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Reference Concepts for a Space-Based Hydrogen-Oxygen Combustion, Turboalternator, Burst Power System

Michael W. Edenburn

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REFERENCE CONCEPTS FOR A SPACE-BASED HYDROGEN-OXYGEN COMBUSTION, TURBOALTERNATOR, BURST POWER SYSTEM

Michael W. Edenburn
Advanced Power Systems Division
Sandia National Laboratories

Abstract

This report describes reference concepts for a hydrogen-oxygen combustion, turboalternator power system that supplies power during battle engagement to a space-based, ballistic missile defense platform. All of the concepts are "open"; that is, they exhaust hydrogen or a mixture of hydrogen and water vapor into space. We considered the situation where hydrogen is presumed to be free to the power system because it is also needed to cool the platform's weapon and the situation where hydrogen is not free and its mass must be added to that of the power system. We also considered the situation where water vapor is an acceptable exhaust and the situation where it is not. The combination of these two sets of situations required four different power generation systems, and this report describes each, suggests parameter values, and estimates masses for each of the four. These reference concepts are expected to serve as a "baseline" to which other types of power systems can be compared, and they are expected to help guide technology development efforts in that they suggest parameter value ranges that will lead to optimum system designs.

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EXECUTIVE SUMMARY

This report describes reference concepts for a hydrogen-oxygen combustion, turboalternator power system that supplies power during battle engagement to a space-based, ballistic missile defense platform. For each concept, we have estimated the sizes and masses of major components and have suggested values for several design parameters. We call them reference concepts because design parameter values were selected to minimize power system mass; thus, the concepts are optimum based on our current understanding of requirements and our current ability to estimate component masses. The concepts can and should be used to help guide technology development efforts, and they can be used as a reference, or "baseline" to which other types of power systems can be compared. The reference power systems use what we consider to be near-term technology. Our definition of near-term technology is taken from Sandia's space power information base: "We expect that necessary parts and materials could be developed and a prototype proven by testing on the ground within 5 years if a concerted effort is made and funding is available to do so." In this study, only proven materials and processes were assumed, and we believe that it is possible to successfully develop and ground-test a system by 1995 if a concerted effort is made and adequate funding is available to do so.

We assumed that the power system will supply power to a neutral particle beam weapon. This allows us to relate power levels to weapon power demands and to place rational restrictions on the availability of "free" hydrogen including its temperature, pressure, and flow rate. We assumed that the weapon produces a 20 MW charged beam (this is at the point in the weapon immediately preceding the beam neutralizer) requiring 38.46 MWe of input power and that the weapon operates for 750 seconds which includes both testing and battle engagement time. For scaling studies, we also considered charged beam powers of 40 and 100 MW and operation times of 1000 and 1500 seconds.

Four systems were needed to meet the following four requirements.

Case 1. Hydrogen is "free" and both hydrogen and water vapor exhaust are acceptable.
Case 2. Hydrogen is not "free" but both hydrogen and water vapor exhaust are acceptable.
Case 3. Hydrogen is "free," hydrogen is an acceptable exhaust, but water vapor is not.
Case 4. Hydrogen is not "free," hydrogen is an acceptable exhaust, but water vapor is not.

Water was retained, in the cases where water was not an acceptable exhaust, using a method proposed by Sundstrand for the Martin Marietta Space Power Architecture Study. It will be described later.

As an additional requirement, we assumed that each power system must expel its exhaust at 2000 m/s or more through a supersonic nozzle. We do not know if this velocity is sufficiently high to keep exhaust density below necessary limits. The exhaust velocity required depends on the quantity and composition of gas being exhausted, the sensitivity of platform components to the exhaust, and the platform's geometry. Systems which generate more power will exhaust greater quantities of gas; thus, we expect the required exhaust velocity to increase as system power requirements increase. The 2000 m/s exhaust velocity requirement has a significant effect on design parameters, particularly for the "free" hydrogen system which exhausts both hydrogen and water vapor (case 1).

Schematics for the four systems are shown in Figures 1a through 1d. In all of the cases, cold hydrogen is used to cool the alternator and power conditioning unit before entering the combustion process. These figures show suggested temperatures, pressures, and flow rates. Values are approximate and should not be considered as absolute requirements for future designs. For each of these systems, we have suggested design parameter values which minimize power system mass based on our current understanding of power system requirements and our current ability to estimate component masses. The suggested parameter values should be viewed as approximate and should not be considered as absolute requirements for future designs. Many of them will change as our understanding of the system and our ability to accurately model components improve.

Table 1 suggests some technology development directions. Turbines will need relatively high work coefficients in the range of around 4 to 5, and they will need a variety of pressure ratios, from around 15 up to 250, depending on the system's requirements. Turbines for this application will not need exotic, high temperature materials since turbine inlet temperatures range from 700 to 1350 K. Steel turbines at the low temperatures and nickel superalloy turbines for the higher temperatures are adequate, and these are standard materials used in current turbines. Disk cooling will be beneficial, but blade cooling appears to be unnecessary. Low mass turbine-alternator combinations and power conditioning units are needed as are reliable refrigeration units to keep hydrogen and oxygen supplies cool. Low mass meteoroid shields (roughly half the mass listed for the hydrogen subsystems is due to meteoroid shielding) are required for hydrogen and oxygen tanks and other system components, and some effort is

Table 1
Hydrogen-Oxygen Combustion Reference Power System
Concept Parameters: 38.46 MWe, 750 s Operation

H_2 Free	Case 1 H_2 Free H_2O OK	Case 2 H_2 Not Free H_2O OK	Case 3 H_2 Free H_2O Not OK	Case 4 H_2 Not Free H_2O Not OK
Trb inlet temp K	850	1350	700	900
Trb inlet pres MPa	2.5	2.5	2.5	2.5
Pressure ratio	15.4	165	98	250
Trb out temp K	501	534	321	359
Trb efficiency %	77	82	75	77
Trb speed rpm	10,000	10,000	10,000	10,000
Trb work coeff	4	4	5	5
Trb disk temp K	850	900	700	900
Trb material	Ni/Steel	Ni Alloy	Ni/Steel	Ni alloy
Trb stages	7	15	11	17
Number of turbines	4	4	4	4
Nozzle velocity m/s	2040	2032	2460	2700
Pump power MW	.41	.17	.41	.3
Refgr power kW	6.3	3.4	6.2	5.0
Mass Estimates in Metric Tons				
Hydrogen subsystem	0.0	5.2	0.0	8.8
Oxygen subsystem	4.5	3.6	2.9	3.5
Water condenser	0.0	0.0	.2	.2
Combustor heat exch	0.0	0.0	3.0	4.0
Turbine	1.5	3.8	2.7	4.5
Alternator	4.1	4.1	4.1	4.1
Flywheel	1.2	1.2	1.2	1.2
Power conditioning	7.7	7.7	7.7	7.7
Miscellaneous	1.9	2.6	2.2	3.4
Total	20.9	28.1	24.0	37.4

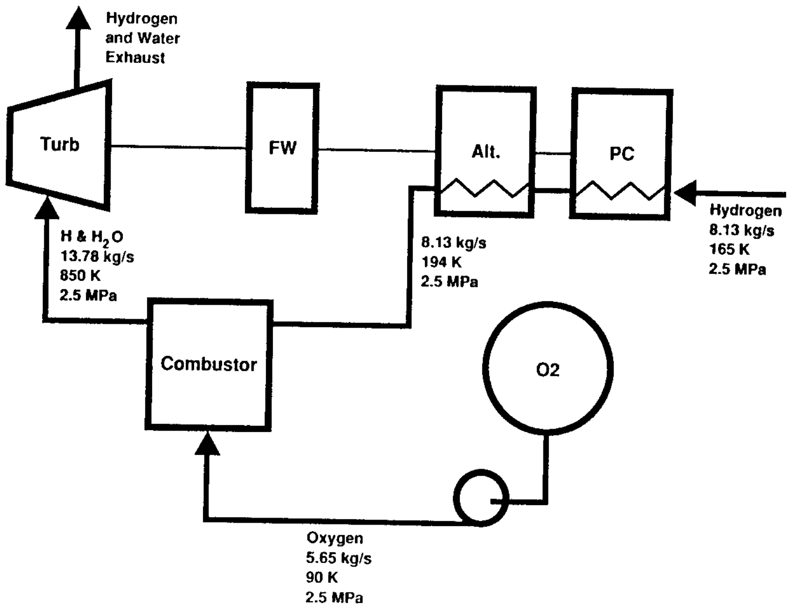

Figure 1a. H2-O2 Combustion Reference Power System -- 38.46 MWe, 750 s. Operation Time, Hydrogen is Free, Water Exhaust is OK.

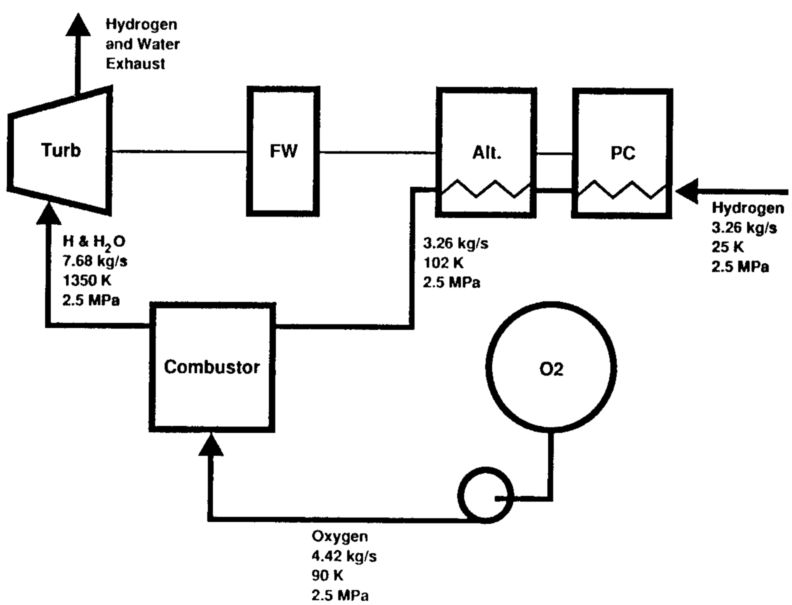

Figure 1b. H2-O2 Combustion Reference Power System -- 38.46 MWe, 750 s. Operation Time, Hydrogen is Not Free, Water Exhaust is OK.

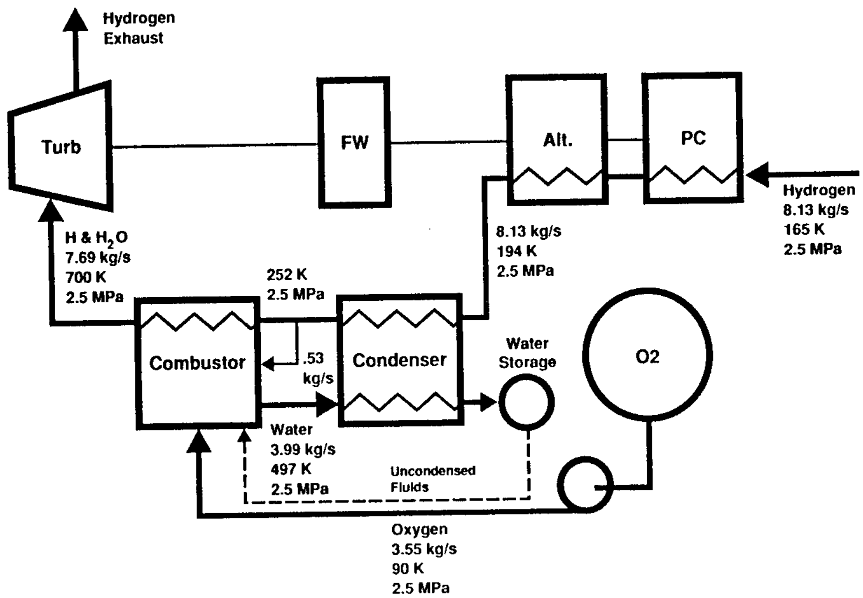

Figure 1c. H2-O2 Combustion Reference Power System -- 38.46 MWe, 750 s. Operation Time, Hydrogen is Free, Water Exhaust is Not OK.

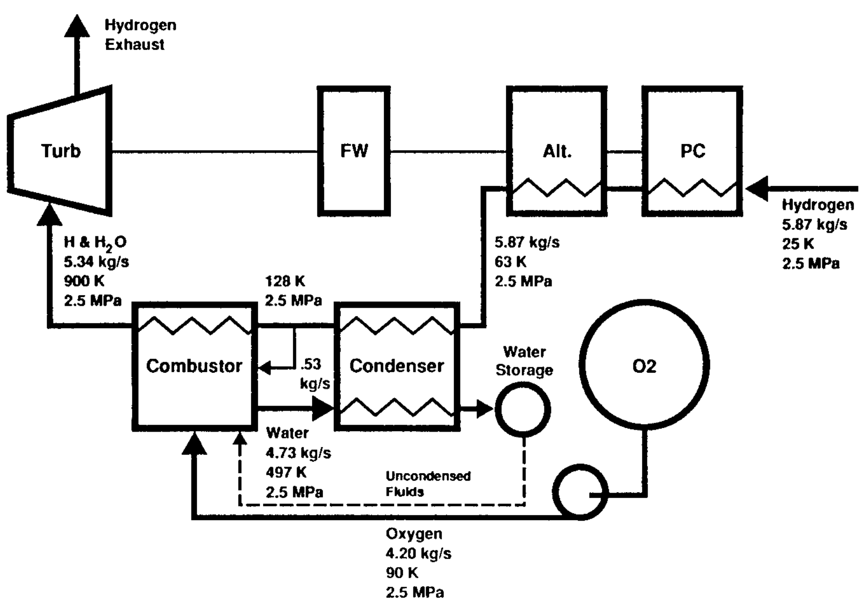

Figure 1d. H2-O2 Combustion Reference Power System -- 38.46 MWe, 750 s. Operation Time, Hydrogen is Not Free, Water Exhaust is Not OK.

required to address the space debris shielding problem. We have assumed the use of shields that will stop meteoroids but not space debris. Debris shields are unacceptably heavy using current shield technology in high debris orbits.

