2	2	1	1
H-O Combstion-turboalternator H effluent	1	1			2	2
H-O Combstion-turboalternator absorbs all effl	5	5				
H-O Fuel Cell H+W effluent					5	5
H-O Fuel Cell H effluent					4-1	4-1*
H-O Fuel Cell no effluent from pow sys	2	2			6,8	6,8**
LMR/Solid Oxide Fuel Cell H effluent			4	3		
H-O Combstion-MHD H+W+Cs					7	7
Gas Reactor-MHD H+Cs	8	8	3	4		
Gel MHD BeO+NOx+KOH+LiO	4	4				
Thor (thermionic with LiH) no effluent from PS	7	7				
Lithium thionyl cloride battery H effluent			7	7		
Li-Acid Battery H effluent			5	5		
Star M/Li metal sulfide battery no PS effluent	6	6				
Flywheel no effluents from PS			6	6		
LMR Rankine no effluent from pow sys					9	9
LMR Thermionic no effluent from pow sys					10	10

*rated first for solid state RF load **two versions of this considered

THESE ARE THE SPAS CONTRACTOR BURST POWER SYSTEM RANKINGS FOR TUBE RF POWERED NPB AND FEL WEAPONS (cont.)

but they ranked their reactor powered MHD system lowest. Their reason for this was that they had already ranked a reactor system #3 and an MHD system #4 and their reactor - MHD system had nothing new to offer.

TRW and Martin Marietta got the same ranking for NPB and FEL systems while GE's ranking changed a little between the two types of weapons. Their fuel cell and MHD ranking changed places because of the system size (the NPB required twice as much power as the FEL). Their scaling with power level gave a slight advantage to the fuel cell for the smaller system.

Another very interesting aspect of the ratings is that Martin Marietta rated their fuel cell #4 when RF generators use high voltage tubes, but they rated it #1 when low voltage solid state RF generators are used. This illustrates the difference between power conditioning units for the two types of systems.

These are the SPAS Contractor Burst Power System Rankings for Tube RF Powered NPB and FEL Weapons

		TRW		GE		MM
	NPB	FEL	NPB	FEL	NPB	FEL
NDR reactor-turboalternator H effluent	3	3	1	1	3	3
H-O Combst-turboalternator H+W effluent			2	2	1	1
H-O Combstion-turboalternator H effluent	1	1			2	2
H-O Combstion-turboalternator absorbs all effl	5	5				
H-O Fuel Cell H+W effluent					5	5
H-O Fuel Cell H effluent					4-1	4-1*
H-O Fuel Cell no effluent from pow sys	2	2			6,8	6,8**
LMR/Solid Oxide Fuel Cell H effluent			4	3		
H-O Combstion-MHD H+W+Cs					7	7
Gas Reactor-MHD H+Cs	8	8	3	4		
Gel MHD BeO+NOx+KOH+LiO	4	4				
Thor (thermionic with LiH) no effluent from PS	7	7				
Lithium thionyl cloride battery H effluent			7	7		
Li-Acid Battery H effluent			5	5		
Star M/Li metal sulfide battery no PS effluent	6	6				
Flywheel no effluents from PS			6	6		
LMR Rankine no effluent from pow sys					9	9
LMR Thermionic no effluent from pow sys					10	10

*rated first for solid state RF load **two versions of this considered

ALL THREE SPAS CONTRACTORS CONCLUDED THAT OPEN, BURST POWER SYSTEMS ARE LIGHTER THAN CLOSED

All three contractors concluded that open systems are the lightest, and all three generally rated open systems highest, with TRW's rating the closed fuel cell #2 being an important exception. But, the ranking among the open systems were not completely consistent, and turboalternator, MHD, and fuel cell systems must be considered to still be in the running.

There was a wide variety of performance assumptions about MHD conversion. Specific powers ranged from 22 MJ/kg for advanced disk generators to 3 MJ/kg for more state-of-the-art systems. How attractive MHD looks depends a great deal on the optimism of the assumptions.

Fuel cell technology assumptions are also important. The fuel cell performances considered were generally beyond current technology but are probably achievable with development. The main question with fuel cells is -- can both high power density and high efficiency be achieved simultaneously?

In short, the system weights are close enough together that other considerations, listed in the chart, will likely help determine the winner.

All Three SPAS Contractors Concluded that Open, Burst Power Systems are Lighter than Closed

Two of the three (MM & TRW) Rated the Hydrogen - Oxygen Turboalternator #1. GE Rated the Reactor Turboalternator #1.

There were no Consistent Open System Winners.

Reactor and H-O Combustion Turboalternator, Reactor and Combustion MHD, and open Fuel Cells are Still in the Running.

How Good MHD and Fuel Cells Look Depends Strongly on Performance Assumptions.

Selection Will Depend on Many Other Factors:

Run Time	Power Level	Development Cost	Safety
Lightweight PC Advances	Weapon Cooling Interfaces	Launch Costs	Control Issues
Deployment Date	Survivability	RF Generator Voltage	Etc.

OPEN BURST SYSTEMS ARE LIGHTER (cont.)

As run time and power decrease, weights get closer together because expendables make less of a difference. This tends to help make chemical systems that use more expendables more competitive.

If effluents are not acceptable, then open power systems cannot be used. For the same reasons, open weapons cannot be used. This would favor power systems and weapons that have little or no exhaust. A little exhaust may be allowed since it can be captured in a container or by using a chemical reaction. The most attractive of the closed power systems appears to be the closed fuel cell. There will be a mass penalty if closed systems are needed. TRW estimates that the penalty for a closed fuel cell is not large (a factor of 2), but the Field Support Team believes that they have underestimated the weight of a closed fuel cell system.

Batteries and Flywheels are quite heavy and are not likely to be used as a stand alone power source; however, they may have a place as buffers to counteract the effects of power and load transients.

Closed, reactor powered thermodynamic cycle (Brayton, Rankine, thermionic, HYTEC) systems are also quite heavy. Their weights do not change with run time however, and if run time is extremely long, greater than 2000 sec., they may have a place for burst power applications. Nothing in the SDI architecture studies suggest such a long run time. They are, however, the system of choice for continuous operation.

Open Burst Systems are Lighter, cont.

Shorter Run Time and Lower Power Tend to Favor Chemical Over Nuclear for the Open, Burst Power Systems.

If Effluents are Not Acceptable, Closed Chemical and Energy Storage Systems are Next, But The FST Believes They Have A Large Mass Penalty.

Batteries and Flywheels are Heavy but May be Useful as Short-Term Transient Buffers.

Closed Reactor Powered Systems Will Only be Chosen for Burst Operation if Run Time Exceeds 2000 sec.

ALL MULTIMEGAWATT STEADY STATE SYSTEMS CONSIDERED WERE REACTOR POWERED

The contractors considered multimegawatt steady state systems for powering surveillance platforms and orbital transfer vehicles. All of the systems considered were nuclear reactor powered, and nuclear power is the most reasonable option for continuous power when megawatts are required. The contractors estimated that all of the power systems considered, Rankine, Brayton, thermionic, and HYTEC were fairly close in weight. The Field Support Team found many inconsistencies in the designs and weight assumptions. The resulting inconsistencies in weight were larger than the differences in estimated weight among the systems considered. Thus, based on the close results, a clear steady state power system winner cannot be selected.

All Multimegawatt Steady State Systems Considered were Reactor Powered

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All of the Systems (Rankine, Brayton, Thermionic, Hytec) Had Similar Weights.

Assumptions Used Contained Several Inconsistencies.

There were no Clear Winners.

HIGH MACH NUMBER NOZZLES ARE REQUIRED TO REDUCE EFFLUENT CONCENTRATION IN THE BEAM PATH

All three contractors concluded that high mach number nozzles are required to accelerate exhaust away from the platform. When they are used the density of effluents along the path of a FEL or NP beam are low enough that they will attenuate the beams by less than 1%. They further conclude that neutral and naturally ionized hydrogen will not interfere with sensors. The results for water and other effluents were inconclusive. Both Martin Marietta and TRW suggested methods by which water can be removed from exhaust without a severe mass penalty. Thus, if hydrogen is acceptable but water is not, power systems that generate hydrogen and water can be used with water absorbing equipment.

This issue is not fully resolved however, because the results are based on analysis and have not been substantiated by experiment; because exhaust nozzle vibrations may be difficult to attenuate to required levels; and because ions may possibly be trapped in weapon magnetic fields, build up, and interfere with weapon or sensor operation.

High Mach Number Nozzles are Required to Reduce Effluent Concentration in the Beam Path

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All Three Contractors Agree That Neutral Hydrogen Should Not Significantly Affect Beams or Sensors.

This is Based on Analysis, not Experiment.

Results for Water and Other Effluents are Inconclusive.

It Appears that Water can be Removed from Exhaust with Little Mass Penalty.

Nozzle Vibration, Ion Trapping, and Experimental Verification of Effluent Analyses are Still Concerns.

POWER CONDITIONING IS A DISCRIMINATOR

Power conditioning may be an important discriminator between low and high voltage power systems. Martin Marietta and TRW estimate that low-to-high voltage power conditioning units needing transformers will be heavy and will be required by low voltage sources that supply power to high voltage loads such as tube type RF generators. They also estimate that high voltage alternator power conditioning units will not need transformers and will not pay a large PC mass penalty. Thus, the low voltage power systems will pay a much higher PC mass penalty than turbo-alternator power systems.

GE, on the other hand, estimates that power conditioning can be made very light by cryo-cooling the PC unit's transformer. These light PC units will not penalize low voltage sources more than high voltage sources. As stated earlier, the Field Support Team thinks that GE's PC weight estimates are optimistic but believes that some, maybe even substantial, PC weight reduction is possible. In short, we believe that there will be a PC penalty for low voltage sources, but it is likely to be less significant that stated by TRW or Martin Marietta.

The impact that PC will have in discriminating between systems, therefore, depends on the success of developing high voltage alternators and on the success of lowering transformer weight by cryo-cooling.

Power Conditioning is a Discriminator

TRW & Martin Marietta Show a Large PC Mass Penalty for Low Voltage Sources (Fuel Cell, MHD).

- Require Heavy Step-Up Transformers
- High Voltage Alternators don't Need Transformers

GE Shows no PC Penalty for Low Voltage Sources.

- Cryo Cooled Transformers are Very Light

PC Impact Depends on Ability to Develop High Voltage Alternators and/or Lightweight, Cryo-Cooled Transformers.

