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

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

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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		Case 2		Case 3		Case 4	
	H ₂ Free		H ₂ Not Free		H ₂ Free		H ₂ Not Free	
	<u>H₂O OK</u>		<u>H₂O OK</u>		<u>H₂O Not OK</u>		<u>H₂O Not OK</u>	
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	
<u>Mass Estimates in Metric Tons</u>								
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	<u>1.9</u>		<u>2.6</u>		<u>2.2</u>		<u>3.4</u>	
Total	20.9		28.1		24.0		37.4	

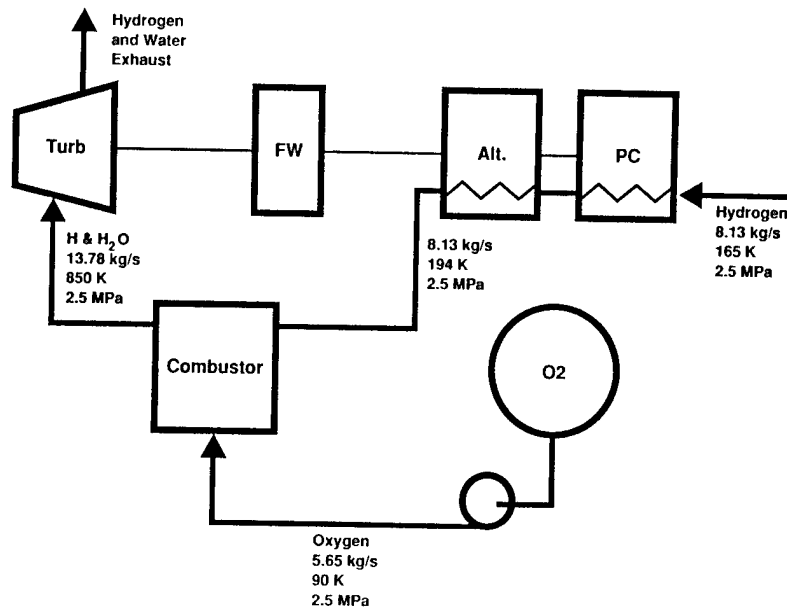


Figure 1a. H₂-O₂ Combustion Reference Power System -- 38.46 MWe, 750 s. Operation Time, Hydrogen is Free, Water Exhaust is OK.

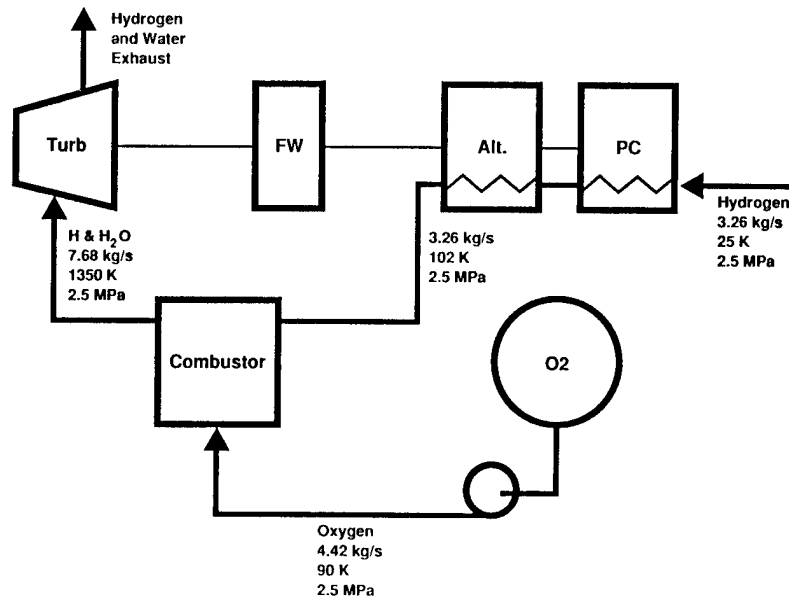


Figure 1b. H₂-O₂ Combustion Reference Power System -- 38.46 MWe, 750 s. Operation Time, Hydrogen is Not Free, Water Exhaust is OK.