INTRODUCTION

This report describes reference concepts for a hydrogen-oxygen combustion, turboalternator power system that supplies power during battle engagement to a space-based, ballistic missile defense platform. They are concepts and not designs because they address only the major components in the power system and do not explore design details for any components. We do, however, estimate the sizes and masses of major components and suggest values for several design parameters. We call them reference concepts because parameter values have been selected which minimize power system mass; thus, the concepts are optimum based on our current understanding of requirements and our current ability to estimate component masses. The concepts can and should be used to help guide technology development efforts, and they can be used as a reference, or "baseline" to which other types of power systems can be compared. The reference power systems use what we consider to be near-term technology. Our definition of near-term technology is taken from Sandia's space power information base:[1] "We expect that necessary breakthroughs will be made, parts and materials developed, and a prototype proven through hardware testing on the ground by 1995". In this study, only proven materials and processes were assumed, and we believe that it is possible to successfully develop and ground-test a system by 1995 if a concerted effort is made and funding is available to do so.

We have assumed that the power system will supply power to a neutral particle beam (NPB) weapon. This allows us to relate power levels to weapon power demands and to place rational restrictions on the availability of "free" hydrogen including its temperature, pressure, and flow rate. "Free" hydrogen means that it is available from the weapon subsystem and its mass is not attributed to the power system. To characterize the "free" hydrogen available, we relied on NPB platform studies done by Dean Rovang[2] in which he quantified hydrogen flow rates, temperatures, and pressures that tend to minimize platform mass for a Ground Test Accelerator type of weapon. Based on his studies, we have selected a hydrogen flow rate of 8.13 kg/s, a weapon exit temperature of 165 K, and a pressure of 2.5 MPa for a weapon which produces a 20 MW charged beam (this is at the point in the weapon immediately preceding the beam neutralizer which removes the extra electron from the accelerated ion) and requires 38.46 MW of conditioned electrical power. This power level is derived from an accelerator efficiency of 80% and a radio frequency power conversion efficiency of 65%. Thus, 38.46 MWe is used by radio frequency generators to produce 25 MW of radio frequency power that is fed to the weapon's accelerator. We assumed a weapon operation time of 750 seconds which includes both testing and battle engagement time. For scaling studies, we also considered charged beam powers of 40 and 100 MW and operation times of 1000 and 1500 seconds.

Four systems were needed to meet the following four requirements.

Case 1. Hydrogen is "free" and both hydrogen and water vapor exhaust are acceptable. We interpret the assumption that hydrogen is free to mean that the power system can use up to the quantity of hydrogen required by the weapon, but the hydrogen's mass is not counted as part of the power system's mass.

Case 2. Hydrogen is not "free" but both hydrogen and water vapor exhaust are acceptable. Here, the mass of hydrogen required is an integral part of the power system mass and the hydrogen flows from storage directly to the power system without intermediate weapon cooling.

Case 3. Hydrogen is "free," hydrogen is an acceptable exhaust, but water vapor is not. This means that all water vapor generated must be retained by the power system.

Case 4. Hydrogen is not "free," hydrogen is an acceptable exhaust, but water vapor is not.

Besides the requirement for power, we assumed that the power system must expel its exhaust through a supersonic nozzle at 2000 m/s or more. We do not know if this velocity is sufficiently high to keep exhaust density below necessary limits. The required exhaust velocity depends on the quantity and composition of the gas being exhausted, the sensitivity of platform components to the exhaust, and the platform's geometry. Systems which generate more power will exhaust greater quantities of gas; thus, we expect the required exhaust velocity to increase as system power requirements increase. Increasing the required exhaust velocity above 2000 m/s will require added system mass and may favor higher turbine inlet temperatures for some of the systems. The 2000 m/s exhaust velocity requirement has a significant effect on design parameters, particularly for the "free" hydrogen system that exhausts both hydrogen and water vapor (case 1).

The first effect is brought about by requiring the turbine to use all of the hydrogen available from the weapon so that all fluids can be exhausted through the turbine and nozzle. This requirement makes the system for case 1 slightly heavier than it really needs to be. For this case, the turbine does not need all of the hydrogen supplied by the weapon, and an alternative is to combust the excess hydrogen with a small amount of oxygen and exhaust the excess combustion products through a nozzle instead of having it all pass through the turbine. Less total oxygen would be needed and the system would be lighter; however, the system would be slightly more complicated having an added combustion chamber and an added set of nozzles.

A second effect is brought about by requiring the turbine's outlet enthalpy to be sufficiently high to accelerate the exhaust to 2000 m/s. The third effect comes from requiring the systems that exhaust both hydrogen and water to have an exhaust temperature high enough so that the water in the exhaust cannot condense or freeze as it exits the nozzle. For case 1, these three effects cause the turbine pressure ratio to be lower than that which would minimize system mass if there was no exhaust velocity requirement, and more oxygen is required for combustion.

For case 2, the exhaust velocity requirement has less impact than for case 1 because pressure ratios which minimize system mass also provide turbine exit enthalpies which are high enough to power an exhaust velocity of 2000 m/s without added measures. The exhaust velocity requirement had almost no effect on cases 3 and 4 because only hydrogen is exhausted and it can be exhausted at a much lower temperature (we assumed 150 K) without condensing problems and because pure hydrogen has a higher specific enthalpy than does a mixture of hydrogen and water vapor at the same temperature.

Schematics for the four systems are shown in Figures 1a through 1d. In all of the cases, cold hydrogen is used to cool the alternator and power conditioning unit before entering the combustion process. These figures specify suggested temperatures, pressures, and flow rates. Values are approximate and should not be considered as absolute requirements for future designs.

COMPONENT DESCRIPTIONS

The two systems that retain water instead of exhausting it use a water condenser and combustion chamber in a configuration similar to that suggested by Sundstrand in Martin Marietta's Space Power Architecture Study.[3] It and other components will be discussed more thoroughly in the following paragraphs and in still more detail in Sandia's Space Power Information Base[1] and Models for Multimegawatt Space Power Systems.[4]

Hydrogen and Oxygen Subsystems--The hydrogen and oxygen subsystems consist of the stored hydrogen or oxygen, a tank, multifoil insulation, a refrigeration system, and a meteoroid shield. We assume that hydrogen and oxygen are stored at one atmosphere pressure and at a temperature of 20 K for hydrogen and 90 K for oxygen. The tanks are aluminum surrounded by multifoil insulation--4 cm for hydrogen and 2 cm for oxygen. The tanks are cooled using a reverse Brayton refrigeration system (proposed by Garrett in the Space Power Architecture

Studies[3,5,6]) which is powered by an SP-100 type of continuous power system and uses a 355 K radiator to dissipate heat. A hydrogen evaporation cooling system could have been used for cooling, but it would have added roughly 30% to the hydrogen subsystem's mass if operated for seven years compared to roughly 4% for refrigeration. The tank's aluminum meteoroid shield was designed to have a 99% survival probability over a seven year period. It may be possible to reduce the mass of the meteoroid shield by using several smaller tanks instead of a single large one and allowing some tanks to be lost to meteoroids. Our analysis shows that mass can be reduced by using multiple tanks, but the reduction is very small. We also estimated the size of a hydrogen tank debris shield, but its mass was not practical. A better method for protecting against debris will have to be found or platforms will have to operate in relatively debris free orbits. We have not done an analysis to see what effect multiple tanks might have relative to debris shielding. More thorough descriptions of hydrogen and oxygen subsystem algorithms are given in Reference 1, articles TMRF01, TMST01, and TMST02.

Combustion Chambers--The combustion chamber for a system which allows water vapor exhaust will mix and combust hydrogen and oxygen and send the combustion products on to the turbine. Algorithms for the combustion process can be found in Reference 1, article PSCB01. Reactants will flow to cool the walls as they are preheated. We did not estimate the mass of such a chamber because we believe it will not be significant compared to the mass of other components. An idea for a combustion chamber for the system in which water vapor exhaust is not allowed is shown in Figure 2. It is patterned after the one suggested by Sundstrand in Martin Marietta's Space Power Architecture Study.[3] In this combustor, cold hydrogen is used to condense water vapor in a condenser and is then divided into two paths--one which passes through a heat exchanger in the combustor where it is heated before entering the turbine, and one which is fed into the combustion chamber where it burns in oxygen. Thus, only hydrogen enters the turbine and the combustion products are kept separate from the turbine fluid. The combustion process is staged. The hydrogen is mixed with a little oxygen and combusted. At this point the mixture is rich in hydrogen and the temperature of the combustion products is much lower than for stoichiometric combustion. The combustion products transfer heat to hydrogen in the heat exchanger. Then, a little more oxygen is added and combusted, followed by more heat exchange. In the last stage, enough oxygen is added to burn the remaining hydrogen (the mixture must be kept within flammability limits) and the combustion product temperature is considerably below a stoichiometric combustion temperature because there is now steam in the mixture which absorbs part of the combustion heat. The combustion product steam is condensed by hydrogen in the condenser and uncombusted hydrogen and oxygen and uncondensed steam are recirculated to the combustion chamber.

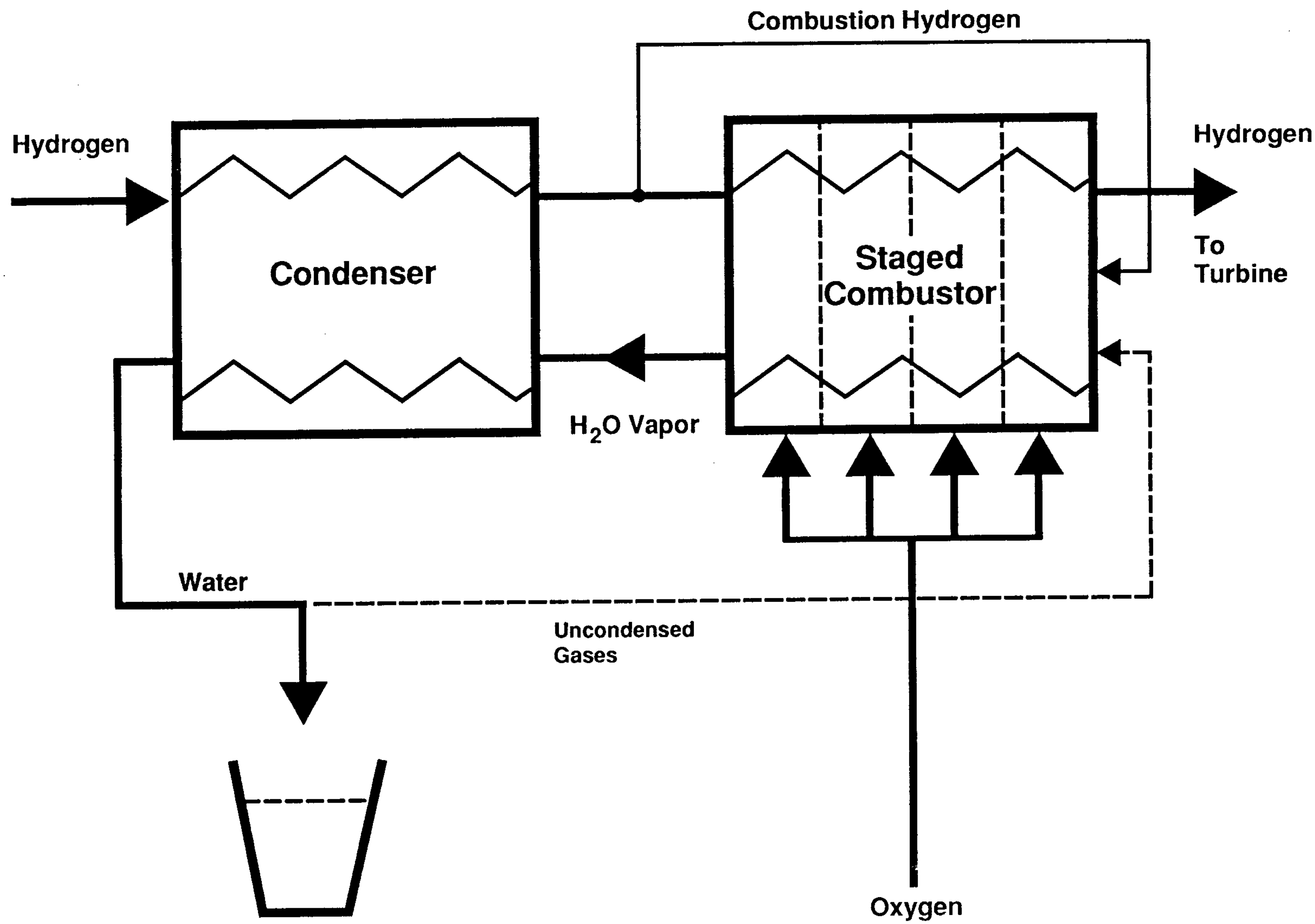

Figure 2. Hydrogen-Oxygen Combustion System With No Water Vapor Exhaust.

We have estimated the masses of the combustion chamber and condenser heat exchangers using the following procedure. The condenser is assumed to be a tube-and-shell type of shear flow condenser. The tubes are assumed to be 1.5 cm in diameter, have 3 mm thick walls, and are constructed from aluminum with a density of 2700 kg/m^3. Steam flows over the tubes and condenses with a heat transfer coefficient of 20,000 W/m^{2}K. Hydrogen flows through the tubes at 20 m/s and has a heat transfer coefficient found using the following relation.

$$Nu = .023\ Re^{.8}\ Pr^{.33}$$

This relation is for turbulent flow inside tubes. Nu is the Nusselt number, Re is the Reynold's number , and Pr is the Prandtl number. All are based on the properties of hydrogen at the average hydrogen temperature in the condenser. The steam and hydrogen heat transfer coefficients are combined with the wall resistance to find the total heat transfer coefficient. The total heat transfer coefficient, the average temperature difference between the two fluids in the heat exchanger, and the rate of heat transfer are combined to find the required heat exchange area. The heat exchange area is multiplied by wall thickness, by density, and by a factor of 2.0 to get condenser mass. The factor of 2.0 accounts for the heat exchanger's shell, manifolds, other necessary hardware, and design features needed to separate the liquid and vapor phases. It should be noted that the pressure difference across the heat exchange walls is very small.