Platform Dynamic Issues

The SPAS contractors identified a wide variety of 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 interaction with users is needed to qualify and resolve issues.

PLATFORM DYNAMIC 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

SUMMARY, CONCLUSIONS & COMMENTS

SURVIVABILITY

- o Debris/meteoroid and radiation shielding are design drivers; analytical tools/mitigation strategies are available
- o Natural plasma and plasma/neutral interactions with high voltage and large magnetic fields inadequately addressed
  - -- TRW design avoids HV issue by requiring full insulation; results in very heavy debris/meteoroid shielding requirements
  - -- Plasma/neutral breakdown not addressed
  - -- Weapon-generated fields inadequately addressed
- o Effluent cloud impact not fully addressed; better understanding of cloud expansion/ionization/dispersion and consequences needed
  - -- May require flight experiments
- o Need improved understanding of strategies for high voltage and strong field system operation in space environments to enable design of lighter weight power distribution/conditioning systems
- o Need more complete designs and more interaction with weapon/sensor users

CONCLUSIONS

SPAS SURVIVABILITY STUDIES

Further Effort Required

- o Quantify effluent cloud ionization and evolution -- theory, ground test, flight experiment
- o Quantify breakdown/arcing and current collection effects in partially ionized gases. Use to develop strategies for high voltage and high field systems to operate in space environments and to resolve open/closed cycle issues
- o Examine effects of weapon-generated magnetic fields operating in plasma environments
- o Examine interactions between weapons and effluent clouds
- o Develop more complete platform and system designs
- o Define and conduct focussed flight experiments; instrument weapons/sensors flight experiments to assess survivability aspects

Platform Perspective Required for Survivability Assessments

- o Need strong interactions with weapon/sensor users to enable accurate evaluation of effects on realistic systems
- o Definition of platform orbits needed for accurate assessment

THE SPAS EFFORT IDENTIFIED SOME KEY TECHNOLOGY NEEDS

Based on the work the SPAS contractors did, the Field Support Team has selected some key technology needs for space power. Each of these needs is enabling to at least some type of power system.

Vibration isolation will be needed by open, burst power systems to attenuate the severe vibrations caused by high mach number, effluent exhaust nozzles. TRW was the only contractor to examine this issue, and, based on their results, this will be a challenging problem.

High voltage alternators remove the need for heavy transformers in power conditioning systems. The voltages proposed for these machines are considerably higher than present alternators. The penalties associated with constructing a high voltage alternator have not been quantified, but the potential benefits are significant. If very lightweight power conditioning transformers can be developed, then the need for high voltage alternators is diminished. But, such development is anything but certain, and high voltage alternators should be pursued. At the same time, high power space turbines do not exist and must be developed.

Lightweight power conditioning units with transformers are particularly important to low voltage sources such as fuel cells, and MHD. And, they will be important to turboalternator systems if high voltage alternators prove infeasible.

Nearly all of the open power systems and all of the weapon cooling systems required the use of large quantities of stored cryogens, mostly hydrogen but also oxygen for fuel cell and combustion systems and helium for superconducting accelerators. All three contractors used cryo-refrigerators to maintain storage temperatures. The only option is a boil-off system that appears to be somewhat heavier than refrigeration. The refrigeration systems would have to have long life and be reliable, characteristics for which they are not presently noted.

High performance fuel cells are an attractive open system option and the most attractive closed system option considered. They will be particularly attractive if little hydrogen is available from the weapon because they use little hydrogen and if low voltage RF generators are used because fuel cells produce low voltage and are modular.

Nuclear, multimegawatt, continuously operating power systems were used in SPAS to power surveillance platforms and orbital transfer vehicles, which the present SDI architecture does not call for. However, if they do become necessary, nuclear, multimegawatt, continuous power systems should be developed.

The SPAS Effort Identified Some Key Technology Needs

1. Vibration Isolation
2. High Voltage Alternators (and Turbines to Drive Them)
3. Lightweight Power Conditioning
4. Long Life Cryo-Refrigerators
5. High Performance Fuel Cells
   - Particularly if Closed Power Systems are Required
   - Little Hydrogen is Available from the Weapon
   - Low Voltage, Solid State, RF Generators are used
6. Nuclear, Multimegawatt, Steady State Power Systems
   - Particularly if Orbital Transfer Vehicles are needed

THE SPAS EFFORT IDENTIFIED SOME KEY TECHNOLOGY NEEDS (CONT'D)

Nuclear, multimegawatt, continuously operating power systems were used in SPAS to power surveillance platforms and orbital transfer vehicles, which the present SDI architecture does not call for. However, if they do become necessary, nuclear, multimegawatt, continuous power systems should be developed.

The SPAS Effort Identified Some Key Technology Needs

1. Vibration Isolation

2. High Voltage Alternators (and Turbines to Drive Them)

3. Lightweight Power Conditioning

4. Long Life Cryo-Refrigerators

5. High Performance Fuel Cells

   Particularly if Closed Power Systems are Required
   Little Hydrogen is Available from the Weapon
   Low Voltage, Solid State, RF Generators are used

6. Nuclear, Multimegawatt, Steady State Power Systems

   Particularly if Orbital Transfer Vehicles are needed

SOME SYSTEM DISCRIMINATOR ISSUES STILL NEED TO BE RESOLVED

Most of the issues on the facing chart were probably out of the scope of SPAS but will be discriminators and need to be resolved. The first five were pretty thoroughly covered earlier in this report, but the remaining six need additional comment.

It is almost certain that platforms will have to load follow to some extent and that weapon faults will require that power be interrupted on occasion. This means that the power system cannot be turned and left on, but it will have to respond to a transient power demand. These transients will have to be quantified to some extent so that their impact on the power system and its control system can be determined. Some types of power systems may accommodate transients more easily than others.

The quantity of weapon hydrogen coolant that may be used by the power system will be an important discriminator not only between types of power systems but between operating parameters such as turbine inlet temperature for turboalternator systems.

Orbital altitude will be important because of space debris protection. Low altitudes will require more protection and so far the weight penalty for low altitudes looks very severe.

The SPAS concepts were developed for specified survivability threats. There is some concern that these threats were not severe enough for the time-frame in which they will be used.

Vibration mitigation was postulated to reduce vibrations to levels that can be tolerated by the weapons for both accelerator performance and beam pointing accuracy. There is some concern that the weapon community has really not defined these requirements based on a rigorous analysis of weapon performance

SPAS conceived power system concepts that met the requirements of specific weapon designs. There were no total platform design trade-offs except for matching weapon coolants to power system reactants and working fluids. Another level of integrated system design can be done. An example would be to look at the effect that accelerator gradient has on coolant and power system requirements and to select a value that minimizes the weight of the total platform.

Some System Discriminator Issues Still Need to be Resolved

1. Engagement Time
2. Tube Vs. Solid State RF (voltage requirement)
3. NPB, or FEL, or Other as the Primary User
4. Effluent -- Nozzle Vibrations, Ion Trapping
5. Other Effluents Besides Hydrogen
6. Load Following and Fault Recovery Transients
7. Superconducting Vs. Cryo-Cooled Accelerators
8. Orbital Altitude -- Effect on Debris
9. Survivability Requirements (are they tough enough?)
10. Weapon Dynamic Requirements (what are they really?)
11. Total Platform Optimization

VIII. APPENDICES

A. COMPONENTS

1. REACTORS

REACTORS CONSIDERED

All three SPAS contractors have considered a variety of reactor sources since the inception of the SPAS program. Out of this variety, only four reactor types were considered for the final review. The four reactor types were the NERVA derivative reactor, the Particle Bed reactor, a liquid metal cooled reactor, and thermionic reactor. Two varieties of thermionic reactors were investigated. Brief descriptions of these reactors, their modes of operation, and their purposes follow:

NERVA Derivative Reactor

The core of the gas-cooled NERVA derivative reactor is made up of closely packed fuel modules. Each fuel module consists of six hexagonal graphite fuel elements surrounding a central support element or tie tube. Each support element contains a central coolant tube and an annular return flow channel. These coolant channels are used to maintain the tie rods at a temperature below the bulk core temperature. The basic NERVA fuel element contains coated UC_2 fuel particles embedded in a graphite matrix. A typical fuel element is 1.91 cm across its flats, and contains 19 small holes. Since the NERVA derivative reactor is based on the developed technology of the NERVA reactor program, we consider this concept to be a low risk approach. The NERVA derivative also has the advantages of a large heat capacity and the potential for redundant cooling through the tie tubes. All three contractors have considered the NERVA derivative for open cycle burst mode operation using weapon hydrogen and a turbo-alternator. TRW has also investigated an open-cycle NERVA derivative reactor using MHD power conversion for the burst mode. A helium cooled steady state version of the NERVA derivative concept, using a closed Brayton cycle, was also considered by TRW for an orbital transfer vehicle. Martin Marietta assumed coolant outlet temperatures of less than 1100 K and the other two contractors assumed temperatures of 1700 K or less for turbine/generator concepts. These temperatures are well below demonstrated operating temperatures (~2500 K). TRW assumed outlet temperatures of 2900 K for the MHD approach. Advanced NERVA fuel would have to be demonstrated to operate at these temperatures.

Particle Bed Reactor

The gas-cooled particle bed reactor fuel element is composed of coated UC_2 fuel particles contained between two porous cylindrical frits (screens). The fuel elements are inserted in a solid moderator (usually $ZrH_{1.7}$). Coolant flows axially through channels in the moderator

Reactors Considered

Reactor	TRW	GE	MM
NERVA Deravitive			
-Open Cycle	X	X	X
-Closed Cycle	X		
Particle Bed (Open)		X	X
Cermet (Open)		X	
Liquid Metal Cooled		X	X
STAR-M	X		X
THOR	X		

then radically inward through the outer frit, fuel particle bed, and inner frit into the central fuel element channel where it exits at one end of the element. Fuel in the micro-particle form may be especially tolerant to rapid power changes; however, the particle bed reactor has not been developed and represents a greater risk than the NERVA derivative approach. GE has considered the particle bed concept for open-cycle burst mode operation using MHD power conversion.

Liquid Metal Cooled Reactor

General Electric and Martin Marietta have both investigated UN fueled liquid metal cooled reactors in which the fuel is in a pin geometry with a refractory metal cladding. Both contractors explored Rankine power cycles. The General Electric Rankine cycle system was proposed for the steady state operation of an orbital transfer vehicle and Martin Marietta's system was considered for burst mode operation. The use of a high temperature liquid metal (~1500 K) and two-phase fluid considerations in a micro-g environment are important issues for the Rankine cycle approach. General Electric has also explored AMTEC power conversion with its liquid metal cooled reactor concept. AMTEC is at a very early stage of development and should be considered as a high risk approach.