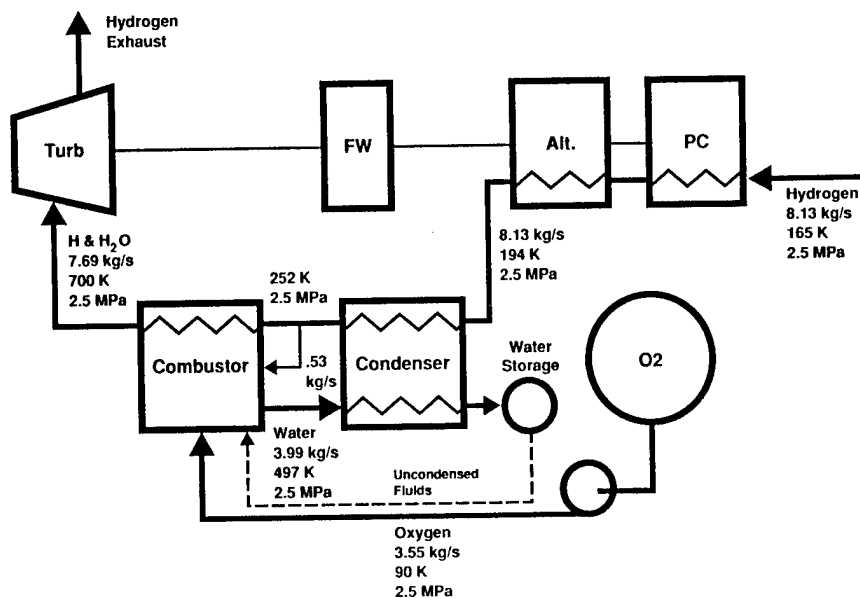


Figure 1c. H₂-O₂ Combustion Reference Power System --
38.46 MWe, 750 s. Operation Time, Hydrogen is
Free, Water Exhaust is Not OK.

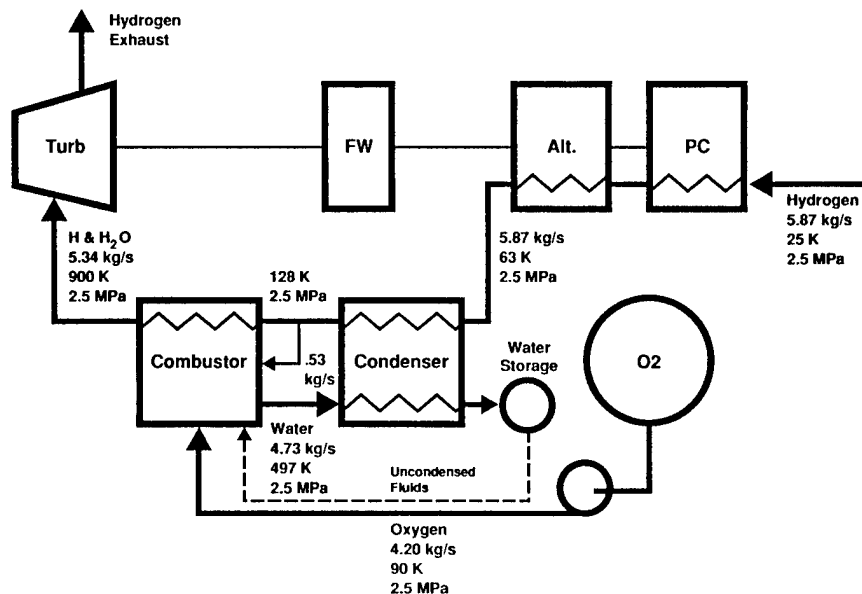


Figure 1d. H₂-O₂ Combustion Reference Power System --
38.46 MWe, 750 s. Operation Time, Hydrogen is Not
Free, Water Exhaust is Not OK.

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 Rovang² 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 Base¹ 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.