The combustion chamber heat exchanger is sized in a similar manner. We assumed that it is a tube-and-shell type of counterflow heat exchanger with 1.5 cm diameter tubes. The tubes have a wall thickness of 2 mm and are constructed from nickel superalloy with a density of 8900 kg/m^3. Superalloy is used because of the high temperatures in the heat exchanger. A hot steam and hydrogen mixture which starts at 1700 K flows over the tube bundles at an assumed 12 m/s. The heat transfer coefficient on the outside of the tubes is found using the following expression.

$$Nu = .33\ Re^{.6}\ Pr^{.3}$$

This expression is for turbulent flow over tube bundles. Fluid properties at the entrance to the heat exchanger are based on the properties of a steam and hydrogen mixture when the proper ratio of hydrogen and oxygen are burned to give a combustion product temperature of 1700 K. These properties result in an entrance heat transfer coefficient. At the exit of the heat exchanger, all of the hydrogen and oxygen have been combusted so we have only steam. We assumed that heat exchange to the hydrogen has cooled the steam to a saturated vapor condition (497 K at 2.5 MPa). We used saturated vapor properties to calculate the heat transfer coefficient at the exit. Then we averaged the entrance and exit heat transfer coefficients to estimate the average heat transfer coefficient.

The hydrogen heat transfer coefficient inside the tubes was calculated in the same manner as for the condenser, but we used properties for the higher temperature hydrogen. The thermal conductivity of nickel superalloy is quite low for a metal, 15 W/mK. The inside and outside heat transfer coefficients were combined with the wall resistance to calculate the overall heat transfer coefficient. And, as before, we divided the heat transfer rate by the heat transfer coefficient and by the average temperature difference to find heat exchange area. Area multiplied by thickness, density, and a factor of 1.25 gave us mass. The factor of 1.25 accounts for the shell, manifolds, and other hardware. It was assumed to be smaller than for the condenser because separation of liquid from vapor is not a factor for this heat exchanger. Nevertheless, the combustor heat exchanger is several times as massive as the condenser because of lower heat transfer coefficients, higher heat exchange rates, and greater material density. (It should be possible to reduce heat exchanger mass significantly by increasing heat exchanger gas velocity and allowing a higher pressure drop.[7] Our recent calculations show this mass can be decreased by about a factor of three if a 3% pressure drop is assumed. If so, optimum turbine inlet temperatures may change slightly for the systems which do not allow water exhaust.)

<u>Turbines</u>--The turbines assumed for this application are constructed from a nickel superalloy which allows temperatures up to 1350 K without cooling. However, turbines for the "hydrogen free" cases can use stainless steel because their inlet temperatures are below the temperature limit for stainless steel. Turbine working fluid is a mixture of hydrogen and water vapor for the systems where water vapor is an acceptable exhaust. When water vapor is not acceptable, the turbine uses pure hydrogen. We assumed that turbine disks are cooled to 900 K or less to reduce the number of stages needed, and that blade cooling is only used when turbine inlet temperature exceeds 1350 K. We assumed turbine speeds of 10,000 rpm because we believe that near-term alternators can achieve this speed. Turbine geometries and performance parameters were estimated using Steve Hudson's gas turbine model[1] articles ECTU01 and ECTU02.

We have included a flywheel energy storage unit to remind us that some sort of energy storage may be necessary as a means of gracefully handling weapon and battle transients. We arbitrarily assumed that the energy storage system must provide power at the peak rate for 10 s. Eventually, the proper storage capacity will be determined by engagement scenario and system fault studies. We also assume that the flywheel has a specific energy of 100 Wh/kg, which is based on what we judge to be near-term flywheel technology.

Alternators--We assumed the use of iron core alternators with cryogenic hydrogen for cooling and speeds of 10,000 rpm. Alternator mass is assumed to be 0.1 kg/kW, and efficiency is assumed to be 95%. Hyperconducting and superconducting alternators have been proposed by Westinghouse and GE, and these might offer lower mass, 0.02 to 0.05 kg/kW, and higher efficiency, 98 to 99%. These alternators could reduce the mass of the power system, but would change the basic design very little. Cooling system implications should be evaluated before adopting either of them. We have not assumed an alternator voltage. Wright Aeropropulsion Lab is having high voltage alternators developed. If voltages in the range of 75 kV to 100 kV can be achieved, power conditioning mass can be reduced dramatically because step-up transformers will be unnecessary to obtain the 100 kV or so needed by an NPB weapon's radio frequency converters.

Power Conditioning--We assumed that power conditioning weighs 0.2 kg/kW and has an efficiency of 95%. The Space Power Architecture[3,5,6] contractors estimated masses between 0.014 and 0.46 kg/kW for NPB power conditioning depending on the voltage of the source and the efficacy of cryocooling the power conditioning unit. Our 0.2 kg/kW serves as a place holder until we get more definitive mass values for power conditioning. We expect that any technical developments would be uniformly applicable to the different systems considered in this study and would not change our results.

Miscellaneous--We add 10% to the component subtotal to account for structure, piping, and other hardware we have neglected or forgotten.

REFERENCE POWER SYSTEM CONCEPTUAL DESIGNS

Figures 3,4,5, and 6 show combustion power system mass estimates for the four different cases as a function of turbine inlet temperature. The power system shown for each temperature has already been optimized with respect to turbine pressure ratio. This optimization is important because turbine mass, hydrogen mass, and oxygen subsystem mass are very sensitive to pressure ratio. In general, as pressure ratio increases, turbine mass increases because stages have to be added to the large, exit end of the turbine. But, hydrogen and oxygen subsystem masses decrease because the turbine is extracting more enthalpy from the working fluid and less working fluid is needed. Thus, the optimization trades off turbine mass for hydrogen and oxygen subsystem mass. This is not specifically true for cases where turbine outlet enthalpy is restricted by nozzle requirements as described earlier.

These graphs also show a very interesting relation between oxygen use and turbine inlet temperature. Higher turbine inlet temperatures require that the ratio of oxygen to hydrogen increase because more combustion heat is needed to heat the working fluid. At the same time, higher turbine inlet temperature results in lower working fluid flow rates. The combined effect of these two things is that the mass of oxygen can decrease as turbine inlet temperature increases because less working fluid is used, but then, at some temperature, the oxygen subsystem mass starts to increase because its ratio to hydrogen increases to achieve the desired turbine inlet temperature. The result is that a turbine inlet temperature exists which minimizes the use of oxygen.

The following sections will discuss the reference power system for each of the four cases in more detail.

Case 1: Hydrogen is Free and Water Exhaust is Acceptable--
Figure 3 shows how system mass and the mass of each component depends on turbine inlet temperature. The only significant difference between the masses of these systems is due to the oxygen subsystem mass. Hydrogen subsystem mass is fixed by the weapon cooling requirement and oxygen increases as turbine inlet temperature increases because more of it must be burned with hydrogen to get the desired combustion product temperature. The system with a minimum mass has a turbine inlet temperature around 850 K, and this is the one we have chosen as a reference system; however, temperatures up to 1000 K would not increase mass by much and these differences are within the accuracy of our models. Using lower temperatures, on the other hand, would increase mass significantly because excess hydrogen is necessary. Notice that the 800 K system needs more hydrogen than the weapon supplies. That is because weapon hydrogen is not sufficient to power the turbine when nozzle velocity requirements are imposed. In other words, pressure ratio had to be reduced to the point where extra hydrogen was needed in order to provide adequate turbine outlet enthalpy to accelerate exhaust gases to 2000 m/s. Table 2 gives suggested parameter values for this power system. Others are given in Figure 1a.

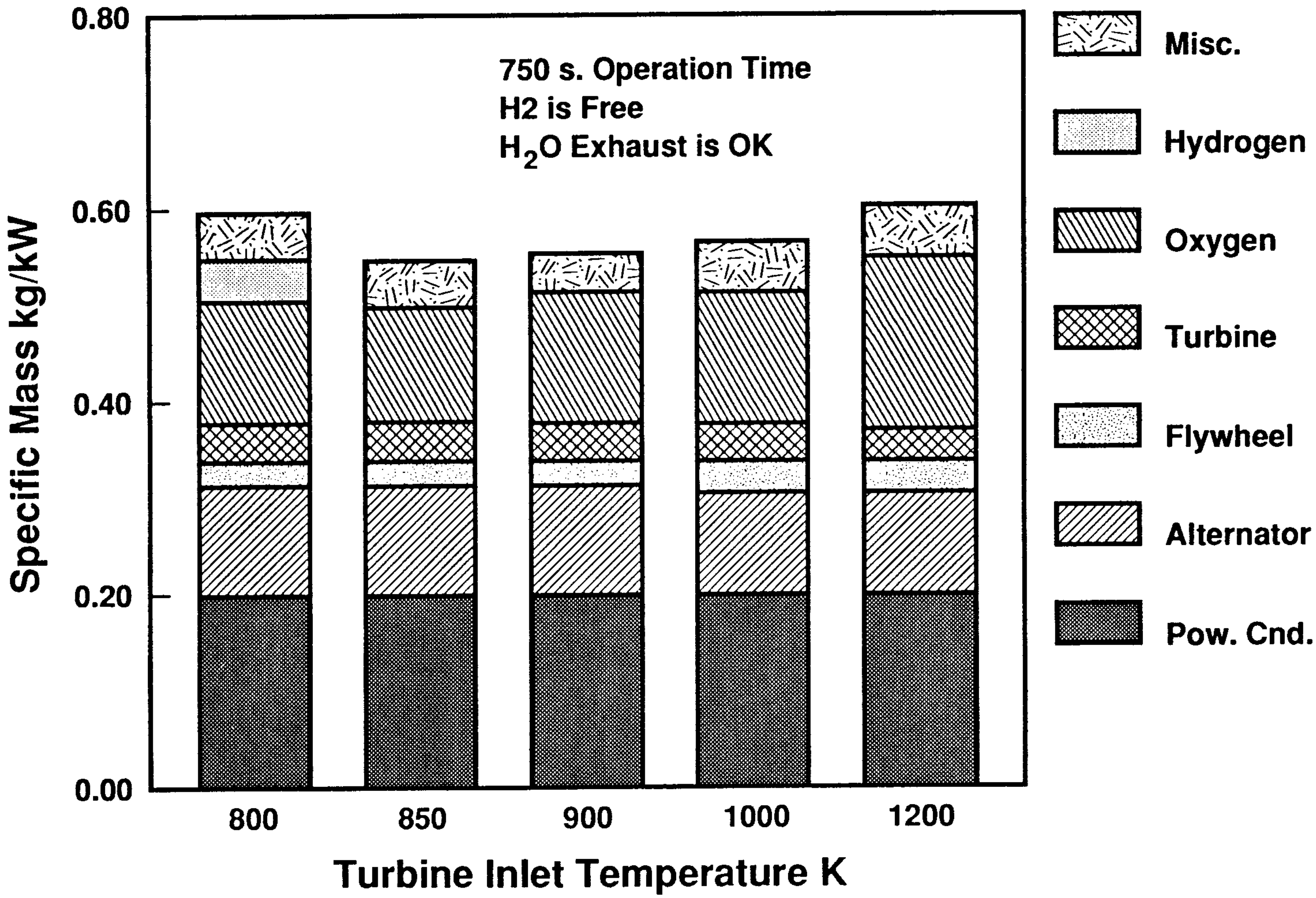

Figure 3. 38.46 MW H2-O2 Combustion Reference Power System.

Table 2. Case 1
38.46 MW H2-O2 Combustion Reference Power System
750 Second Operation
Hydrogen is Free
Water Vapor Exhaust is Acceptable

Turbine inlet temperature	850 K
Turbine inlet pressure	2.5 MPa
Turbine pressure ratio	15.4
Turbine outlet temperature	501 K
Turbine efficiency	77%
Turbine and alternator speed	10,000 rpm
Turbine work coefficient	4
Turbine disk temperature	850 K
Turbine material	Ni superalloy or stainless
Turbine stages	7
Number of turbines	4
Nozzle outlet velocity	2040 m/s
Pump power (H2 & O2)	.41 MW
Refrigeration power (H2 & O2)	6.3 kW

Mass Estimates (metric tons)	
Hydrogen Subsystem	0.0 (hydrogen is free)
Oxygen subsystem	
Oxygen	4.2
Tank	.008
Insulation	.02
Refrigeration	.01
Meteoroid shield	.3
Turbine	1.5
Alternator	4.1
Flywheel	1.2
Power conditioning	7.7
Miscellaneous	1.9
Total	21.0 Mg

Case 2: Hydrogen is Not Free, Water Vapor Exhaust is Acceptable--Figure 4 shows system and component masses for various turbine inlet temperatures. As temperature increases, turbine mass increases up to 1350 K and then remains fairly constant, the hydrogen subsystem gets lighter, and the oxygen subsystem gets lighter up to 1500 K before it starts increasing. Between 1350 K and 1700 K, system mass is fairly constant (it starts to increase again at 1800 K which is not shown on the chart), but we selected the 1350 K system as our reference power system. We selected it because it was very close in mass to those with temperatures up to 1700 K and its turbine does not need blade cooling. We believe that simplifying the system by having no blade cooling is worth the small added mass. (We could also have selected a turbine inlet temperature as low as 1200 K with very little mass penalty.) This system optimizes at a much higher turbine inlet temperature than the previous one because hydrogen is not free. The turbine goes to a higher temperature and pressure ratio to save hydrogen even though its own mass is increased. Table 3 and Figure 1b give system parameter values.