Thermionic Reactor

Both TRW and Martin Marietta have studies the STAR-M thermionic reactor for burst power. The STAR-M reactor fuel rods resemble conventional fuel rods for a liquid metal cooled reactor. The fuel elements are constructed by stacking several UO_2 fueled thermionic diodes in series inside of a sealed cladding. Martin Marietta's concept would deliver burst electrical power directly from the thermionic devices while TRW's STAR-M reactor would be used to charge a battery and the battery would then be used for burst power. TRW assumed a 1900 K emitter temperature, which is somewhat hotter than GA' current baseline design of 1700 K. Although some successful thermionic fuel element testing has been completed, thermionic reactors are still in the developmental stage and performance remains an important issue.

TRW has also considered the THOR thermionic reactor for burst mode electrical power. The THOR concept incorporates a LiH heat sink within the core rather than a flowing coolant and a radiator to remove waste heat. The LiH also

Reactors Considered

Reactor	TRW	GE	MM
NERVA Deravitive			
-Open Cycle	X	X	X
-Closed Cycle	X		
Particle Bed (Open)		X	X
Cermet (Open)		X	
Liquid Metal Cooled		X	X
STAR-M	X		X
THOR	X		

serves as a moderator. TRW assumed a 2600 K emitter thermionic devices tested in the United States and the THOR configuration is entirely new. An appreciable development effort may be required for THOR. For high power, long duration operational requirements, the THOR concept is very heavy.

Reactors Considered

Reactor	TRW	GE	MM
NERVA Deravitive			
-Open Cycle	X	X	X
-Closed Cycle	X		
Particle Bed (Open)		X	X
Cermet (Open)		X	
Liquid Metal Cooled		X	X
STAR-M	X		X
THOR	X		

SPAS CONTRACTOR DISCUSSION OF REACTORS

Sandia's RSMASS code was used to estimate the reactor masses for each of the reactors discussed for the assumed operating conditions. All of the reported reactor masses were found to be in reasonably good agreement with the RSMASS estimates. Contractor mass estimates can be found in the System Studies section of this report.

Very little discussion was given of the reactor merits and issues or safety and reliability considerations.

Evaluation of Spas Reactors

1. All Masses Appear Reasonable and Consistent Among the Contractors for the Assumed Conditions.
2. Very Little Discussion of Reactor Merits, Issues Safety and Reliability

VIII. APPENDICES

A. COMPONENTS

2. TURBINES

PROPOSED HYDROGEN TURBINES OPERATING AND DESIGN CONDITIONS

All three contractors proposed modular turboalternator units for their open systems. Their platform designs incorporated as many turbine units as necessary for the required power. The MM concept was unique in that their module was really a multiple of three turbines. One high pressure turbine drove a 12.5 MWe generator with its exhaust flow equally split into two separate low pressure turbines that powered another identical 12.5 MWe machine. MM provided for 50 MWe module sizes by simultaneously operating four of these generators through a series of idler gears (which they indicated was to insure synchronous operation). The three contractors assumed different turbine material technologies. Martin Marietta's turbine material was unspecified, but their turbine inlet temperatures suggest the use of current technology stainless steel or perhaps a nickel superalloy. GE uses their more advanced high strength nickel alloy, and TRW assumes the use of a very advanced carbon composite.

The turbine inlet temperatures, pressures, and pressure ratios were selected somewhat arbitrarily by all contractors. No system mass optimizations were performed. Only weapon and turbine hydrogen flows were balanced. The indicated number of stages and unit mass for the GE design are reasonable for their special high strength nickel alloy material (although some temperature protection would be required in the higher temperature stages). However, for GE's stated efficiency of 85% the actual pressure ratio would be about 32 (not the 24.2 indicated in their report). TRW's design values were reasonable although their indicated unit mass seems somewhat high for the relatively low material density of carbon-carbon composite. TRW's smaller number of stages was due to the higher specific strength (and correspondingly higher blade speed) of the proposed carbon- carbon design. MM's high number of stages (despite the very high rotational speed) is due to the low work coefficient used in their design. Further, the disk and blade strengths required to achieve their high speed may not be obtainable with stainless steels or nickel superalloys for their low pressure turbine design. A more feasible MM design would be to reduce their rotational speed somewhat and increase their design work coefficient.

PROPOSED HYDROGEN TURBINES OPERATING AND DESIGN CONDITIONS

	Power MW	Inlet Temp K	Inlet Press MPa	Press Ratio	Eff %	# of Stages	RPM	Mass Kg
GE	50	1500	3.63	24.2	85	19	16500	860
TRW	50	1700	6.89	33.3	70	10	12000	1136
MM	25*	874*	2.02	20.0	78	25*	33000	625

*MM proposed a dual turbine-generator assembly, each unit rated at 12.5 MW and 10-15 stages each; TIT was 874 K for the combustion, NPB turbine and varied from 805-1251 K for other designs

HYDROGEN TURBINES - OBSERVATIONS AND CONCLUSIONS

All contractors utilized direct drive turbine-generator units to eliminate the need for gear boxes. MM proposed idler gears between the modular generators to provide synchronous operation, but little or no torque would be transmitted through these gears. (Utility power grids do not need idler gear arrangements to maintain generator synchronization.)

Although the contractor hydrogen turbines were based on somewhat arbitrary data inputs, their conceptual designs revealed that the turbine mass is not a significant platform mass item. For example, from the contractors data the turbine has a specific mass of only 0.017 to 0.025 kg/KW. This specific mass will not significantly change as system data inputs improve unless very high pressure ratio turbine designs are pursued.

Hydrogen turbines will require a significantly greater number of stages than combustion turbines (when operated at similar temperature limits or pressure ratios). This is due to hydrogen's very high value of specific heat.

MM's low turbine inlet temperature (TIT) was due to matching the turbine and weapon hydrogen flow rates. Recall that Martin Marietta used a cryo-cooled rather than a superconducting accelerator; thus, their platform used twice as much hydrogen as GE's or TRW's platform. Since the flow rate was higher, sufficient power was generated with a low turbine inlet temperature. The lower resultant temperature was not based on comparative or optimization studies.

HYDROGEN TURBINES – OBSERVATIONS AND CONCLUSIONS

- All turbogenerator units were direct drive to eliminate gear boxes.
- Turbine mass is not a significant platform mass item.
- Hydrogen turbines will require a greater number of stages than similar pressure ratio combustion turbines.
- MM lower TIT was based on the assumed large weapon hydrogen mass flow rates.

PROPOSED H2-O2 COMBUSTION TURBINES OPERATING AND DESIGN CONDITIONS

Although all three contractors proposed chemical (hydrogen/oxygen) combustion power systems, TRW did not require a turbine different from their hydrogen design since their concept removed all oxygen from the combustion products using a titanium reduction reaction which formed titanium-oxide (thereby leaving only hydrogen to enter the turbine). GE's combustion turbine had a lower turbine inlet temperature, fewer number of stages, and a higher inlet pressure and pressure ratio than their hydrogen turbine design. GE's combustion turbine design used very realistic design parameters and was the best documented turbine design of the three contractors. MM specified the same inlet pressure, pressure ratio, efficiency, rotational speed, and mass as for their hydrogen turbine. MM did not indicate the number of stages on their combustion turbine, but did lower their design turbine inlet temperature to balance hydrogen flow rates (although again no trade-off system studies were involved). MM's combustion turbine probably should not be considered a proven design.

PROPOSED H2-02 COMBUSTION TURBINES OPERATING AND DESIGN CONDITIONS

	Power MW	Inlet Temp K	Inlet Press MPa	Press Ratio	Eff %	# of Stages	RPM	Mass Kg
GE	50	1394	6.24	41.6	87	10	16500	624
MM	25*	779*	2.01	20.0	78	?	33000	625

Note: TRW did not propose a H2-O2 combustion turbine design.

*MM turbine inlet temperature was 779 K for the NPB and was 1079 K for the FEL; each generator was 12.5 MWe.

PROPOSED POTASSIUM TURBINES OPERATING AND DESIGN CONDITIONS

This view graph shows the proposed design conditions for the GE and MM potassium vapor turbines. Martin Marietta used a potassium vapor turbine for their closed, reactor powered, Rankine cycle, burst power system and for their orbital transfer vehicle system. The 12.5 MW version shown in the table is for their burst power system where four modules of four turbines (sixteen altogether) are used. GE used a potassium turbine for their 5 MW orbital transfer vehicle system. Both turbine inlet temperatures suggest turbines that use refractory metal technology although it is possible that GE could use their advanced nickel alloy. TRW did not have a potassium turbine power system. Note that both GE and MM proposed superheated vapor (versus saturated vapor) inlet conditions in order to minimize the liquid fraction of potassium in the turbine exhaust. Also, the indicated exit quality shown here was based on no liquid extraction or separation within the turbine. GE's design would probably require an interstage liquid separator in order to keep turbine exit quality above 85% to minimize turbine erosion. However, this minimum exhaust quality is not a totally recognized value (as of this date) and should not be considered as an absolute criteria. GE proposed a much smaller diameter turbine than MM, which then required many more stages despite its higher rotational speed. GE also proposed tantalum based T-111 or ASTAR 811C refractory alloy turbine material. MM did not indicate a turbine material of construction. Further, MM's proposed blade speed (which determines turbine stresses and is required for the limited number of stages shown) could probably not be handled by refractory alloys at 1500 K. A refractory metal turbine would also have a greater mass than that shown for MM. Finally, MM's stated turbine efficiency is not possible. These short comings for the MM potassium turbine design most likely indicate that only a cursory look was given to this portion of their power systems.

PROPOSED POTASSIUM TURBINES OPERATING AND DESIGN CONDITIONS

	Power MW	Inlet Temp K	Inlet Press MPa	Press Ratio	Eff %	# of Stages	RPM	Exit Qual %*	Mass Kg
GE	5	1420	1.1	29.7	81	10	15000	82	3140
MM	12.5	1500	1.01	10	96	2	9900	86	235

* With no liquid extraction

OBSERVATIONS

- Both turbine designs are for superheated vapor inlet conditions
- GE proposed ASTAR 811C or T-111 refractory metal
- MM turbine efficiency is unachievable; the unit mass is too low (for refractory metals); and no construction materials were proposed.