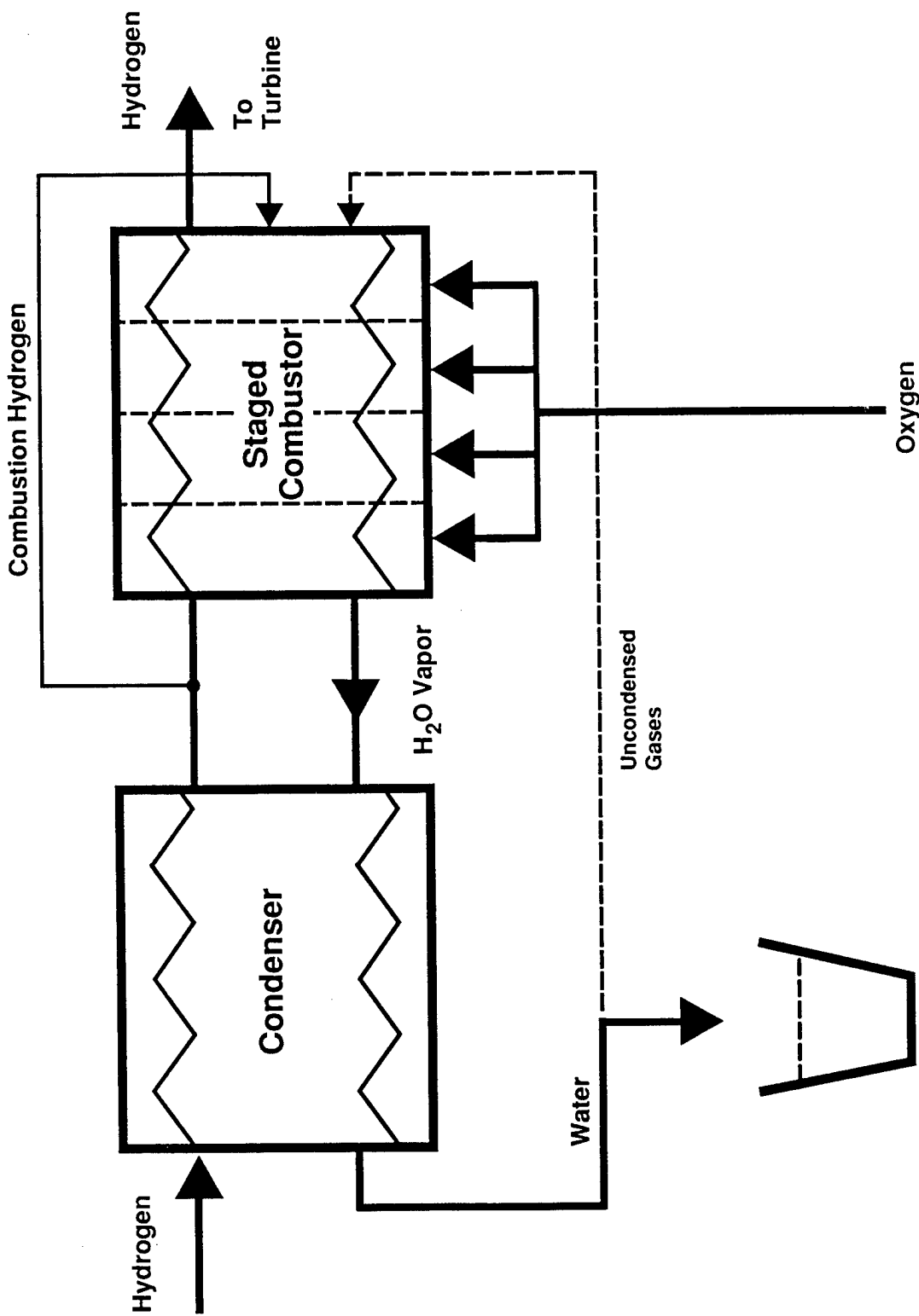


Figure 2. Hydrogen-Oxygen Combustion System With No Water Vapor Exhaust.

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/m³. Steam flows over the tubes and condenses with a heat transfer coefficient of 20,000 W/m²K. 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/m³. 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.)

Turbines--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 model¹ 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.