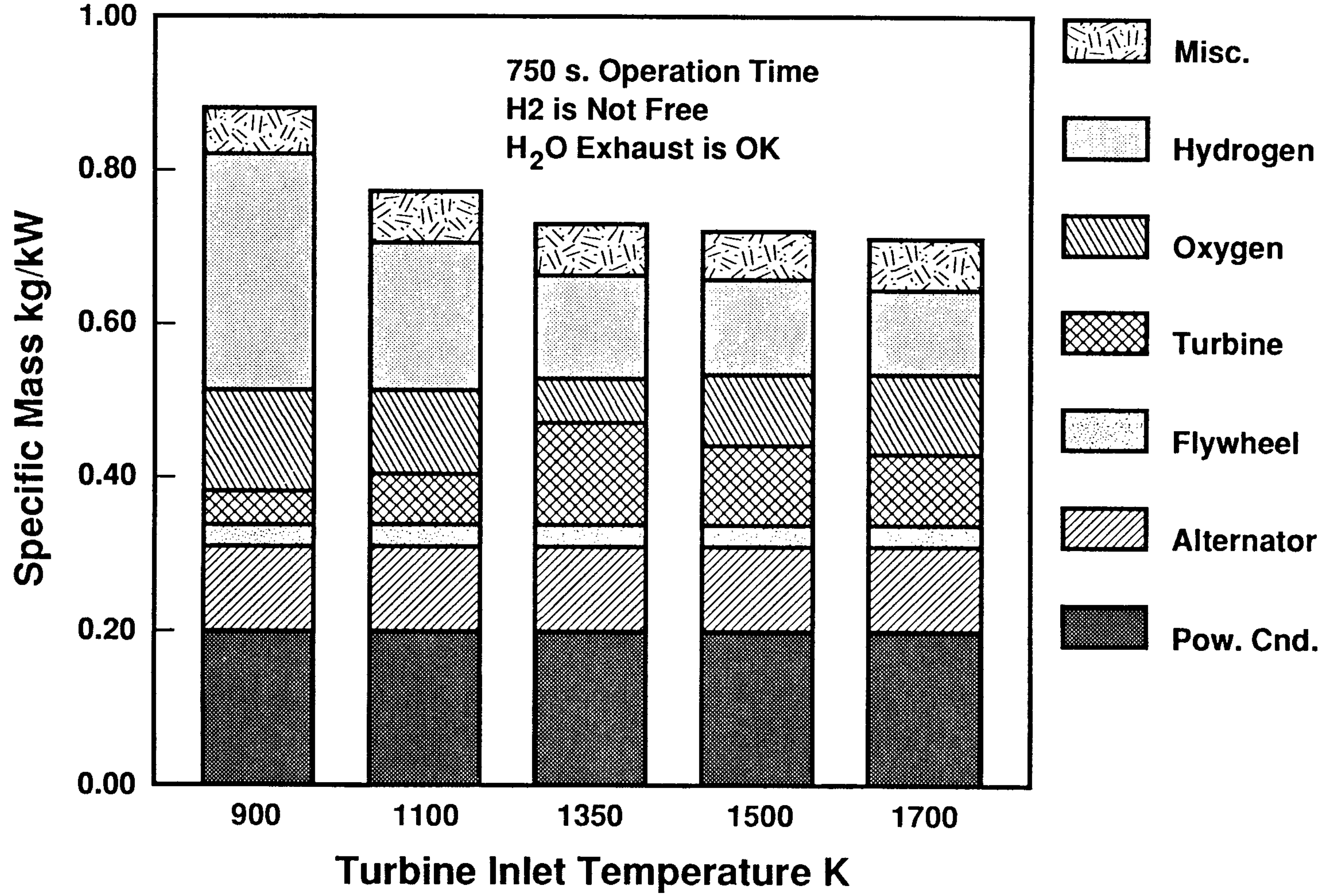

Figure 4. 38.46 MW H2-O2 Combustion Reference Power System.

Table 3. Case 2
38.46 MW H_2-O_2 Combustion Reference Power System
750 Second Operation
Hydrogen is Not Free
Water Vapor Exhaust is Acceptable

Turbine inlet temperature	1350 K
Turbine inlet pressure	2.5 MPa
Turbine pressure ratio	165
Turbine outlet temperature	534 K
Turbine efficiency	82%
Turbine and alternator speed	10,000 rpm
Turbine work coefficient	4
Turbine disk temperature	900 K
Turbine material	Ni superalloy
Turbine stages	15
Number of turbines	4
Nozzle outlet velocity	2032 m/s
Pump power (H_2 & O_2)	.17 MW
Refrigeration power (H_2 & O_2)	3.4 kW

Mass Estimates (metric tons)	
Hydrogen subsystem	
Hydrogen	2.4
Tank	.07
Insulation	.2
Refrigeration	.3
Meteoroid shield	2.2
Oxygen subsystem	
Oxygen	3.3
Tank	.006
Insulation	.02
Refrigeration	.01
Meteoroid shield	.3
Turbine	3.8
Alternator	4.1
Flywheel	1.2
Power conditioning	7.7
Miscellaneous	2.6
Total	28.1 Mg

This system is not restricted to a turbine inlet pressure of 2.5 MPa, which was the pressure dictated by the weapon. Since hydrogen is not free, the power system will not use weapon hydrogen but will carry its own supply and can operate at a pressure which is most beneficial to it. We could have used a higher pressure which would reduce turbine mass a little.

Case 3: Hydrogen is Free, Water Vapor Exhaust is Not Acceptable--Masses for this system are shown in Figure 5. Turbine mass decreases as turbine inlet temperature increases. At the same time, oxygen subsystem mass increases. The net effect is that system mass would not be very sensitive to temperature except for the condenser and combustor heat exchangers. Heat exchanger mass increases significantly with turbine inlet temperature. This is because more heat must be transferred across the combustor heat exchanger and its temperature difference is reduced because of the higher turbine inlet temperature. As a result, these systems optimize at even lower temperatures than for the case where hydrogen is free and water vapor exhaust is acceptable. The lowest mass system is at 600 K, but we have selected 700 K as a reference design. At 600 K the turbine design is more tenuous than at 700 K because blade lengths are getting rather short and a lower work coefficient must be used. We decided to avoid possible design problems by selecting the 700 K system. By comparing Figures 3 and 5 and Tables 2 and 4, one can see that the water removal system is only 14% heavier than the system for which water exhaust is acceptable even though the equipment used to retain water adds 17% to the mass of its system. There is a small benefit to retaining water--the water vapor's enthalpy of evaporation is recovered rather than exhausted. Also, the turbine can have a higher enthalpy extraction because its exhaust temperature is not constrained since only hydrogen is exhausted and hydrogen does not have potential condensation problems at the nozzle exit. But, the benefits do not overcome the mass of the heat exchangers.

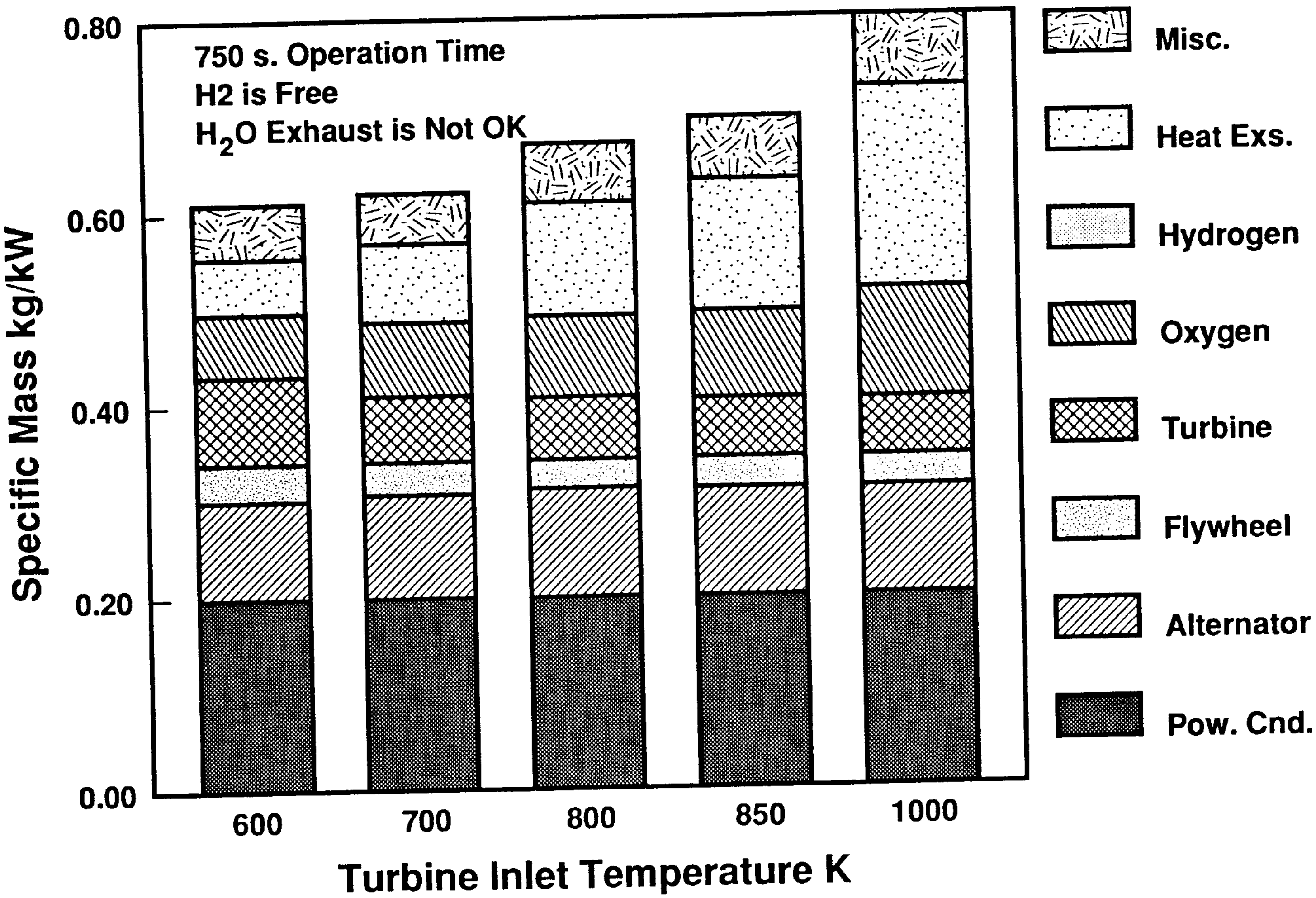

Figure 5. 38.46 MW H2-O2 Combustion Reference Power System.

Table 4. Case 3
38.46 MW H2-O2 Combustion Reference Power System
750 Second Operation
Hydrogen is Free
Water Vapor Exhaust is Not Acceptable

Turbine inlet temperature	700 K
Turbine inlet pressure	2.5 MPa
Turbine pressure ratio	98
Turbine outlet temperature	321 K
Turbine efficiency	75%
Turbine and alternator speed	10,000 rpm
Turbine work coefficient	5
Turbine disk temperature	700 K
Turbine material	Ni superalloy or stainless
Turbine stages	11
Number of turbines	4
Nozzle outlet velocity	2460 m/s
Pump power (H2 & O2)	0.41 MW
Refrigeration power (H2 & O2)	6.2 kW
Mass Estimates (metric Tons)	
Hydrogen subsystem	0.0 (hydrogen is free)
Oxygen subsystem	
Oxygen	2.7
Tank	.005
Insulation	.01
Refrigeration	.01
Meteoroid shield	.2
Water Condenser	.2
Combustor heat exchanger	3.0
Turbine	2.7
Alternator	4.1
Flywheel	1.2
Power conditioning	7.7
Miscellaneous	2.2
Total	24.0 Mg

Case 4: Hydrogen is Not Free, Water Vapor Exhaust is Not Acceptable--Figure 6 shows mass estimates for this system. As in the previous one, the heat exchangers force us to a relatively low turbine inlet temperature. The minimum mass system has a turbine inlet temperature of 900 K, and this is the one we have selected as a reference system; although, temperatures as low as 800 or as high as 1000 K would give an insignificant mass increase.

Table 5. Case 4
38.46 MW H2-O2 Combustion Reference Power System
750 Second Operation
Hydrogen is Not Free
Water Vapor Exhaust is Not Acceptable

Turbine inlet temperature	900 K
Turbine inlet pressure	2.5 MPa
Turbine pressure ratio	250
Turbine outlet temperature	359 K
Turbine efficiency	77%
Turbine and alternator speed	10,000 rpm
Turbine work coefficient	5
Turbine disk temperature	900 K
Turbine material	Ni superalloy
Turbine stages	17
Number of turbines	4
Nozzle outlet velocity	2700 m/s
Pump power (H2 & O2)	0.3 MW
Refrigeration power (H2 & O2)	5.0 kW
Mass Estimates (metric Tons)	
Hydrogen subsystem	
Hydrogen	4.4
Tank	.1
Insulation	.2
Refrigeration	.4
Meteoroid shield	3.7
Oxygen subsystem	
Oxygen	3.2
Tank	.005
Insulation	.01
Refrigeration	.01
Meteoroid shield	.3
Water condenser	.2
Combustor heat exchanger	4.1
Turbine	4.5
Alternator	4.1
Flywheel	1.2
Power conditioning	7.7
Miscellaneous	3.4
Total	37.4 Mg