TURBINE MATERIAL TECHNOLOGY WAS DETERMINED BY THE ACCELERATOR COOLING METHOD

All contractors identified a hydrogen flow rate based on their assumed weapon accelerator cooling method. A turbine inlet temperature was then identified that would utilize this quantity of hydrogen without the requirement of very large pressure ratios. No trade-off studies or optimizations were performed. Thus, the lower the assumed hydrogen flow rate, the higher the required turbine inlet temperature. MM had the largest hydrogen flow rate and the lowest turbine inlet temperature. On the other hand, GE and TRW assumed superconducting weapon accelerators with correspondingly lower hydrogen flow rates. These two contractors also specified higher turbine inlet temperatures which then required higher temperature materials. None of the proposed turbine materials are on an equal developmental basis. While MM proposed stainless steel or nickel superalloy construction (considered off-the-shelf technology), GE proposed an advanced coated or cooled nickel superalloy material (likened to state-of-the-art), and TRW indicated carbon-carbon technology (considered advanced). None of the contractor's turbine inlet temperatures or material selections should be considered as being adequately justified from a system view.

TURBINE MATERIAL TECHNOLOGY WAS DETERMINED BY THE ACCELERATOR COOLING METHOD

MM	779-1251 K	Stainless steel, Ni superalloy
GE	1394-1500 K	Monocrystal Ni alloy, blade cooling, ceramic
TRW	1700 K	Carbon/carbon composite

POWER TURBINE TECHNOLOGY NEEDS

Hydrogen and hydrogen-oxygen turbines will need to be developed for open, burst, multimegawatt power systems because these systems provide the lowest mass option. This development effort will need to include low vibration, high reliability bearings (perhaps gas or magnetic), hydrogen compatible materials , hydrogen gas-cooled turbine shafts, disks, and blades, and high gas velocity, high stage work turbine aerodynamic designs to minimize the number of stages in hydrogen turbines.

Finally, the hydrogen power turbines should be developed for system-optimized pressure ratios, inlet pressures, and inlet temperatures.

Power Turbine Technology Development Needs

- Hydrogen and Hydrogen-Steam Working Fluid Turbines Including:

  - Hydrogen compatible materials and coatings
  - High stage work turbines to minimize the number of stages
  - Hydrogen gas-cooled blades and disks for high speed, lower mass
  - Turbines should be for pressure ratios and inlet temperatures based on platform system optimizations

- Low Vibration, High Reliability Bearings for Multimegawatt Power Levels

VIII. APPENDICES

A. COMPONENTS

3. ALTERNATORS

ALTERNATOR WEIGHTS AND VOLTAGES VARIED

Alternators were proposed for a variety of both burst and steady state power applications. The ones in the facing chart are for burst power systems. The alternator voltages selected by the contractors varied by a factor of two. Perhaps more importantly, the alternator specific masses varied by more than a factor of three. The higher voltages assumed by MM and TRW allowed a reduction in power conditioning weights by eliminating transformers. However, these assumed voltages are a significant increase in present alternator technology and will only be possible with substantial improvements in electrical insulation.

ALTERNATOR WEIGHTS AND VOLTAGES VARIED

GE	50 KV	0.047 kg/kw
MM	74 KV	0.160 kg/kw
TRW	105 KV	0.060 kg/kw

- MM & TRW assumed high voltage to reduce PC weight (no transformer)
- Getting high voltage at low weight will be a technical challenge

ALL CONTRACTORS HAD DIRECT DRIVE, OPPOSED ROTATION MULTIPLE GENERATORS

All three contractors had direct driven generators to eliminate gear boxes, except MM which proposed their idler gear arrangement discussed earlier. All contractors also proposed opposed rotation paired generators to minimize platform startup/shutdown torques and gyroscopic effects. Operational frequencies were 1 to 2 kHz for TRW and MM. GE's indication of 16,500 kHz must surely be a typographical error (indication of rotational speed). TRW and GE proposed cryogenically cooled generators. TRW used liquid hydrogen cooling, although TRW claimed credit for superconducting capabilities at higher temperatures (supposedly through material breakthroughs from recent advances in superconducting material research). GE based their power system designs on liquid helium superconducting generators. MM proposed a solid rotor Lundell-Rice generator to obtain their very high rotational speeds. However, MM's calculated rim speed (based on their indicated generator diameter) is not achievable with present materials and may require significant development work. GE's and TRW's generators were wound rotor designs.

ALL CONTRACTORS HAD DIRECT DRIVE, OPPOSED ROTATION MULTIPLE GENERATORS

	Voltage $\phi 3$, L-L	Freq	Module Power MWe	RPM	Eff %	Rim Speed m/sec	Specific Mass kg/kWe
GE✓	50KV	?*	50	16,500	98	596	.047
MM	74KV	2 kHz	12.5	33,000	97	1123	.160
TRW✓	105KV	1 kHz	50	12,000	98.5	?	.060

* GE's report indicated 16,500 kHz (obviously a typographical error)

✓ GE used LHe superconducting rotor; TRW used LH_2 superconducting rotor

OUR COMMENTS ON GENERATOR DESIGNS

All of the proposed generator voltages are high when compared to present day machines. However, MM's and TRW's voltage selections of 74 KV and 105 KV line-to-line are especially so. These latter voltages will only be achievable after significant development.

We believe that a generator specific mass of 0.05 kg/KW, suggested by GE and TRW, is possible using state-of-the-art technology without the requirement of superconducting rotors or windings. Whether this specific mass can be achieved in a high voltage machine remains to be seen. Increased rotational speeds (e.g., above 10,000 to 15,000 rpm) should tend to slightly decrease this specific mass. The Lundell-Rice generator selected by Martin Marietta at 0.16 kg/kW may not lend itself to significant mass reduction because of its particular design. It remains to be seen whether superconducting alternator technology offers significant mass reduction.

MM's 12.5 MWe module designs require many generators for a typical weapon power level (i.e., 16 generators for a 200 MWe system). This number of generators may have an impact on platform design or reliability considerations. Also, as mentioned earlier, MM's generator rim speed may not be achievable with present materials.

OUR COMMENTS ON GENERATOR DESIGNS

- Generator specific mass of 0.05 kg/kw should be possible without superconducting (MM specific mass is three times this value).
- MM and TRW generator voltages are high.
- MM module size requires many generators for typical weapon power level.
- MM rim speed may be unobtainable.

COMPULSATORS AND HOMOPOLAR GENERATORS HAVE LOWER SPECIFIC MASSES THAN GENERATORS

The available compulsator and homopolar generator design information is summarized in this figure for GE and MM. These machines would be used for EML applications. TRW did not discuss homopolar generator powered EML gun applications. The contractors' mass estimates showed that even though their rotational speed was reduced, compulsator (or homopolar generators) specific masses were about half that of the ac generators proposed for each contractor's NPB application. Unfortunately, compulsators and homopolar generators provide only low voltage dc. It should be noted that the efficiency indicated here for the MM homopolar generator (>99%) was calculated from state points for the associated potassium turbine operating conditions. It is doubtful that MM's homopolar generator would be this efficient and the efficiency should probably be like that indicated for GE's design (about 96%).

COMPULSATORS AND HOMOPOLAR GENERATORS HAVE LOWER SPECIFIC MASSES THAN GENERATORS

	Voltage	Power Level	RPM	EFF %	Specific Mass kg/kw
GE	56V	84 MW	11,500	96	.023
MM	?	200 MW	4167	>99*	.070

(TRW did not provide this information)

* Based on system state points

ALTERNATOR TECHNOLOGY DEVELOPMENT NEEDS

Space power alternators will need the development of low vibration, high reliability bearings to minimize the impact on the weapon platform. Also, high alternator output voltages (70 kV to 100 kV) will allow reduced mass in power conditioning by eliminating the need for transformers in matching the alternators to high voltage loads. Finally, MMW alternators developed with moderate rotational speeds of 10,000 to 16,000 rpm would provide significant mass reductions in the direct drive turbines when compared to standard power plant generators of 3600 rpm.

Alternator Technology Development Needs

- Low Vibration, High Reliability Bearings
- High Voltage Output
- Moderate Rotational Speeds (10,000 to 16,000 rpm)

VIII. APPENDICES

A. COMPONENTS

4. RADIATORS

HEATPIPE RADIATORS WERE TOO LIGHT

The specific mass estimates for heat pipe radiators that were made by all of the contractors for temperatures above 600 K were low. There are two reasons that the estimates are low. First, the mass of a single heat pipe was based on the mass of heat pipes that have been developed or are currently under development. These heat pipes have not been designed with meteoroids or spaced debris in mind. Additional mass must be included to shield these heat pipes. Second, an actual radiator would need redundant heat pipes to make up for pipes destroyed by meteoroids or space debris. Preliminary calculations done at Sandia indicate that 20% redundancy may be required. And third, the mass for radiator heat exchangers was not included.