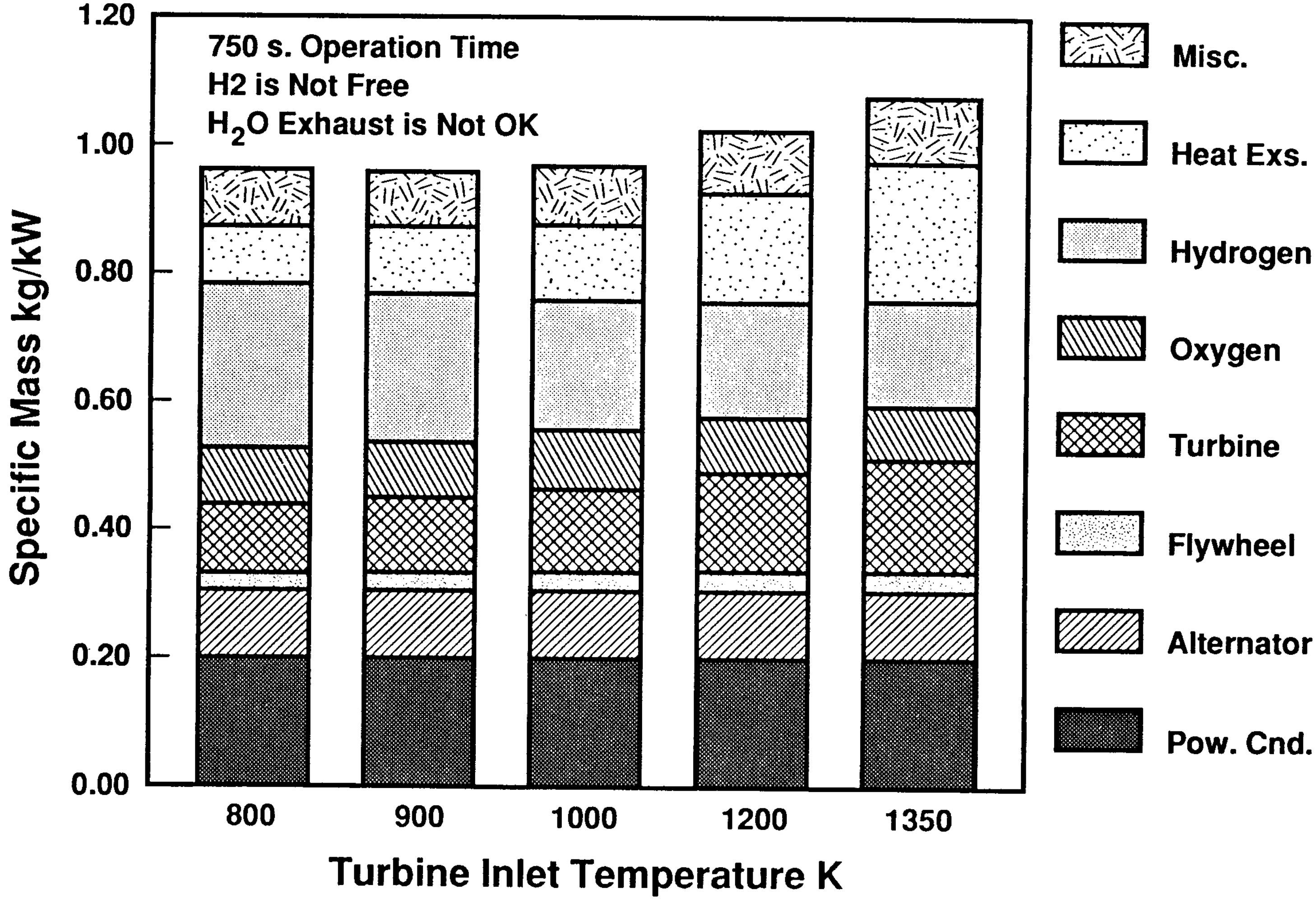

Figure 6. 38.46 MW H2-O2 Combustion Reference Power System.

POWER LEVEL AND RUN TIME SCALING

The following figures show how the system's design changes for different power levels (38.46, 76.92, and 192.3 MW corresponding to 20, 40, and 100 MW charged beams) and for different operation times (750, 1000, and 1500 s). In general, different power levels and run times will encourage parameters to be optimized at different values. For example, longer run times require greater fuel masses. The optimization will try to reduce the fuel mass at the expense of making the turbine heavier by using a higher pressure ratio or a higher turbine inlet temperature and thereby increasing enthalpy extraction from the working fluid. Also, very high power levels may require relatively high turbine mass because lower speeds or lower work coefficients are necessary to avoid exceeding blade or disk strength limits. This will tend to encourage the use of lower turbine inlet temperature or lower pressure ratios. As can be seen from the following figures, some parameters have a weak dependence on power level and run time over the ranges considered. Optimum turbine inlet temperature decreases from 1350 K at 76.92 MW to 1300 K at 192.3 MW for the hydrogen not free system with water exhaust acceptable. Optimum turbine inlet temperature increases from 900 K at 1000 s to 1000 K at 1500 s for the hydrogen not free, water not acceptable system. Pressure ratios decrease as power increases for all but the free hydrogen, water acceptable case. In our analyses and plotted data, we used temperature increments of 50 or 100 K; thus, small but steady changes in parameter values cannot be seen in our results. The results do, however, illustrate trends. We generally assumed the use of four turbines for each power system. For some of the higher power systems, large turbine designs were not practical and more than four had to be used. For example, six turbines were required for the 192.3 MW hydrogen not free, water not acceptable system.

CONCLUSIONS

We have described reference concepts for a hydrogen-oxygen combustion, space power system. These concepts are intended to serve as a reference, or "baseline," to which other "burst mode" power systems can be compared. For each of these systems, we have suggested design parameter values which minimize power system mass based on our current understanding of power system requirements and our current ability to estimate component masses. The suggested parameter values should be viewed as approximate and should not be considered as absolute requirements for future designs. Many of them will change as our understanding of the system and our ability to accurately model components improve.

The results suggest some technology development directions. Turbines that use pure hydrogen or a mixture of hydrogen and steam will be needed depending on whether water vapor is an acceptable exhaust. In either case, they will require relatively high work coefficients in the range of around 4 to 5, and they will need a variety of pressure ratios, from around 15 up to 250, depending on the system's requirements. Turbines for this application will not need exotic, high temperature materials since turbine inlet temperatures range from 700 to 1350 K. Steel turbines at the low temperatures and nickel superalloy turbines for the higher temperatures are adequate, and these are standard materials used in current turbines. Disk cooling will be beneficial, but blade cooling appears to be unnecessary. Low mass turbine-alternator combinations and power conditioning units are needed as are reliable refrigeration units to keep hydrogen and oxygen supplies cool. Low mass meteoroid shields are required for hydrogen and oxygen tanks and other system components, and some effort is required to address the space debris shielding problem. Debris shields are unacceptably heavy using current shield technology in high debris orbits.

We believe that these reference concepts point in the right general direction and that our results can be used to help guide technology development and to help define future reference concepts.

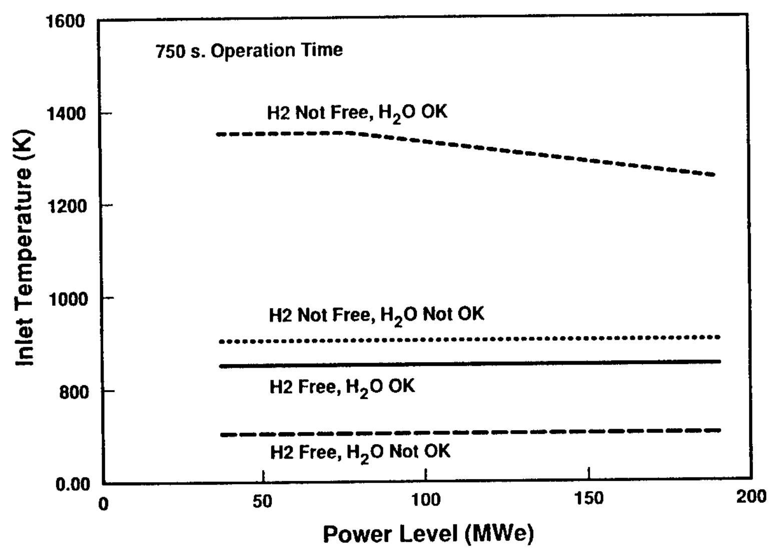

Figure 7. Optimum Turbine Inlet Temperature Depends Weakly on Power Level.

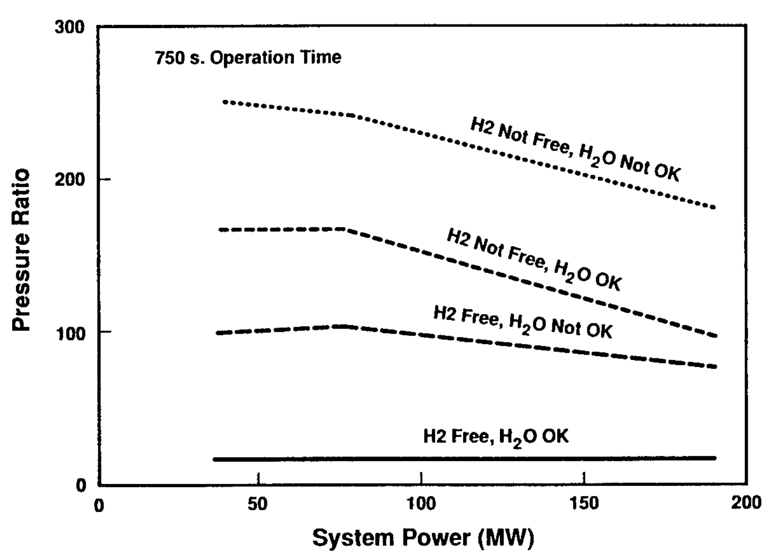

Figure 8. Optimum Turbine Pressure Ratio Depends on Power Level.

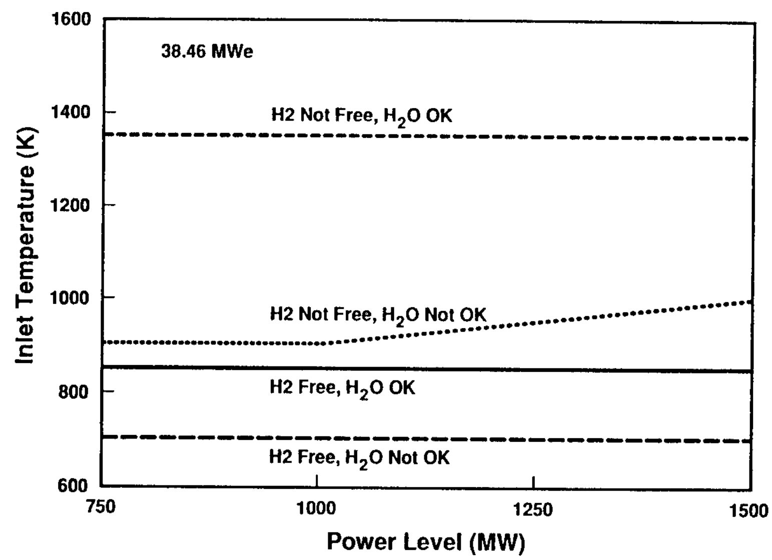

Figure 9. Optimum Turbine Inlet Temperature Depends Weakly on Operation Time.

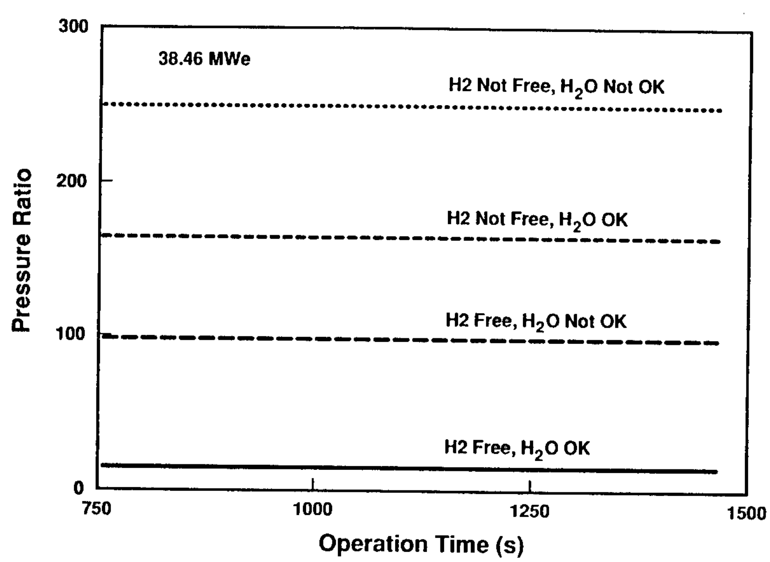

Figure 10. Optimum Turbine Pressure Ratio Is Not Sensitive to Operation Time.

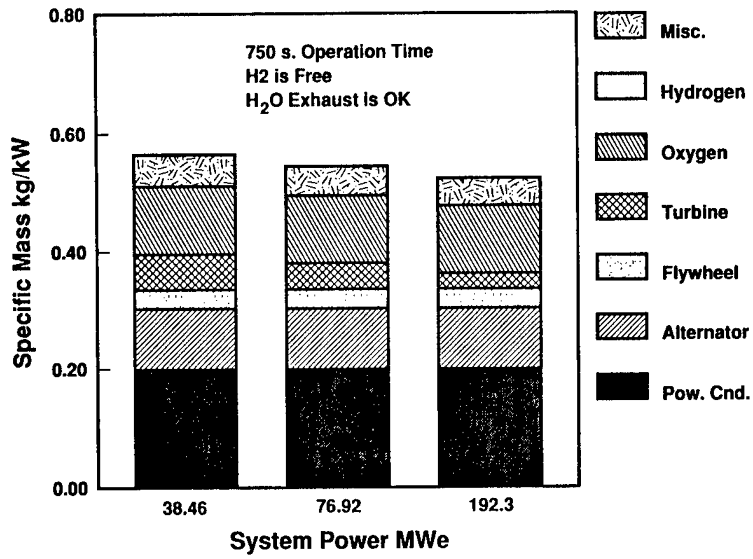

Figure 11. H2-O2 Combustion Reference Power System -- 750 s. Operation Time; H2 is Free; H_2O Exhaust is OK.

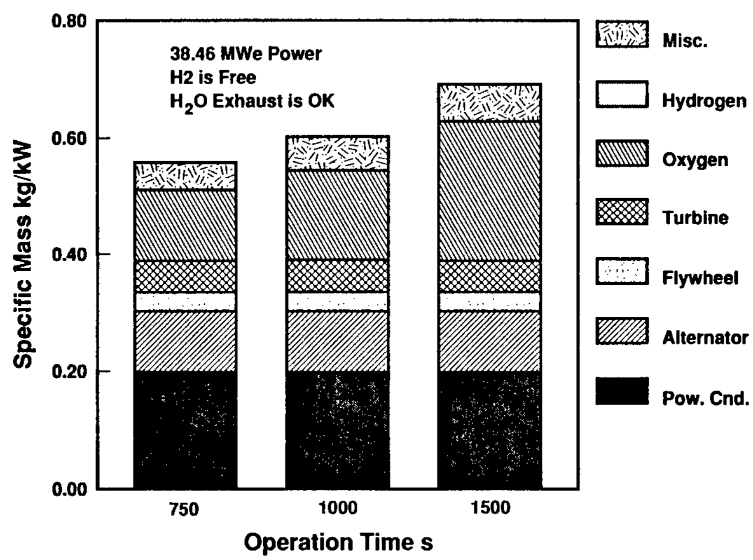

Figure 12. H2-O2 Combustion Reference Power System -- 38.46 MWe Power; H2 is Free; H_2O Exhaust is OK.