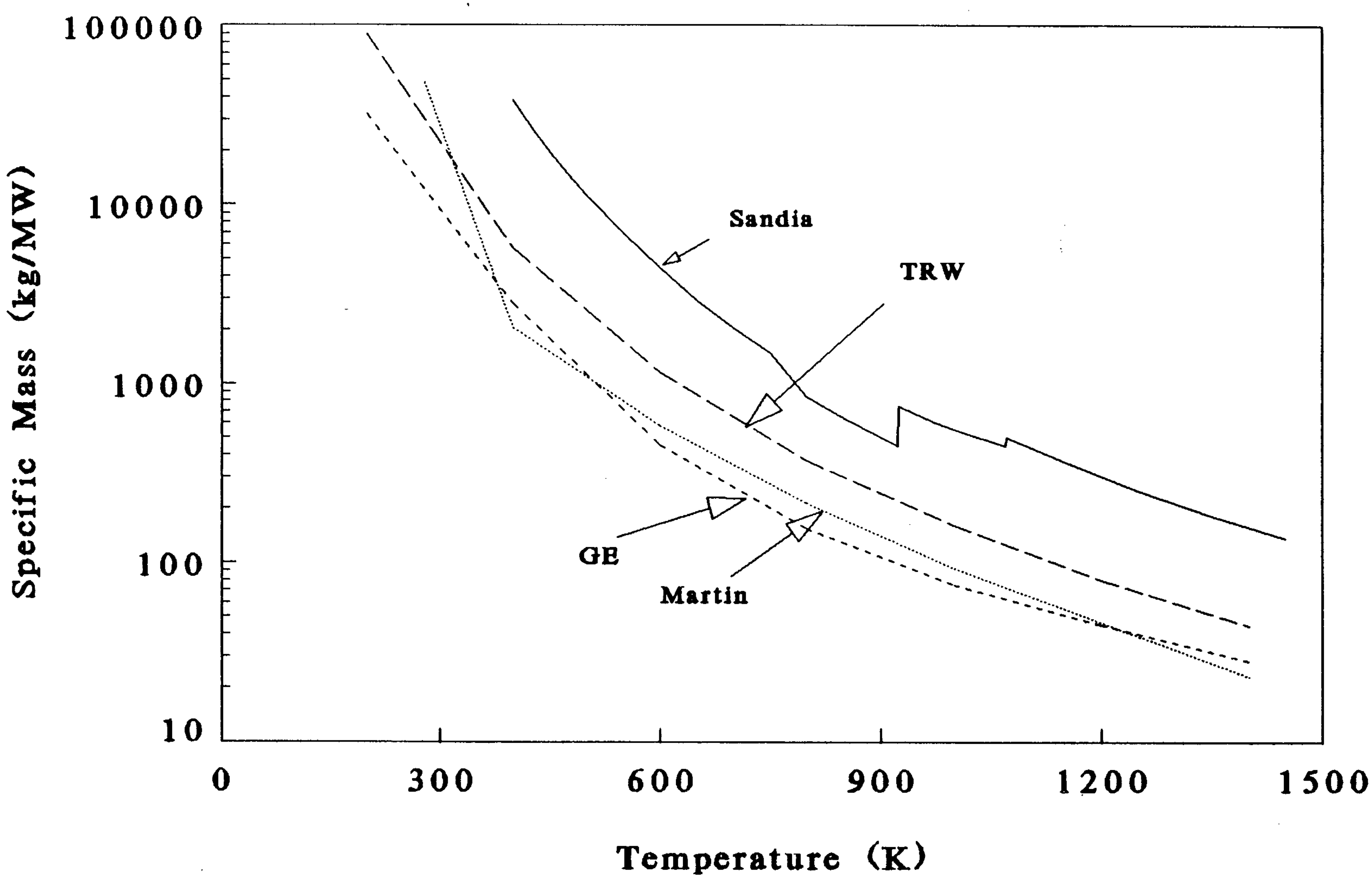
Heatpipe Radiators were Too Light

- Low Specific Mass
- No Meteoroid and Debris Armor
- No Extra Area for Meteoroid Loss
- Heat Exchanger Mass Not Included

SPECIFIC MASS OF 10MW RADIATORS

This graph presents the specific mass estimates (kg/MW) of heat pipe radiators that were made by the three contractors as a function of temperature. These estimates are compared with preliminary estimates made by Sandia for armored radiators. The Sandia estimates were made using the code MACRAD. (MACRAD is a code that is being developed to estimate and optimize the mass of heat pipe radiators. It is a parametric code that calculates masses based on heat pipes that meet operational requirements, e.g., the capillary limit, and uses temperature dependent material properties.) The contractor estimates are basically consistent with the mass of unarmored heat pipes. However, when armoring is taken into account, the contractor estimates are low.

Specific Mass of 10MW Radiators



CONCLUSIONS ABOUT RADIATORS WERE MIXED

All three contractors used radiators to remove waste heat from steady state power systems and from refrigeration units used to maintain cryogens for burst systems. TRW and Martin Marietta used them to cool burst mode power conditioning units. GE used them to remove waste heat from battery powered burst systems; Martin used them in closed, reactor powered, Rankine and thermionic burst power systems; and TRW used them for waste heat removal from their combustion turboalternator system that absorbed all of the platform's effluents.

The conclusions reached by each of the contractors about which type of radiator (or heat sink) should be used were mixed. TRW concluded that hydrogen should be used for burst mode heat rejection when operation time is less that 1000 seconds for rejection temperatures less than 1000 K. Heat pipe radiators should be used otherwise. This conclusion is based on a mass analysis that does not include proper armoring for either the cryogen tanks of the heatpipe radiators. The tradeoff results might change if survivability requirements for both natural and hostile threats are included in the mass estimates. TRW further suggested the use of conventional heat pipe radiators for steady-state heat rejection. This was based on the fact that advanced radiators would require substantial development. Martin Marietta concluded that liquid droplet radiators are unacceptable because of the contamination problem caused by loss of the working fluid. They did not make a recommendation on the type of heat sink that should be used for burst power operation although they did look at several options. Martin Marietta also concluded that heat pipe radiators should be used with steady-state power systems. GE concluded that expandable radiators should be used for closing burst power systems with a heat rejection temperature below 500K and an operation time less that 500 sec. Above 500K, advanced heat pipe radiators should be used to close the system. This conclusion is based on a mass analysis summarized in the chart following this one.

Conclusions About Radiators Were Mixed

Hydrogen Should be Used for Heat Rejection for Burst Mode Operation Lasting Less than 1000 s at 1000 K. (TRW)

Use of Conventional Heat Pipe Radiators is Recommended For Steady State Power Rejection. Advanced Radiators Require Substantial Development. (TRW)

LDRs Unacceptable Because of Sensor Contamination. (MM)

Expandable Radiators Should be Used For Closed Platforms When Radiator Temperature is Less than 500 K. (GE)

Advanced Heat Pipe Radiators Should be Used Above 500 K for Closed Platforms (GE)

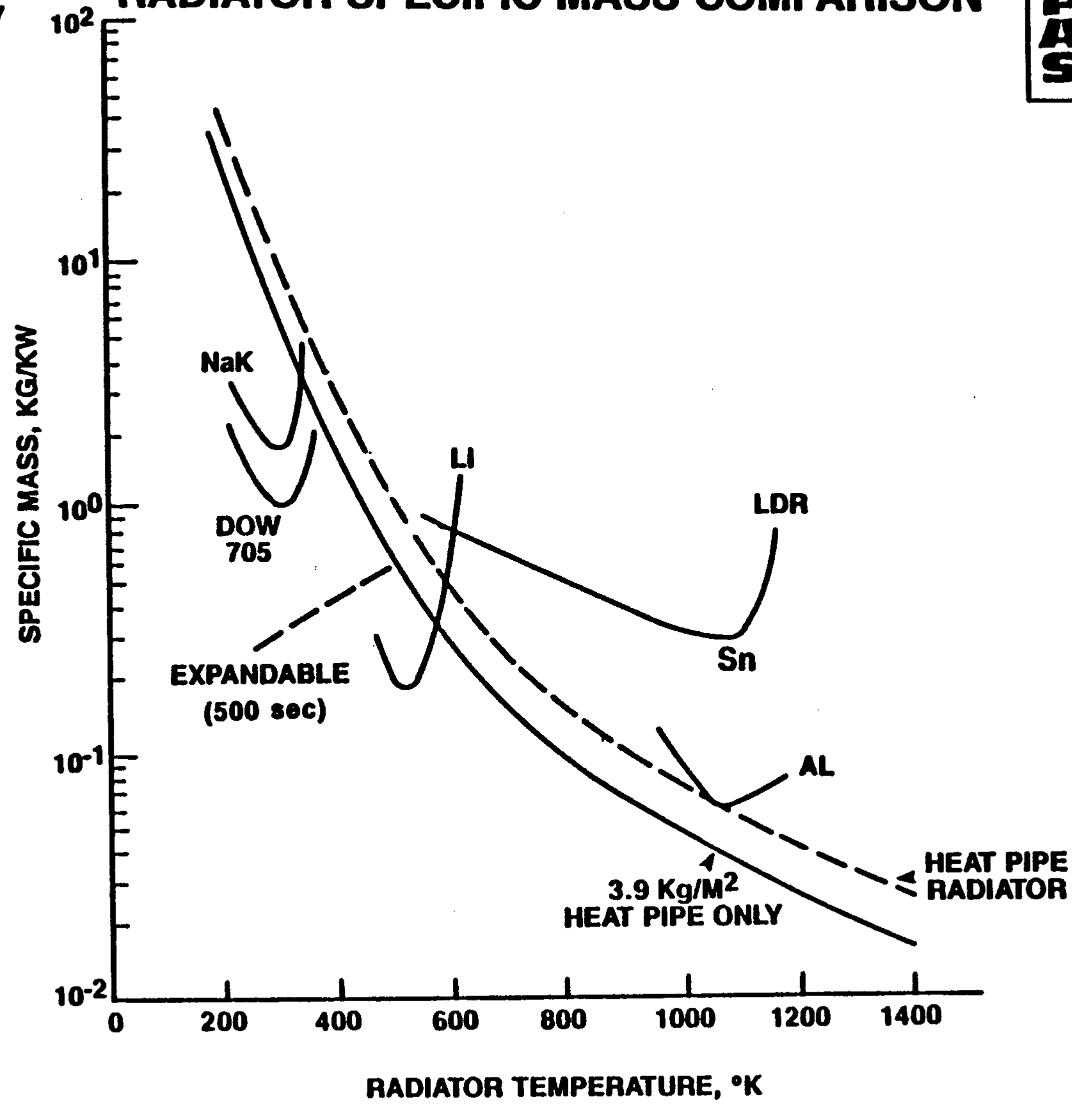
RADIATOR SPECIFIC MASS COMPARISON

This is a GE viewgraph that supports their conclusion that expandable radiators should be used at temperatures below 500K and run times less than 500 sec. The graph shows the specific mass of several potential heat sinks as a function of temperature. This graph shows that for temperatures below 500 K, an expandable radiator that will collect gas for 500 seconds is less massive than a heat pipe radiator. If the run time increases, this line will move upward. This would reduce the cut-off temperature for going to advanced heat pipe radiators. The graph also shows that advanced heat pipe radiators are preferable above 500 K for operation times above 500 sec. If the operation time is reduced, the cut-off temperature for going to the advanced heat pipe radiator would increase. (Note: The advanced heat pipe radiator is based on heat pipes that have a specific mass of 3.9 kg/m^2. This is represented by the indicated solid line in the figure. In order to make a radiator, structural material and heat exchangers must be added. The radiator mass based on the 3.9 kg/m^2 heat pipe is shown by the indicated dashed line.)