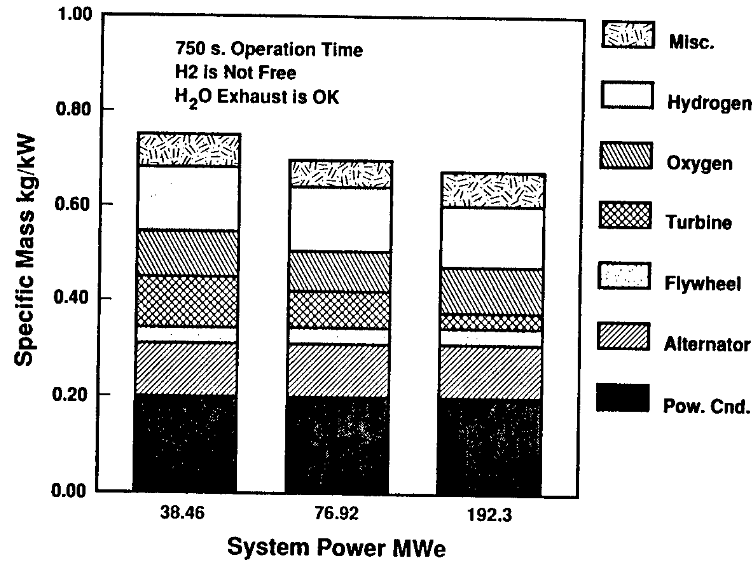

Figure 13. H2-O2 Combustion Reference Power System -- 750 s. Operation Time; H2 is Not Free; H_2O Exhaust is OK.

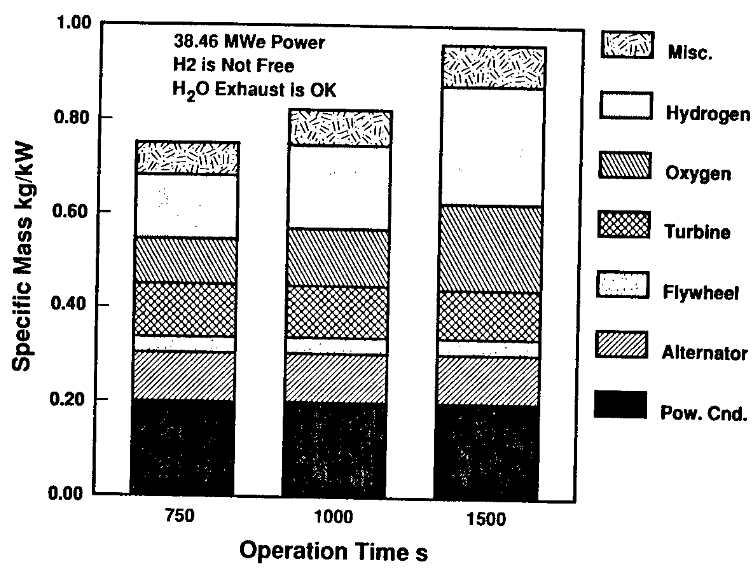

Figure 14. H2-O2 Combustion Reference Power System -- 38.46 MWe Power; H2 is Not Free; H_2O Exhaust is OK.

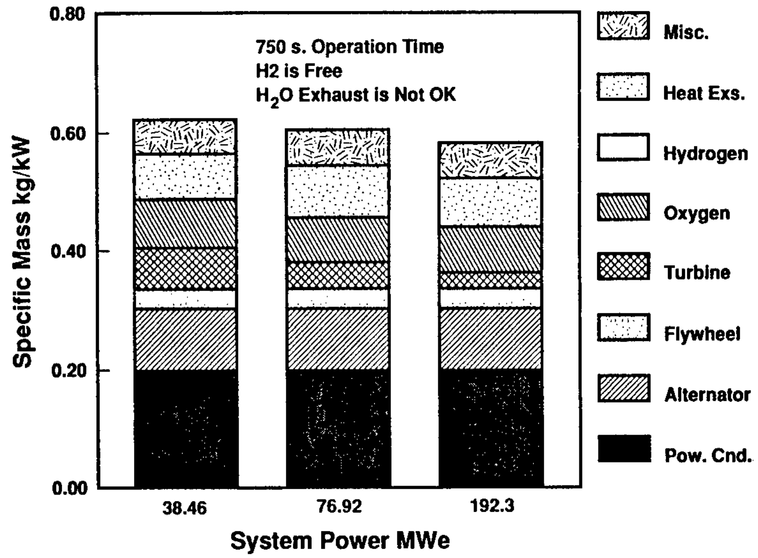

Figure 15. H2-O2 Combustion Reference Power System -- 750 s. Operation Time; H2 is Free; H_2O Exhaust is Not OK.

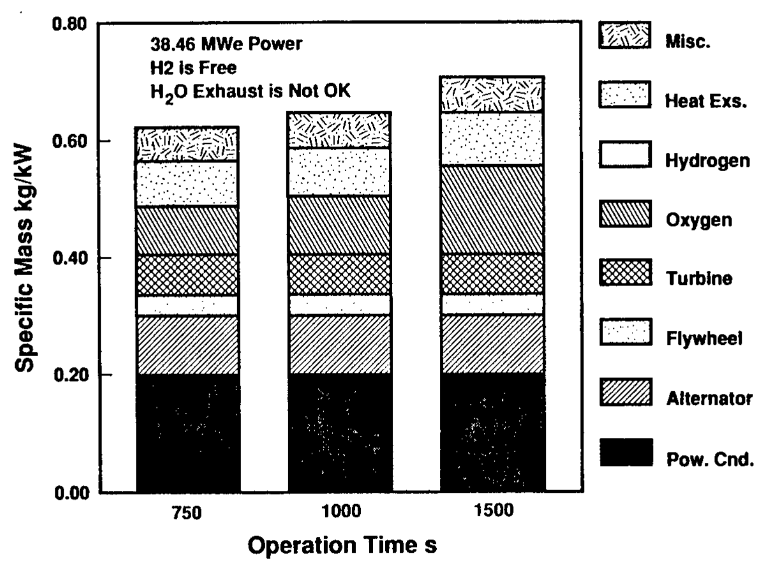

Figure 16. H2-O2 Combustion Reference Power System -- 38.46 MWe Power; H2 is Free; H_2O Exhaust is Not OK.

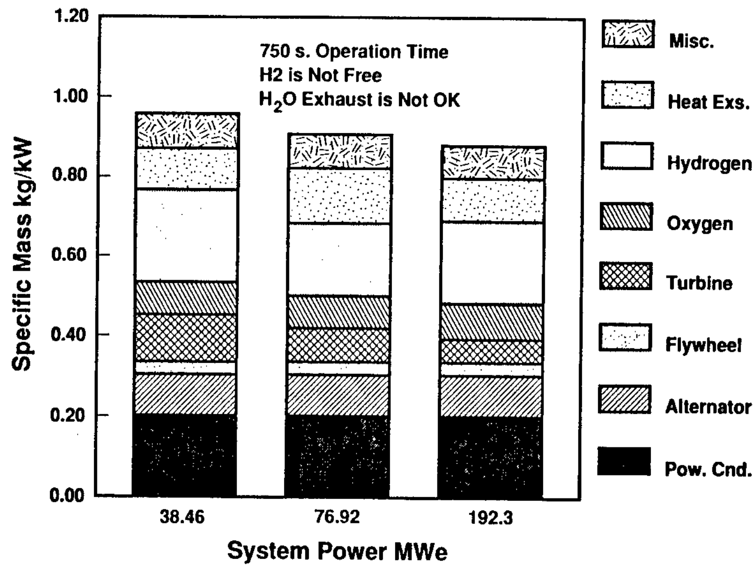

Figure 17. H2-O2 Combustion Reference Power System -- 750 s. Operation Time; H2 is Not Free; H_2O Exhaust is Not OK.

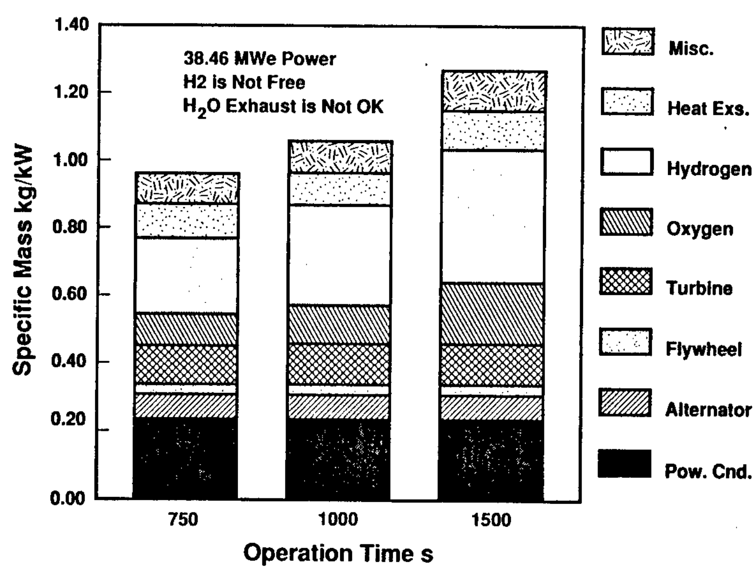

Figure 18. H2-O2 Combustion Reference Power System -- 38.46 MWe Power; H2 is Not Free; H_2O Exhaust is Not OK.

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Julio C. Acevedo
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Lewis Research Center
21000 Rd.
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Dr. C. A. Aeby
WL/NTC
Weapons Laboratory
Kirtland AFB, NM 87117

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Kirtland AFB, NM 87117

Douglas Allen
W. J. Schafer Associates
1901 No. Ft. Myers Drive
Suite 800
Arlington, VA 22209

L. Amstutz
U.S. Army Belvoir RDE Ctr.
STRABE-FGE
Fort Belvoir, VA 22060-5606

Larry Atha
U.S. Army Strategic Defense Com.
106 Wynn Drive
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Lt. Dale Atkinson
WL/NTCA
Weapons Laboratory
Kirtland AFB, NM 87117

H. S. Bailey
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General Electric NSTO
310 DeGuigne Drive
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Major W. Barattino
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J. O. Barner
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P. O. Box 999
Richland, WA 99352

D. Bartine
Oak Ridge National Laboratory
P. O. Box Y
Bldg 9201-3, MS-7
Oak Ridge, TN 37831

Ormon Bassett
W. J. Schafer Associates
1901 No. Ft. Myers Drive
Suite 800
Arlington, VA 22209

Ms. Kathleen Batke
NASA Lewis Research Center
Research/Technology Branch
21000 Brookpark Road
MS 3350
Cleveland, OH 44135

J. Beam
AFWRDC/POOS
Wright-Patterson Air Force Base
Ohio 45433

J. A. Belisle
Manager, Energy Programs
Grumman Aerospace Corp.
MS B20-05
Bethpage, NY 11714

C. Bell
Los Alamos National Laboratory
P.O. Box 1663
MS-F611
Los Alamos, NM 87545

D. Bennett
U. S. Department of Energy
NE-521
Germantown, MD 20874

RP/Gary Bennett
NASA Headquarters
600 Independence Ave.
Washington, DC 20546

David Bents
NASA Lewis Research Center
21000 Brookpark Road
MS 301-5, Rm. 101
Cleveland, OH 44135

J. A. Bernard
Massachusetts Institute of Technology
1328 Albany Street
Cambridge, MA 02139

Dave Berwald
Grumman Aerospace Corporation
MS B20-05
Bethpage, NY 11714

F. Best
Assistant Professor
Texas A&M University
Nuclear Engineering Dept.
College Station, TX 77843-3133

Mark Bezik
NASA Lewis Research Center
3160
21000 Brookpark Rd.
Cleveland, OH 44135

Samit K. Bhattacharyya
Argonne National Laboratory
9700 So. Cass Avenue
Bldg. 207
Argonne, IL 60439-4841

H. S. Bloomfield
Program Manager
NASA Lewis Research Center
MS 301-5, Rm. 103
21000 Brookpark Road
Cleveland, OH 44135

Ron Boatwright MS-L-8030
Attn: Document Control
Martin Marietta Space Systems
P O Box 179
Denver, CO 80201

Richard J. Bohl
Los Alamos National Laboratory
MS K560
P. O. Box 1663
Los Alamos, NM 87545

James Bolander
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

William Borger
AFWRDC/POOA
Aeronautical Laboratory
Wright Patterson AFB
Ohio 45433

S. Borowski
NASA Lewis Research Center
MS: 501-6
21000 Brookpark Road
Cleveland, OH 44135

D. Bouska
U.S. Army Strategic Defense Command
106 Wynn Drive
Huntsville, AL 35807

T. Bowden
Brookhaven National Laboratory
P. O. Box 155
Upton, NY 11973

Robert Boyle
Garrett Fluid Systems Co.
P. O. Box 5217
Phoenix, AZ 85010-5217

Mr. Dick Bradshaw
CSSD-H-SAV
US Army Strategic Defense Command
106 Wynn Drive
P. O. Box 1500
Huntsville, AL 35807-3801

Bruce Bremer
Riverside Research Institute
1701 No. Ft. Meyers Drive
Suite 700
Arlington, VA 22209

Jerry Bueck
W. J. Schafer Associates
2000 Randolph Road, SE
Suite 205
Albuquerque, NM 87106

Wade Carroll
U.S. Department of Energy
NE 52
Germantown Building
Washington, DC 20545

R. D. Casagrande
General Electric
Astro Systems
P. O. Box 8555
Philadelphia, PA

L. Cavery
SDIO/IST
Washington, DC 20301-7100

B. Chadsey
SAIC
1710 Goodridge Drive
McLean, VA 22101

T. S. Chan
General Electric
Astro Systems/SCO
P. O. Box 8555
35T15, Bldg. 20
Philadelphia, PA 19101

John W. H. Chi
Westinghouse Electric Corp.
Advanced Energy Systems
P.O. Box 158
Madison, PA 15663

W. Chiu
General Electric
Space Systems Division
Valley Forge Space Center
P. O. Box 8555
Rm. 35T20, Bldg. 20
Philadelphia, PA 19101

Paul Chivington
TRW, Inc.
Suite 200
2340 Alamo, Se
Albuquerque, NM 87106

Lynn Cleland
Lawrence Livermore National Laboratory
P.O. Box 808
MS L-144
Livermore, CA 94550

Robert Cooper
MS MS-241
Aerospace Corporation
P. O. Box 92957
Los Angeles, CA 90009-2957

E. P. Coomes
Battelle Pacific Northwest Laboratory
P. O. Box 999
Richland, WA 99352

Carl Cox
Westinghouse Hanford
MS C-27
P.O. Box 1970
Richland, WA 99352

Cecil Crews
MS M5-614
Aerospace Corporation
P. O. Box 92957
Los Angeles, CA 90009-2957

J. Crissey
W. J. Schafer Associates
1901 No. Ft. Myers Drive
Suite 800
Arlington, VA 22209

R. Dahlberg
General Atomics
P. O. Box 85608
San Diego, CA 92138

Dr. Gracie E. Davis
RAEE
HQ Defense Nuclear Agency
6801 Telegraph Road
Alexandria, VA 22213

Dan DeLong
Teledyne Brown Engineering
Cummings Research Park
Huntsville, AL 35807

R. Dewitt
Naval Surface Weapons Ctr.
Code F-12
Dahlgren, VA 22448-5000

N. Diaz
INSPI
202 NSC
University of Florida
Gainesville, FL 32611

P. W. Dickson
EG&G Idaho, Inc./INEL
P. O. Box 1625
Idaho Falls, ID 83415

P. J. Dirkmaat
U.S. Department of Energy/Idaho
785 DOE Place
Idaho Falls, ID 83402

J. DiTucci
AF Space Technology Ctr.
SWL
Kirtland AFB, NM 87117-6008

M. P. Dougherty
Martin Marietta Corporation
Astronautics Group
Space Systems
P.O. Box 179
Denver, CO 80201

Rudy Duscha
NASA Lewis Research Center
PSIO
21000 Brookpark Rd.
Cleveland, OH 44135

Mr. Richard Dudney
CSSD-H-YA
US Army Strategic Defense Command
106 Wynn Drive
P. O. Box 1500
Huntsville, AL 35807-3801

D. S. Dutt
Manager, Fuel Design
Westinghouse Hanford
Engineering Development Lab.
P. O. Box 1970
Richland, WA 99352

G. Edlin
U.S. Army Strategic Defense Cm.
106 Wynn Drive
Huntsville, AL 35807

R. L. Eilbert
Naval Research Laboratory
Washington, DC 20375-5000

M. El-Genk
University of New Mexico
Chemical and Engineering Department
Albuquerque, NM 87131

Jeffrey George
MS 501-6
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

David M. Ericson
ERC
1717 Louisiana NE
Suite 202
Albuquerque, NM 87110

D. Escher
TRW
One Space Park
Redondo Beach, CA 90278

J. Farber
Defense Nuclear Agency
RAEV
6801 Telegraph Road
Alexandria, VA 22310-3398

G. Farbman
Westinghouse
Advanced Energy Systems Division
P. O. Box 158
Madison, PA 15663

D. C. Fee
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

M. Firmin
Aerospace Corporation
P.O. Box 9113
Albuquerque, NM 87119

C. Fisher
GA Technologies
P. O. Box 85608
San Diego, CA 92138

T. Fitzgerald
TRW
One Space Park
Redondo Beach, CA 90278

Terry Flannagan
JAYCOR
11011 Torreyana Road
P.O. Box 85154
San Diego, CA 92138-9259

Dr. Dennis Flood
NASA Lewis Research Center
Mail Stop: 302-1
2100 Brookpark Road
Cleveland, Ohio 44135

J. Foster
Defense Nuclear Agency
RAEV
6801 Telegraph Road
Alexandria, VA 22310-3398

E. P. Framan
California Inst. of Technology
Jet Propulsion Lab.
4800 Oak Grove Drive
MS 301-285
Pasadena, CA 91109

Dr. Mike Frankel
SPAS
HQ Defense Nuclear Agency
6801 Telegraph Road
Alexandria, VA 22213

Robert Franklin
U.S. Army Strategic Defense Cm.
106 Wynn Drive
Huntsville, AL 35807

Bob Gardner
Mission Research Corporation
1720 Randolph Road, SE
Albuquerque, NM 87106-4245

James Garner
TRW
One Space Park
Redondo Beach, CA 90278

Dr. James Gee
MS M7-633
Aerospace Corporation
P. O. Box 92957
Los Angeles, CA 90009-2957

Jeffrey George
MS: 501-6
NASA Lewis Research Center
21000 Brookpark Rd.
Cleveland, OH 44135

R. Giellis
Martin Marietta Corp.
P. O. Box 179
MS 0484
Denver, CO 80201

Bruce Glasgow
R1/1070
TRW-ATD
One Space Park
Redondo Beach, CA 90278

Lt. M. Good
Air Force Space Technology Center
TP
Kirtland Air Force Base
New Mexico, 87117-6008

Capt. J. Gray
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Weapons Laboratory
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One Space Park
Bldg. R-4/2190
Redondo Beach, CA 90278

R. Hammond
SDIO/DE
Washington, DC 20301-7100

W. R. Hardie
Deputy Group Leader
Los Alamos National Laboratory
MS F611
P. O. Box 1663
Los Alamos, NM 87545

Neal Harold
AFWAL/POOC-1
Wright-Patterson AFB
Ohio 45433-6563

Mr. Charlie D. Harper
CSSD-H-YA
US Army Strategic Defense Command
106 Wynn Drive
P. O. Box 1500
Hunstville, AL 35807-3801

Dr. M. Harrison
WL/NTCA
Weapons Laboratory
Kirtland AFB, NM 87117

S. Harrison
Office of Science & Technology
Executive Office of the President
Mailing Room 5013
New Executive Office Bldg.
Washington, DC 20506

K. C. Hartkay
ANSER Corporation
Crystal Gateway 3
1225 Jefferson Davis Highway #800
Arlington, VA 22208

J. K. Hartman
U. S. Department of Energy
San Francisco Operations Office
1333 Broadway Avenue
Oakland, CA 94612

L. Hatch
Rasor Associates
253 Humboldt Ct.
Sunnyvale, CA 94089

Col. C. Heimach
U. S. Air Force
SD/XR
P.O. Box 92960 WPC
Los Angeles AFB
CA 90009-2960

I. Helms
U. S. Department of Energy
NE-54
Washington, DC 20545

J. W. Henscheid
EG&G Idaho, Inc./INEL
P. O. Box 1625
Idaho Falls, ID 83415

Mr. R. Herndon
AFSTC/SWL
Kirtland AFB, NM 87117

Lt. Col. C. Hill
SDIO/INK
Pentagon, Rm 1E178
Washington, DC 20301-7100

J. Hipp
S-Cubed
2501 Yale Blvd., SE
Suite 300
Albuquerque, NM 87106

J. Hnat
General Electric
Astro Systems
P. O. Box 8555
Bldg. 100, Rm. M2412
Philadelphia, PA 19101

E. E. Hoffman
U. S. Department of Energy
Oak Ridge Operations Office
P. O. Box E
Oak Ridge, TN 37830

H. W. Hoffman
Oak Ridge Nat'l Lab.
P.O. Box X
Oak Ridge, TN 37831

K. W. Hoffman
Air Force Foreign
Technology Division
TDTQ
Wright-Patterson AFB
Ohio 45433

R. L. Holton
U.S. Department of Energy
ALO/ETD
P.O. Box 5400
Albuquerque, NM 87115

J. L. Hooper
U. S. Department of Energy
Chicago Operations Office
9800 So. Cass Avenue
Argonne, IL 60439

CNSE/Capt. Howard
Space Systems Division
P. O. Box 92960
Worldway Postal Center
Los Angeles, CA 90009-2960

A. Huber
Air Force Space Technology Center
XLP
Kirtland Air Force Base
New Mexico 87117-6008

A. K. Hyder
W. J. Schafer Associates
1901 No. Ft. Myers Drive
Suite 800
Arlington, VA 22209

Dr. T. Hyder
Auburn University
202 Sanform Hall
Auburn, AL 36849-3501

L. Isenberg
California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
MS 264-770
Pasadena, CA 91109

D. E. Jackson
BDM Corporation
1801 Randolph Rd., SE
MS BV-24
Albuquerque, NM 87106

Jerry Jaggers
Attn: Document Control
for Bldg. 593
Lockheed Missiles and
Space Co. Inc.
P O Box 3504
Sunnyvale, CA 94088

Frank Jankowski
WL/TAPN
Kirtland AFB, NM 87117

Marshall Jew (MS: A02-105)
Grumman Aerospace Corporation
CDC (Ms: A04-35)
Bethpage, NY 11714

B. M. Johnson
Batelle Pacific Northwest Lab.
P.O. Box 999
Richland, WA 99352

R. Johnson
Rocket Dyne
HB-13
6633 Canoga Ave.
Canoga Park, CA 91303

A. Juhasz
NASA Lewis Research Center
MS 301-5, Rm. 101
21000 Brookpark Road
Cleveland, OH 44135

Col. John A. Justice
WL/NTN
Weapons Laboratory
Kirtland AFB, NM 87117

Ehsan Kahn
BDM Corp.
7915 Jones Branch Dr.
MS West Brach 5B37
McLean, VA 22102-3396

Robert Karcher, MS EA-22
Rockwell Int'l Space Transportation
Systems Division
12214 Lakewood Blvd.
Downey, CA 90241

W. Y. Kato
Deputy Chairman
Brookhaven National Laboratory
P. O. Box 155
Upton, NY 11973

R. J. Katucki
Manager, Space Power Programs
General Electric Company
Astro Systems
P. O. Box 8555
Philadelphia, PA 19101

D. Kelleher
Technical Director
Advanced Technology Division
AFWRDC/AW
Kirtland Air Force Base
New Mexico 87117

Peter Kemmey
DARPA
1400 Wilson Blvd.
Arlington, VA 22209

Lt. E. B. Kennel
AFWRDC/POOS
Bldg. 450
Wright Patterson AFB
Ohio 45433

K. Kennerud
Boeing Company
Boeing Aerospace System
P.O. Box 3707
Seattle, WA 98124

O. F. Kimball
Oak Ridge Nat'l Lab.
P.O. Box 2009
Bldg. 4508, MS 080
Oak Ridge, TN 37831-6080

F. King
U. S. Army Defense Command
106 Wynn Drive
Huntsville, AL 35807

W. L. Kirk
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

A. Klein
Oregon State University
Dept. of Nuclear Engineering
Corvallis, Oregon 97331

J. Krupa
U. S. Department of Energy
SAN-ACR Division
1333 Broadway
Oakland, CA 94612

K. D. Kuczen
Argonne National Laboratory
97000 So. Cass Avenue
Argonne, IL 60439

Gerald Kulcinski
University of Wisconsin
Fusion Technology Institute
1500 Johnson Drive
Madison, WI 53706-1687

A. S. Kumar
University of Missouri-Rolla
Department of Nuclear Energy
220 Engineering Research Lab.
Rolla, MO 65401-0249

W. Lambert
U. S. Department of Energy
SAN-ACR Division
1333 Broadway
Oakland, CA 94612

Dick Lancashire
PSIO/NASA
Lewis Research Center
21000 Brookpark Rd.
Cleveland, OH 44135

S. J. Lanes
Deputy Director
Breeding Reactor Program
U. S. Department of Energy
Washington, DC 20545

Lt. Col. F. Lawrence
HQ ASFPACECOM/XPXIS
Peterson Air Force Base
Colorado 80914-5001

R. J. LeClaire
Los Alamos National Laboratory
P. O. Box 1663
MS F611
Los Alamos, NM 87545

CNIS/Lt. Col. J. Ledbetter
Space Systems Division
P. O. Box 92960
Worldway Postal Center
Los Angeles, CA 90009-2960

J. P. Lee
U. S. Department of Energy
MS MA-206
Washington, DC 20545

Dr. James Lee
SDIO/TNK
Washington, DC 20301-7100

Strategic Defense Initiative Org.
The Pentagon
Attn: Dr. James Lee
Washington, DC 20301-7100

Lt. Col. R. X. Lenard
SDIO/KE
The Pentagon
Washington, DC 20301-7100

S. Levy
U. S. Army ARDC
Building 329
Picatinny Arsenal
New Jersey 87806-5000

R. A. Lewis
Argonne Nat'l Lab.
9700 So. Cass Avenue
Argonne, IL 60439

Larry Long
Westinghouse R&D
1310 Beulah Road
Bldg. 501-3Y56
Pittsburgh, PA 15235

L. H. Luessen
Naval Surface Weapons Center
Code F12
Dahlgren, VA 22448-5000

Bruce MacCabee
R/42
Naval Surface Weapons Laboratory
White Oaks
Silver Springs, MD 20910

Phil Mace
W. J. Schafer Associates
1901 North Ft. Myers Drive
Suite 800
Arlington, VA 22209

P. Mahadevan
MS M7-597
Aerospace Corporation
PO Box 92957
Los Angeles, CA 90009-2957

T. Mahefky
Group Leader, Thermal Systems
AFWRDC
Aeronautical Laboratory
Wright Patterson Air Force Base
Ohio 45433

B. J. Makenas
Westinghouse Hanford Company
P. O. Box 1970
Richland, WA 99352

P. Margolis
Aerospace Corporation
P. O. Box 92957
El Segundo, CA 90009

Charles Martin
U. S. Department of Energy
NE-54
F415/GTN
Germantown, MD 20545

Lee Mason
NASA Lewis Research Center
MS: 501-6
21000 Brookpark Road
Cleveland, OH 44135