GENERAL ELECTRIC
Lockheed

RADIATOR SPECIFIC MASS COMPARISON

SPACE POWER ARCHITECTURE STUDY
AFSTC



VIII. APPENDICES

B. SAFETY, RELIABILITY AND CONTROLS

NO SIGNIFICANT CONCLUSIONS WERE REACHED FOR SAFETY, RELIABILITY, OR CONTROL ISSUES

This chart summarizes our evaluation of the SPAS work done on safety, reliability, and controls. The work in these areas was rather lean as would be expected in view of the conceptual nature of the designs in this stage of the program. Each of the three areas is discussed in more detail in the charts that follow.

NO SIGNIFICANT CONCLUSIONS WERE REACHED FOR SAFETY, RELIABILITY, OR CONTROL ISSUES

- No safety analyses were done, but they are probably not a discriminator at this point
- TRW said reliability is a constellation issue, and should trade off individual platform reliability with number of platforms
- MM said reliability should consider on orbit replacement and repair, and they favored repair to high reliability
- No one discussed controls, which may be a discriminator because of response time

NO SAFETY ANALYSES WERE DONE BY ANY CONTRACTOR

None of the contractors performed safety analyses; only very general statements concerning safety were made. These are listed on the facing chart. It was outside the scope of this review for the Field Support Team to perform a safety analysis for any of the concepts. However, several of the system concepts have undergone top-level safety analyses during previous studies by the Field Support Team. These analyses can be found in the referenced documents.

No Safety Analyses were Done by Any Contractor

Neutron Poisons Must be Used in Reactors to Prevent Criticality Upon Water Submersion (MM)

Reactor Will be Designed Fail-Safe (TRW)

GE Made NO Comments on Safety

A Top Level Safety Analysis of Most of the Concepts Can be Found in:

A Review of Gas-Cooled Reactor Concepts for SDI Applications, Sandia National Laboratories, INF-6511-8702, April 1987.

and

Executive Summary: Descriptions and Technical Issues of Concepts Developed for MMW Space Nuclear Power Applications (U), Sandia National Laboratories, RS6510/87/146, June 1987.

SPECIFIC RELIABILITY ISSUES WERE NOT IDENTIFIED

Reliability was not discussed by any of the contractors in terms of probabilities or discrete specific failure modes. Concerns or comments about reliability were general and no specific component reliability issues were identified. Although all contractors indicated that most components had potential for redundancy, none of the contractors identified all specific components where this should be done. GE did not even discuss reliability except to identify some failure modes for power system components and to indicate that these failures could lead to system loss or degradation. TRW considered the power system and weapon platform overall reliability to be a function of constellation size (number of platforms), individual component reliability, and individual component mass. However, TRW did not provide any discussion or conclusions with their concept. MM provided a methodology that related constellation life cycle cost and overall constellation system reliability to some minimum platform reliability. This methodology traded component maintenance requirements with dormant mode platform reliability. MM then concluded that the platforms should be repaired rather than have a high (>0.84) dormant mode reliability. However, real component reliability values (which are not presently available) were not used for MM's analysis.

SPECIFIC RELIABILITY ISSUES WERE NOT IDENTIFIED

- GE did not discuss reliability
- TRW considered platform reliability a constellation (and component mass) trade
  - no discussion or conclusions were provided
- MM presented a methodology that related constllation life cycle cost to platform reliability
  - the method traded component maintenance vs component reliability, but real reliability values were not used
  - MM concluded platforms should be repaired rather than have high (>.84) reliability

RELIABILITY CONCLUSIONS AND RECOMMENDATIONS

MM concluded from their constellation life cycle cost versus reliability model that the lowest overall cost system was not generally at the highest dormant (standby) mode platform reliability. MM reached this conclusion by indicating that very high reliability components (and thus systems) were very expensive to manufacture. Thus, maintenance of failed systems would have lower cost.

The Field Support Team thinks that reliability concerns, although very important, are not a system discriminator at this time, since many specific component reliability values are unknown. Further, we feel that consideration of platform reliability should be consistent with the level of design detail. This would mean that as specific components are identified in regards to their function, material, operating environment, etc., that their specific failure modes also be identified and reliability values assigned to those failure modes (through tests, similarity to other existing components, judgement, etc.). Finally, we should begin to identify components that may have a substantial mass impact on the platform due to reliability concerns. These components should be identified as much as possible prior to obtaining a complete knowledge of their detailed design.

RELIABILITY CONCLUSIONS AND RECOMMENDATIONS

- Lowest cost system is generally not at the highest reliability (MM)
- The FST does not think reliability concerns are a system discriminator at this time
- Components should be identified that will have a substantial mass impact on the platform due to reliability concerns
- Consideration of reliability should be consistent with the level of the design detail

CONTROL STUDIES THAT DISCRIMINATE AMONG TECHNOLOGIES WERE NOT DONE IN SPAS

Some systems may not be able to meet ramp-up requirements. For example, a Rankine cycle with 2-phase flow and potential moisture carryover problems may not be able to ramp 4 to 6 orders of magnitude in a short period of time. Dynamic systems may not be able to respond as readily as a thermionic or thermoelectric system.

Power systems will have to respond to changing loads. The parts of the power system -- power source, power conversion, buffer storage, power conditioning, and the control system that ties all these together -- will interact when subjected to a changing load. These interactions need to be studied to see which components work best together and where intrinsic control can be used to advantage.

Dynamic power conversion systems and open systems that generate exhaust produce instabilities that are different than those produced by static and closed systems. For each design, particular problems and the methods used to circumvent them must be evaluated.

Power source and conversion system designs each produce their own maneuvering problems. Large platforms with large radiators limit direction and speed control that may be important during operation and possibly during reentry if a preferred orientation is required to keep the power system intact. These specifics may be critical to a concept's design and selection.

Some weapon concepts experience impulse and other reactions that will produce platform and power system dynamic control instabilities. An example is the changing angular momentum of a homopolar generator on an EML gun system. These may produce platform and power delivery system problems <u>plus</u> interactions and synergisms.

Control Studies That Discriminate Among Technologies Were Not Done in SPAS

These Control Issues Need to be Addressed:

- Ramp-up for the Burst Mode
- Load Following, Regulation, Buffer Storage Interaction
- Prime Power & Conversion Systems-Load Interaction
- Platform Stability
- Manuvering Control
- Interaction with Fire Control & Battle Manager

THESE ARE THE CONTROL ISSUES WE SHOULD LOOK AT TO IDENTIFY SHOW STOPPERS FOR SPECIFIC DESIGNS

Dynamic power systems may have difficulty responding to the transient loading imposed by some weapons systems. Energy storage buffers may offer a solution but also add mass. It is possible that dynamic interactions may create destructive oscillatory forces if not designed properly. Such issues need to be addressed.

A power source's thermal management and fluid transport subsystems may be too sluggish to respond to needed power changes. This might be true for reactors with large coolant systems and long coolant transit times. "Once-through" cycle time is an important consideration.

Different reactor types have a wide range of characteristics and require different control methods. Some reactor types may not be safely controllable when meeting ramp requirements or when interacting with the balance of plant. "Intrinsic" control may be desirable to relieve the demands placed on electro-mechanical and computer controls.

The reactor's ability to ramp in a required time may be less of a control problem than the balance-of-plant's ability to respond. Power conversion components and power conditioning devices may create transients that cause physical destruction in static systems as well as in dynamic systems. In general these issues are presently not being evaluated. Consideration must be given to power swings that could range between 10 and 100 megawatts.

Some concepts assume that energy storage systems can reduce or possibly eliminate the need for a large active burst power source. Batteries, fuel cells, etc. may be limited in their response to large transients dictated by burst power loads. Batteries, for example, may have plate characteristics that limit current (internal resistance brought about from gas bubble film formation, etc.).

There may be control advantages to having separate power sources for station keeping, alert, and burst modes of operation because of the transient problems associated with transition between them. The nature in which these power sources interact needs to be addressed. A large part of the on-board station keeping and battle management control circuitry may need to be isolated from power line transients that occur during mode changes.

These are the Control Issues We Should Look at to Identify Show Stoppers for Specific Designs

Rotating Machinery & Weapon Impulse Force & Vibration Control

Thermal Mgmt System Controls to Determine Response Time

Reactor Control System to Determine Response Time and Control Methods (May Need Intrinsic Control)

Electrical System Ramp-up Time (Resonance, Oscillations, Charging Time)

Interaction Between Buffer Storage & Burst Power System

Interaction Between Steady-State, Alert & Burst Systems

Control Philosophy - Centralized/Decentralized

Power Plant Operation - Autonomous or Remotely Controlled

THESE ARE THE CONTROL ISSUES WE SHOULD LOOK AT TO IDENTIFY SHOW STOPPERS FOR SPECIFIC DESIGNS (cont.)

Platform controls have a wide range of tasks. They include startup, normal and emergency responses, battle operations, and reactor control for failure prevention and safety for systems that use reactor power. SP-100 plans call for a centralized control system. In a battle scenario, or platform emergency, decentralized and switchable controls with a hierarchy may provide improved control. These issues need to be addressed.

As strategic situations and demands on a platform change, the manner in which these changes are accommodated needs to be addressed. This will depend on whether the platforms are under full- or part-time control from earth or a GEO satellite or whether the entire platform operates autonomously.

These are the Control Issues We Should Look at to Identify Show Stoppers for Specific Designs

Rotating Machinery & Weapon Impulse Force & Vibration Control

Thermal Mgmt System Controls to Determine Response Time

Reactor Control System to Determine Response Time and Control Methods (May Need Intrinsic Control)

Electrical System Ramp-up Time (Resonance, Oscillations, Charging Time)

Interaction Between Buffer Storage & Burst Power System

Interaction Between Steady-State, Alert & Burst Systems

Control Philosophy - Centralized/Decentralized

Power Plant Operation - Autonomous or Remotely Controlled

SAFETY, RELIABILITY, AND CONTROL RECEIVED LITTLE ATTENTION

None of the contractors covered safety, reliability, or control in any detail. This was appropriate considering the conceptual nature of the system designs. All three of these areas will almost certainly become discriminators as designs mature.

Safety, Reliability, and Control Received Little Attention

All Three May Be Discriminators

VIII. APPENDICES

C. FIGURES OF MERIT MODELS

FIGURE OF MERIT MODELS (FOM) OVERVIEW

IN ARRIVING AT A METHOD OF RANKING THE VARIOUS POWER SYSTEMS STUDIED DURING THE SPAS TWO OF THE CONTRACTORS, GENERAL ELECTRIC AND MARTIN MARIETTA, USED A CONVENTIONAL APPROACH: AFTER A NUMBER OF SYSTEM DESCRIPTIVE ATTRIBUTES WERE SELECTED BOTH A WEIGHTING FACTOR AND AN "ATTRIBUTE SCORE" OR "RELATIVE WORTH" VALUE WERE ASSIGNED TO EACH CHARACTERISTIC ATTRIBUTE. THE OVERALL FOM FOR A GIVEN SYSTEMS j WAS THEN EVALUATED FROM THE FORMULA $FOM_j = \sum_{i=1}^{n} f_i \cdot RW_i$; WHERE W_f IS THE WEIGHT FACTOR; RW, THE RELATIVE WORTH; n, THE TOTAL NUMBER OF ATTRIBUTES; AND i, IS THE RUNNING ATTRIBUTE INDEX.

TRW CHOSE AN "EXPERT" DECISION METHODOLOGY REFERRED TO AS A MULTI ATTRIBUTE UTILITY TO DETERMINE THEIR FOM. IT IS BASED ON INTERROGATION OF AN EXPERT DECISION MAKER TO SET PREFERENCES AMONG COMBINATIONS OF ATTRIBUTE VALUES AND DETERMINE THE DEGREE TO WHICH AN EXPERT MIGHT GAMBLE IN THE CHOICE OF POSSIBLE COMBINATIONS OF ATTRIBUTE VALUE TRADES. THE RESULTING "PAIRED-ATTRIBUTE COMPARISON" AND "INDIFFERENCE CONTOUR" INFORMATION FORMS THE BASIS OF THE MATHEMATICAL EXPRESSIONS OF THE UTILITY FUNCTION FOR A GIVEN SYSTEM. THIS FUNCTION HAS THE FORM $U(x) = \prod_{i=1}^{n} (U_i X_i)$

WHERE $U_i(X_i)$ IS THE ATTRIBUTE UTILITY FOR THE i_{th} ATTRIBUTE
(X_i) IS THE i_{th} ATTRIBUTE
$U(x)$ IS THE OVERALL UTILITY FOR THE SYSTEM

NOTE THAT THE OVERALL UTILITY VALUE LEADS TO THE FOM VALUE AFTER A FINAL WRAP-UP CALCULATION PERFORMED BY USE OF A CUSTOMIZED CODE REFERRED TO AS MUFCAP (MULTI-ATTRIBUTE UTILITY FUNCTION EVALUATOR/FIGURE-OF-MERIT CALCULATOR.

AJJ88-002.2

FIGURE OF MERIT MODELS (FOM)

Sandia NASA

- TRADITIONAL APPROACH USED BY GE, MM

  $$FOM = \sum_{i=1}^{n} (\text{Wt FACT})_i \times (\text{ATTR. SCORE})_i$$

  WHERE n = NUMBER OF ATTRIBUTES

- TRW USED A MULTI-ATTRIBUTE UTILITY FUNCTION REQUIRING "EXPERT" DECISION INPUTS INSTEAD OF "WEIGHT FACTORS"

- NEITHER APPROACH COMPLETELY ELIMINATES SUBJECTIVE BIAS

- RESULTS LIMITED BY DEGREE OF DETAIL USED IN SYSTEM DESCRIPTION i.e., NUMBER OF ATTRIBUTES

- FOM MODELS SHOULD BE USED AS INPUT TO RATHER THAN SUBSTITUTE FOR HUMAN JUDGEMENT IN MAKING FINAL SYSTEM SELECTION

AJJ88-002.1

SYSTEM ATTRIBUTES USED

THE SYSTEM ATTRIBUTES SELECTED BY EACH CONTRACTOR ARE AS SHOWN. NOTE THAT WHILE MASS, VOLUME, COST ARE "OBJECTIVE" ATTRIBUTES MOST OF THE OTHER ATTRIBUTES ARE "SUBJECTIVE," IMPLYING THAT TECHNICAL OPINION OF THE EVALUATOR IS RELIED ON IN ARRIVING AT THE SCORE FOR SUBJECTIVE ATTRIBUTES.

REGARDING WEIGHT FACTORS, GE ASSIGNED A VALUE OF 0.2 FOR MASS AND 0.1 FOR ALL OTHER ATTRIBUTES. MM ASSIGNED A VALUE OF 5 TO: RISK, MASS, VOLUME, SURVIVABILITY, CONTAMINATION AND OPERATIONAL CONSIDERATIONS. ALL OTHERS WERE SET AT UNITY, EXCEPT FOR THE WEIGHT FACTOR FOR COST, WHICH WAS SET AT 3.

THE TRW WEIGHT FACTORS ARE INTEGRAL WITH THE UTILITY FUNCTIONS REFERRED TO PREVIOUSLY.

AJJ88-002.4

SYSTEM ATTRIBUTES USED

GE	MM	TRW
MASS	MASS	COST
DYN. INTERACTIONS	VOLUME	SCHEDULE (TECH. READINESS)
EFFLUENT	COST	AREA
RELIABILITY	RISK	POWER
VULNERABILITY	OPERATIONAL	RESPONSE TIME
MAINT/SERV.	SURVIVABILITY	
SAFETY	RELIABILITY	
TECH RISK	LIFE	
COST	SAFETY	
	MAINT/SERV	
	SPACE ASS'Y	
	COMPLEXITY	
	EFFLUENT CONTAM.	
	DYN. EFFECTS	

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TRW RESULTS BY MUFCAP

IT IS INTERESTING TO NOTE THAT THE TRW "MULTIPLE UTILITY FUNCTION CALCULATION PROCEDURE" OR MUFCAP RESULTED IN TWO SETS OF RANKING FOR THE FEL AND NPB SYSTEMS. NO ATTEMPT IS MADE BY THE CONTRACTOR TO EXPLAIN THE MAJOR REASONS FOR THE DIFFERENT RESULTS, PARTICULARLY WHY THE GEL/MHD SYSTEM WITH ITS SERIOUS EFFLUENT PROBLEM RANKED FIRST (ALONG WITH THE H+O FUEL CELL) FOR THE FEL, WELL AHEAD OF THE NUCLEAR TURBO-GENERATOR (NDR/TG), WHICH RANKED FIFTH. ON THE OTHER HAND, THE NUCLEAR TURBO-GENERATOR, A HIGH VOLTAGE SYSTEM, RANKED SECOND FOR THE NPB APPLICATION WHILE THE LOW VOLTAGE H+O FUEL CELL RANKED FIRST. THESE RANKINGS, RESULTING FROM APPLICATION OF THE MUFCAP MODEL WERE NOT IN AGREEMENT WITH INDEPENDENT RANKINGS BY TECHNICAL MONITORS OF THE SPAS CONTRACTS, NOR FOR THAT MATTER, DID THEY AGREE WITH INDEPENDENT RANKINGS BY THE SAME EXPERT WHO SUPPLIED THE TECHNICAL INPUT TO THE MUFCAP PROCESS. THIS IS SHOWN NEXT.

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TRW RESULTS BY MUFCAP

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FEL

RANK	DESIGN CONCEPT	FIGURE OF MERIT
1	GEL/MHD	.8640
	H+O/FC	.8640
3	H+O+TI/TG	.8596
4	NDR/MHD	.8532
5	NDR/TG	.8467
6	LI+H/TG	.8283
7	THOR	.8032
8	LMR/BATT	.7833

NPB

RANK	DESIGN CONCEPT	FIGURE OF MERIT
1	H+O/FC	.8689
2	NDR/TG	.8602
3	GEL/MHD	.8597
4	H+P+TI/TG	.8587
5	NDR/MHD	.8552
6	LI+H/TG	.8186
7	LMR/BATT	.7932
8	THOR	.7746

AJJ88-002.5

POWER CONCEPT COMPARISON
NPB APPLICATION - BY SOLLO

THE CONCEPT COMPARISON FOR THE NPB APPLICATION AS WELL AS THE RANKING ARRIVED AT BY THE TECHNICAL EXPERT (C. SOLLO) IS SHOWN HERE. NOTE THAT THIS RANKING WAS ARRIVED AT WITHOUT THE USE OF A SYSTEMATIC PROCEDURE BUT IS BASED ON OVERALL TECHNICAL JUDGEMENT ON EACH CONCEPT IN ITS ENTIRETY.

THE CHEMICAL H + O TURBO-GENERATOR RANKED FIRST BECAUSE OF ITS TECHNICAL READINESS AND BENIGN EFFLUENT (H_2) WITHOUT A HIGH MASS PENALTY (230 METRIC TONS). THE H + O FUEL CELL WAS SECOND BECAUSE OF ITS HIGHER MASS (401 METRIC TONS) EVEN THOUGH ITS TECHNICAL READINESS AND RELIABILITY WERE RATED HIGHEST OF ALL CONCEPTS. THE NUCLEAR (NERVA DERIVATIVE) TURBO-GENERATOR WAS RANKED THIRD BECAUSE OF ITS LONGER DEVELOPMENT TIME AND COST, EVEN THOUGH IT SHOWED A SIGNIFICANT MASS ADVANTAGE.

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POWER CONCEPT COMPARISON
NPB APPLICATION - BY SOLLO

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POWER SOURCE CONCEPT	MASS (TONNE)	AREA (M^2)	MODULE QTY	DEVELOPMENT TIME (YEARS)	EFFLUENT TYPE	DYNAMIC DISTURBANCE SOURCES	RESPONSE TIME (SEC)	RANK
NDR/TG	142	160	1 + 8	11.5	H	TG + EFF	5-20	3
NDR/MHD	202	70	1	15.5	H + Cs	EFF	5-15	8
H+O/TG	230	160	8	8.5	H	TG + EFF	5-20	1
Gel/MHD	342	130	4	10	MISC	EFF	0-2	4
H+O/FC	401	400	130	8	NONE	STATIC	0-2	2
THOR	488	1255/2510	1	9.5	NONE	STATIC	20-60	7
Li+H/TG	581	2120	8	10.5	NONE	TG	5-20	5
LMR/BAT	744	400	1 + 130	14	NONE	STATUC	10-40	6

AJJ88-002.7

GE NPB & FEL MISSIONS

IN THE GE STUDY THE NUCLEAR AND CHEMICAL TURBO-GENERATOR SYSTEMS RANKED AT THE TOP FOR NPB AND FEL APPLICATIONS BASED ON POWER LEVELS OF 20 MWe AND 100 MWe, RESPECTIVELY. ALL CONSUMABLES ARE ASSUMED TO BE STORED AT LAUNCH AND HENCE THERE IS NO NEED FOR ON-ORBIT RESUPPLY AS WAS THE CASE FOR EML MISSIONS. IRONICALLY, NUCLEAR AND CHEMICAL TURBO-GENERATORS ALSO RANKED AT THE TOP FOR EML MISSIONS. THESE RESULTS ARE PROBABLY INFLUENCED BY THE GE EXPERIENCE IN BUILDING LARGE TURBOMACHINES AND THEIR ASSUMPTION OF VERY LOW POWER CONDITIONING WEIGHT. NOTE THAT THE NUCLEAR SUPPORTED FUEL CELL AND MHD TECHNOLOGY BASED SYSTEMS WERE RANKED THIRD AND FOURTH BY GE.