L. D. Massie
AFWRDC/POOC-1
Aeronautical Laboratory
Bldg. 450
Wright-Patterson AFB
Ohio 45433

Bill Matoush
AFSPACESOM/XPXY
Peterson AFB
Colorado Springs, CO 80915-5001

Tom McComas
NASA Lewis Research Center/UF
21000 Brookpark Rd.
Cleveland, OH 44135

Maj. Tom McDowell
SDIO/INK
Pentagon, Rm 1E178
Washington, DC 20301-7100

Glen McDuff
Texas Tech. University
Dept. of Electrical Engr.
Lubbock, TX 79409

Barbara McKissock
NASA Lewis Research Center
MS 301-5
21000 Brookpark Road
Cleveland, OH 44135

D. McVay
United Technologies
International Fuel Cells
195 Governor's Highway
So. Windsor, CT 06074

M. A. Merrigan
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Ira Merritt
CSSD-H-LS
US Army Strategic Defense Command
106 Wynn Drive
P. O. Box 1500
Huntsville, AL 35807-3801

B. Meyers
Naval Space Command
Dahlgren, VA 22448

J. Metzger
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Tom Miller
ASAO/NASA
Lewis Research Center
21000 Brookpark Rd.
Cleveland, OH 44135

J. Mims
S-Cubed
2501 Yale Blvd., SE
Suite 300
Albuquerque, NM 87106

J. F. Mondt
Deputy Project Manager
California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Capt. J. Moody
AFSTC/SWW
Kirtland AFB, NM 87117

J. C. Moyers
Oak Ridge National Laboratory
P. O. Box Y
Bldg. 9201-3, MS-7
Oak Ridge, TN 37831

D. M. Mulder
AFWL/TAPN
Kirtland Air Force Base
New Mexico 87117-6008

Mr. J. Mullis
WL/NTCA
Weapons Laboratory
Kirtland AFB, NM 87117

I. T. Myers
NASA Lewis Research Center
MS 301-2, Rm. 116
21000 Brookpark Road
Cleveland, OH 44135

Joseph Nainiger
MS 501-6
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

D. F. Nichols
AFWL/TAPN
Kirtland AFB
NM 87117-6008

J. P. Nichols
Oak Ridge National Laboratory
Bldg. K-1030, Room 110
P. O. Box 2003
Oak Ridge, TN 37831-7312

M. Nikolich
W. J. Schafer Associates
1901 No. Ft. Myers Drive
Suite 800
Arlington, VA 22209

Commander R. Nosco
Naval Space Command
Dahlgren, VA 22448

George Novak
Cost Analysis Org.
NASA/Lewis Research Center
21000 Brookpark Rd.
Cleveland, OH 44135

Capt. P. D. Nutz
USAF-SD/CNSD
P.O. Box 92960
LA-AFS
Los Angeles, CA 90009-2960

Tuong Nguyen
MS FB25
Rocketdyne
6633 Canoga Ave.
Canoga Park, CA 91303

C. Oberly
AFWRDC/POOC-1
Wright-Patterson AFB
Ohio 45433

M. Olszewski
Oak Ridge National Laboratory
P. O. Box Y
Oak Ridge, TN 37831

D. Palac
NASA Lewis Research Center
MS: 501-6
21000 Brookpark Road
Cleveland, OH 44135

Dr. D. Payton
EOS Technologies Inc.
200 Lomas NW, Suite 1121
Albuquerque, NM 87102

Capt. G. Peredo
U. S. Air Force
SD/XR
P.O. Box 92960 WPC
Los Angeles AFB
CA 90009-2960

Ed Peterson
Code 4611
Naval Research Laboratory
4555 Overlook Drive
Washington, DC 20375-5000

W. Portnoy
Texas Tech University
Dept of Electrical Engineering
Lubbock, TX 79409

J. Powell
Office of Reactor Systems
Brookhaven National Laboratory
MS 820M, Bldg. 701, Level 143
P. O. Box 155
Upton, NY 11973

J. L. Preston, Jr.
United Technologies
International Fuel Cells
195 Governor's Highway
South Windsor, CT 06074

Eric Proust
Commissariat A L'Energie Atomique
Dept. des Etudes Mechaniques
et Thermiques
IRDI/DEDR/DEMT/SERMA
C.E.N. Saclay
91191 Gif-Sur-Yvette Cedex
FRANCE

Lt. Col. H. Pugh
AFSTC/SWL
Kirtland AFB, NM 87117

C. Purvis
NASA Lewis Research Center
MS 302-1, Rm. 101
21000 Brookpark Road
Cleveland, OH 44135

C. Quinn
U. S. Department of Energy
ALO/ETD
P. O. Box 5400
Albuquerque, NM 87115

William A. Ranken
Los Alamos National Laboratory
Mail Stop: E552
P. O. Box 1663
Los Alamos, NM 87545

N. Rasor
Rasor Associates
253 Humboldt Ct.
Sunnyvale, CA 94089

D. Reid
Los Alamos National Laboratory
MS H811
P. O. Box 1663
Los Alamos, NM 87545

CNBSS/Maj. L. Rensing
Space Systems Division
P. O. Box 92960
Worldway Postal Center
Los Angeles, CA 90009-2960

Dick Renski
AFWRDC/AA
Wright-Patterson AFB
Ohio 45433

J. R. Repp
Westinghouse R&D
1310 Beulah Road
Bldg. 501-3Y56
Pittsburgh, PA 15235

W. H. Roach
S-Cubed
2501 Yale Blvd., SE
Suite 300
Albuquerque, NM 87106

Carlos D. Rodriquez
ASAO/NASA
Lewis Research Center
21000 Brookpark Rd.
Cleveland, OH 44135

Frank Rose
Auburn University
Space Power Institute
231 Leach Center
Auburn, AL 36849-3501

J. H. Saloio
ERCE
7301-A Indian School Road, NE
Albuquerque, NM 87110

S. L. Samuelson
U. S. Department of Energy
San Francisco Operations Office
1333 Broadway Avenue
Oakland, CA 94612

R. T. Santoro
Oak Ridge National Laboratory
P. O. Box 22008
Oak Ridge, TN 37831-6363

W. J. Sarjeant
State University of New York at
Buffalo
Dept. of Electrical Engineering
312 Bonner Avenue
Buffalo, NY 14260

Mike Saunders
Booz-Allen and Hamilton Inc.
4330 East-West Highway
Bethesda, MD 20814

L. Schmid
Assistant Project Manager
Battelle Pacific Northwest Lab.
P. O. Box 999
Richland, WA 99352

Paul Schmitz
MS: 301-5
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

Lt. Col. Schneider
WL/NTC
Weapons Laboratory
Kirtland AFB, NM 87117

Col. Garry Schnelzer
SDIO/SATKA
Washington, DC 20301-7100

A. D. Schnyer
NASA Headquarters
Room 600, Code: RP
600 Independence Ave., SW
Washington, DC 20546

A. D. Schonfeld
TRW
One Space Park
Redondo Beach, CA 90278

Col. J. Schofield
SDIO/SY
Washington, DC 20301-7100

J. Scholtis
Directorate of Nuclear Safety
AFISC/SN
DET 1, AFISC/SNRA
Kirtland AFB
New Mexico 87117-5000

M. J. Schuller
WL/TAPN
Kirtland Air Force Base
New Mexico 87117-6008

G. Schwarze
NASA Lewis Research Center
MS 301-2, Rm. 117
21000 Brookpark Road
Cleveland, OH 44135

Jim Scott
Los Alamos National Laboratory
Mail Stop: E552
P. O. Box 1663
Los Alamos, NM 87545

Clarence Severt
AFWRDC/POOC-1
Wright-Patterson AFB
Ohio 45433-6563

Major Seward
AFWRDC/POOC
Aeronautical Laboratory
Bldg. 18
Wright Patterson Air Force Base
Ohio 45433

D. C. Sewell
DCSCON Consulting
4265 Drake Court
Livermore, CA 94550

C. Sharn
SDIO/SY
Washington, DC 20301-7100

B. J. Short
Babcock & Wilcox
Nuclear Power Division
3315 Old Forest Road
P.O. Box 10935
Lynchburg, VA 24506-0935

M. Simon-Tov
Oak Ridge Nat'l Lab.
Bldg. 9201-3, MS-7
Oak Ridge, TN 37831

CNIWT/Capt. Simpson
Space Systems Division
P. O. Box 92960
Worldway Postal Center
Los Angeles, CA 90009-2960

Dr. B. K. Singaraju
WL/NTCA
Weapons Laboratory
Kirtland AFB, NM 87117

Henry Smith
Nichols Research Corp.
4040 So. Memorial Pkwy
Huntsville, AL 35802

John Smith
NASA Lewis Research Center
MS 301-5
21000 Brookpark Road
Cleveland, OH 44135

S. Solomon
Aerospace Corp.
P. O. Box 92957, MS: M1-131
Los Angeles, CA 90009-2957

R. J. Sovie
NASA Lewis Research Center
MS 301-5, Rm. 105
21000 Brookpark Road
Cleveland, OH 44135

O. Spurlock
NASA Lewis Research Center
MS 501-6
21000 Brookpark Road
Cleveland, OH 44135

G. Staats
U. S. Department of Energy
Pittsburgh Energy Tech. Center
PM-20
P. O. Box 18288
Pittsburgh, PA 15236

M. L. Stanley
EG&G Idaho, Inc./INEL
P. O. Box 1625
Idaho Falls, ID 83415

Steve Stevenson
NASA Lewis Research Center
ASAO
21000 Brookpark Rd.
Cleveland, OH 44135

D. C. Straw
W. J. Schafer Associates
2000 Randolph Road, SE
Suite 205
Albuquerque, NM 87106

O. Spurlock
NASA Lewis Research Center
MS: 501-6
21000 Brookpark Road
Cleveland, OH 44135

T. P. Suchocki
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

L. H. Sullivan
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

A. Sutey
Spacecraft Subsystems
Boeing Company
P. O. Box 999
MS 8K-30
Seattle, WA 98124-2499

D. W. Swallom
AVCO Research Laboratory
2385 Revere Beach Parkway
Everett, MA 02149

Major P. Talty
HQ USAF/RD-D
Washington, DC 20330-5042

Owen Taylor
Westinghouse R&D
1310 Beulah Road
Bldg. 501-3Y56
Pittsburgh, PA 15235

Charles Terrell
AFWRDC/TA
Kirtland AFB,
NM 87117-6008

R. Thibodeau
AFWRDC/POOC-1
Bldg. 450
Wright Patterson Air Force Base
Ohio 45433

J. C. Trocciola
United Technologies
International Fuel Cells
195 Governor's Highway
South Windsor, CT 06074

V. C. Truscello
California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Bldg. 264-770
Pasadena, CA 91109

John Uecke
S-Cubed
Suite 300
2501 Yale Blvd., SE
Albuquerque, NM 87106

T. H. Van Hagan
General Atomics
10955 John Jay Hopkins Dr.
P. O. Box 85608
San Diego, CA 92121-1194

G. B. Varnado
Int'l Energy Associates Ltd.
1717 Louisiana NE
Suite 202
Albuquerque, NM 87110

R. Verga
SDI Organization
The Pentagon
Washington, DC 20301-7100

I. M. Vitkovitsky
Naval Research Laboratory
Washington, DC 20375-5000

Susan Voss
Department of Energy
Room GA093
1000 Independence Ave., SW
Washington, DC 20585

D. C. Wade
Applied Physics Division
Argonne National Laboratory
9700 So. Cass Avenue
Argonne, IL 60439

John Wagner
SAIC
2109 Air Park Road, SE
Albuquerque, NM 87106

E. J. Wahlquist
U. S. Department of Energy
NE-54
F415/GTN
Germantown, MD 20545

C. E. Walter, P.E.
Lawrence Livermore National Lab.
P. O. Box 808
MS L-144
Livermore, CA 94550

J. Warren
U. S. Department of Energy
NE-52
GTN
Germantown, MD 20545

C. W. Watson
Los Alamos National Laboratory
MS F607
P. O. Box 1663
Los Alamos, NM 87545

Robert C. Webb
RAEE
HQ Defense Nuclear Agency
6801 Telegraph Road
Alexandria, VA 22213

R. Weed
Nichols Research Corporation
2340 Alamo SE
Suite 105
Albuquerque, NM 87106

Eric Wennas
JAYCOR
11011 Torreyana Road
P. O. Box 85154
San Diego, CA 92138-9259

J. R. Wetch
President
Space Power, Inc.
1977 Concourse Drive
San Jose, CA 95131

J. F. Wett
Space & Defense Program
Westinghouse
Advanced Energy Systems Div.
Route 70, Madison Exit
Madison, PA 15663

J. F. Whitbeck
EG&G Idaho, Inc./INEL
P. O. Box 1625
Idaho Falls, ID 83415

Dan Whittener
U.S. Army Strategic Defense Cm.
106 Wynn Drive
Huntsville, AL 35807

R. D. Widrig
Human Factors Projects
Battelle Pacific Northwest Laboratory
P. O. Box 999
Richland, WA 99352

F. W. Wiffen
Oak Ridge National Laboratory
P. O. Box Y
Bldg. 9201-3, MS-7
Oak Ridge, TN 37831

Major J. Wiley
Naval Space Command
N5
Dahlgren, VA 22448

Robert Wiley
5998 Camelback Lane
Columbia, MD 21045

E. L. Wilkinson
U. S. Army Strategic Defense Command
106 Wynn Drive
Huntsville, AL 35807

N. Wilson
U. S. Army Lab. Com.
SLKET/ML
Pulse Power Technology Branch
Ft. Monmouth, NJ 07703-5000

Jerry Winter
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

William Wright
Ballena Systems Corporation
1150 Ballena Blvd., Suite 210
Alameda, CA 94501

T. S. Wuchte
AFWL/TAPN
Kirtland AFB
NM 87117-6008

E. R. Zercher
Martin Marietta Corporation
MS L8060
P. O. Box 179
Denver, CO 80201

J. Zielinski
U. S. Department of Energy
SAN-ACR Division
13333 Broadway
Oakland, CA 94612

G. L. Zigler
Science & Engineering Associates
6301 Indian School NE
Albuquerque, NM 87110

Internal Distribution

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9340 W. Beezhold

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