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GE NPB & FEL MISSIONS

RANK	TOTAL SCORE	SYSTEM NAME	TOTAL MASS	MASS FACTOR	REL. & SIMPL.	SAFETY FACTOR	DYNAM INTER	VULN. & SURVIV.	EFFLUENT EFFECT	MAINT. & SERV.	TECH. RISK	COST FACTOR
1	3.65	TM-4	47,720	3	2	4	3	5	4	3	4	5
2	3.35	TM-1	78,380	2	3	4	3	3	4	4	5	5
3	3.35	MHD-6	58,880	3	1	4	5	4	4	3	3	4
4	3.00	LMR-FC	78,270	2	1	4	5	4	5	3	3	4
5	2.70	BS-3	112,810	1	4	4	3	2	4	5	4	4
6	2.40	FW-1	210,200	0	2	5	1	5	5	4	5	4
7	2.35	BS-1	321,860	0	5	4	5	5	5	5	5	2
8	0.00	FC-6	0	0	0	0	0	0	0	0	0	0
9	0.00	HYTEC	0	0	0	0	0	0	0	0	0	0
10	0.00	LMR-TM	0	0	0	0	0	0	0	0	0	0

AJJ88-002.9

MM TOP FOUR NPB & FEL POWER SUBSYSTEM OPTIONS

POWER SYSTEM RANKING RESULTS OBTAINED BY MM FOR THE NPB AND THE FEL APPLICATIONS ARE REPRESENTED BY THE TOP FOUR SYSTEMS SHOWN HERE. NOTE THAT THE RANKINGS DEPEND ON WHETHER THE LOAD ELECTRONICS ARE BASED ON TUBE OR SOLID STATE COMPONENTS. FOR THE TUBE LOADS THE CHEMICAL AND NUCLEAR TURBO-GENERATORS RANKED AT THE TOP BECAUSE OF THE GOOD MATCH BETWEEN THE HIGH VOLTAGE GENERATOR OUTPUT CHARACTERISTICS AND THE LOAD REQUIREMENTS WITH A MINIMUM POWER CONDITIONING MASS (28 kg/MW).

FOR TH SOLID STATE LOADS THE OUTPUT CHARACTERISTICS OF FUEL CELLS WERE FOUND TO BE SUITABLE WITHOUT THE NEED FOR POWER CONDITIONING. THIS, COUPLED WITH THE HIGH SCORES ASSIGNED TO FUEL CELLS FOR ATTRIBUTES SUCH AS SAFETY, MAINTENANCE, SPACE ASSEMBLY AND INTEGRATION COMPLEXITY LED TO FUEL CELLS AS THE TOP CONTENDER FOR SOLID STATE LOADS.

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MM TOP FOUR NPB & FEL POWER SUBSYSTEM OPTIONS

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EVALUATION CRITERIA	TUBE OPTIONS: TOP 4 POWER SYSTEMS	TUBE OPTIONS: FOM SCORES	SOLID-STATE OPTIONS: TOP 4 POWER SYSTEMS	SOLID-STATE OPTIONS: FOM SCORES
TOTAL FOM SCORE	CHO/B/HW	3072	HO/FC/H	3320
	CHO/B/H	3041	HO/FC/HW	3244
	NGC/B/H	2996	HO/FC/RAD(1)	3064
	NO/FC/H	2869	HO/FC/RAD(2)	2895
MASS/COST	NGC/B/H	500/300	HO/FC/HW	500/300
	CHO/B/HW	390/293	HO/FC/H	500/300
	CHO/B/H	372/292	HO/FC/RAD(2)	265/283
	HO/FC/HW	295/286	NGC/B/H	247/282
VOLUME	NLM/R/RAD	500	NLM/TI/RAD	500
	NLM/TI/RAD	319	NLM/R/RAD	196
	HO/FC/RAD(2)	65	HO/FC/RAD(2)	82
	HO/FC/RAD(1)	49	HO/FC/RAD(1)	60
RISK	NGC/B/H	500	NGC/B/H	500
	CHO/B/HW	500	CHO/B/HW	500
	CHO/MHD/HWC	500	CHO/MHD/HWC	500
	HO/FC/HW	500	HO/FC/HW	500
	HO/FCH	500	HO/FC/H	500
SURVIVABILITY	NGC/B/H	500	HO/GC/HW	500
	CHO/B/HW	500	HO/GC/H	500
	CHO/B/H	500	HO/FC/RAD(1)	500
	CHO/MHC/HWC	500	(6 SYSTEMS TIED)	250
			HO/GC/RAD(2)	0
CONTAMINATION	NLM/R/RAD	500	NLM/R/RAD	500
	NLM/TI/RAD	500	NLM/TI/RAD	500
	CHO/FC/RAD(1)	500	HO/FC/RAD(1)	500
	CHO/FD/RAD(2)	500	HO/FC/RAD(2)	500

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SUMMARY & CONCLUSIONS

USE OF FIGURE OF MERIT (FOM) CALCULATION PROCEDURES CAN BE USED TO SUPPORT THE OVERALL SYSTEM SELECTION PROCESS BUT A FINAL DECISION NEEDS TO BE MADE ON THE BASIS OF SOUND ENGINEERING JUDGEMENT, AS ILLUSTRATED BY THE TRW EXAMPLE.

CONVENTIONAL FOM MODELS REQUIRING WEIGHTING FACTORS AND INDIVIDUAL SYSTEM ATTRIBUTE SCORES AS INPUT WERE USED BY GE AND MM. TRW ELECTED TO USE A MULTI-ATTRIBUTE DECISION METHODOLOGY REQUIRING SUBJECTIVE INPUT FROM A TECHNICAL EXPERT. HENCE, THE CONVENTIONAL APPROACH SHOULD YIELD MORE TRACEABLE AND REPRODUCIBLE RESULTS.

A GENERAL CONCLUSION THAT CAN BE GLEANED FROM FOM RESULTS IS THAT POWER SYSTEMS BASED ON COMBUSTION DRIVEN TURBO-ALTERNATORS AND H_2- O_2FUEL CELLS WOULD BE THE NEAR TERM CHOICE WHILE NUCLEAR AND GEL MHD SYSTEMS WOULD BE AVAILABLE FOR LATER GENERATION MISSIONS.

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VIII. APPENDICES

D. ABBREVIATIONS and ACRONYMS

ABBREVIATIONS AND ACRONYMS

AC - Alternating Current
AFSTC - Air Force Space Technology Center
ANL - Argonne National Lab
BPI - Boost Phase Intercept
CARDS - Concept and Requirements Definition Studies
DARPA - Defense Advanced Research Projects Agency
DC - Direct Current
DEW - Directed Energy Weapon
DOD - Department of Defense
DOE - Department of Energy
EM - Electromagnetic
EML - Electromagnetic Launcher
FEL - Free Electron Laser
FEM - Free Electron Maser
FST - Field Support Team (see pg. 36)
GBL - Ground Based Laser
GE - General Electric Co
HPD - High Power Density
HV - High Voltage
KKV - Kinetic Kill Vehicle
KV - Kilovolt
KWE - Kilowatt Electric
KWH - Kilowatt Hour
LeRC - Lewis Research Center (NASA)
LMR - Liquid Metal Cooled Reactor
LANL - Los Alamos National Lab (DOE)
MHD - Magnetohydrodynamic
MHz - Megahertz
MM - Martin Marietta
MMWe - Multimegawatts Electric
MWe - Megawatts Electric
NASA - National Aeronautics and Space Adminstration
NDR - NERVA Derived Reactor
NERVA - Nuclear Engines for Rocket Vehicle Applications
NPB - Neutral Particle Beam
OTV - Orbital Transfer Vehicle
PBR - Particle Bed Reactor
PC - Power Conditioning
PS - Power System
RDS - Radar Discrimination System
RF - Radio Frequency
SAS - Systems Architecture Studies
SBFEL - Space Based Free Electron Laser
SBKKV - Space Based Kinetic Kill Vehicle
SBL - Space Based Laser
SDI - Strategic Defense Initiative
SNL - Sandia National Lab
SOFC - Solid Oxide Fuel Cell
SPAS - Space Power Architecture Studies
SPI - Space Power Inc.
SPO - Space Power Office (SDI)

STAR	-	Space Thermionic Advanced Reactor
S3	-	S-Cubed Inc.
TA	-	Turbo alternator
THOR	-	Thermionic Opening Reactor
TRW	-	TRW Inc.
UTC	-	United Technologies Co
UV	-	Ultraviolet

NASA
National Aeronautics and Space Administration

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16. Abstract

The Space Power Architecture Study (SPAS) identified and evaluated power subsystem options for multimegawatt electric (MMWE) space based weapons and surveillance platforms for SDI applications. Steady state requirements of <1 MMWE are adequately covered by the SP-100 nuclear space power program and hence were not addressed in the SPAS. Four steady state power systems <1 MMWE were investigated with little difference between them on a mass basis. The majority of the burst power systems utilized H_2 from the weapons and were either closed (no effluent), open (effluent release) or steady state with storage (no effluent). Closed systems used nuclear or combustion heat source with thermionic, Rankine, turboalternator, fuel cell and battery conversion devices. Open systems included nuclear or combustion heat sources using turboalternator, magnetohydrodynamic, fuel cell or battery power conversion devices. The steady state systems with storage used the SP-100 or Star-M reactors as energy sources and flywheels, fuel cells or batteries to store energy for burst applications. As with other studies the open systems are by far the lightest, most compact and simplist (most reliable) systems. However, unlike other studies the SPAS studied potential platform operational problems caused by effluents, vibration, etc.

17. Key Words (Suggested by Author(s))

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