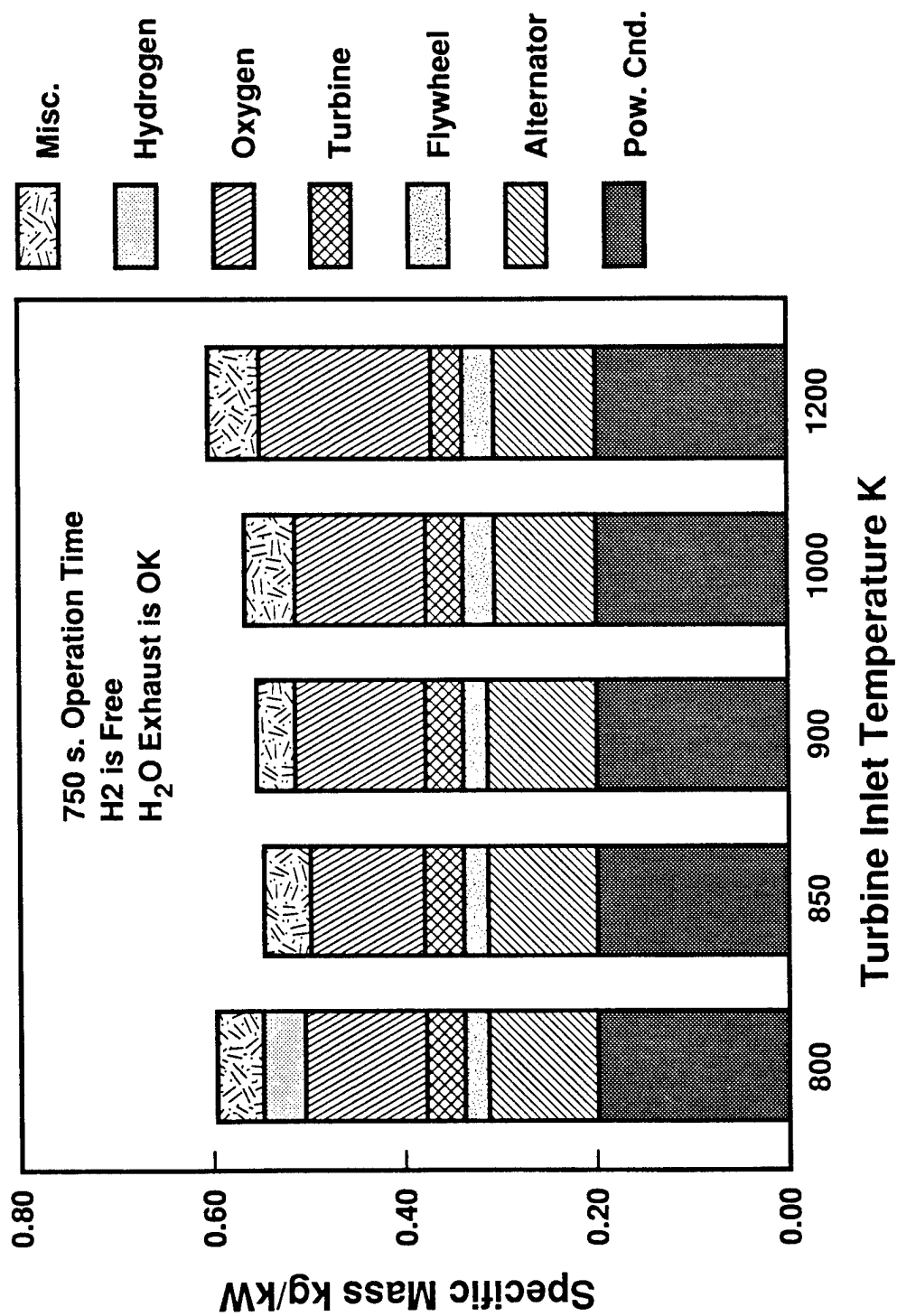


Figure 3. 38.46 MW H₂-O₂ Combustion Reference Power System.

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 (H ₂ & O ₂)	.41 MW
Refrigeration power (H ₂ & O ₂)	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	<u>1.9</u>
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.

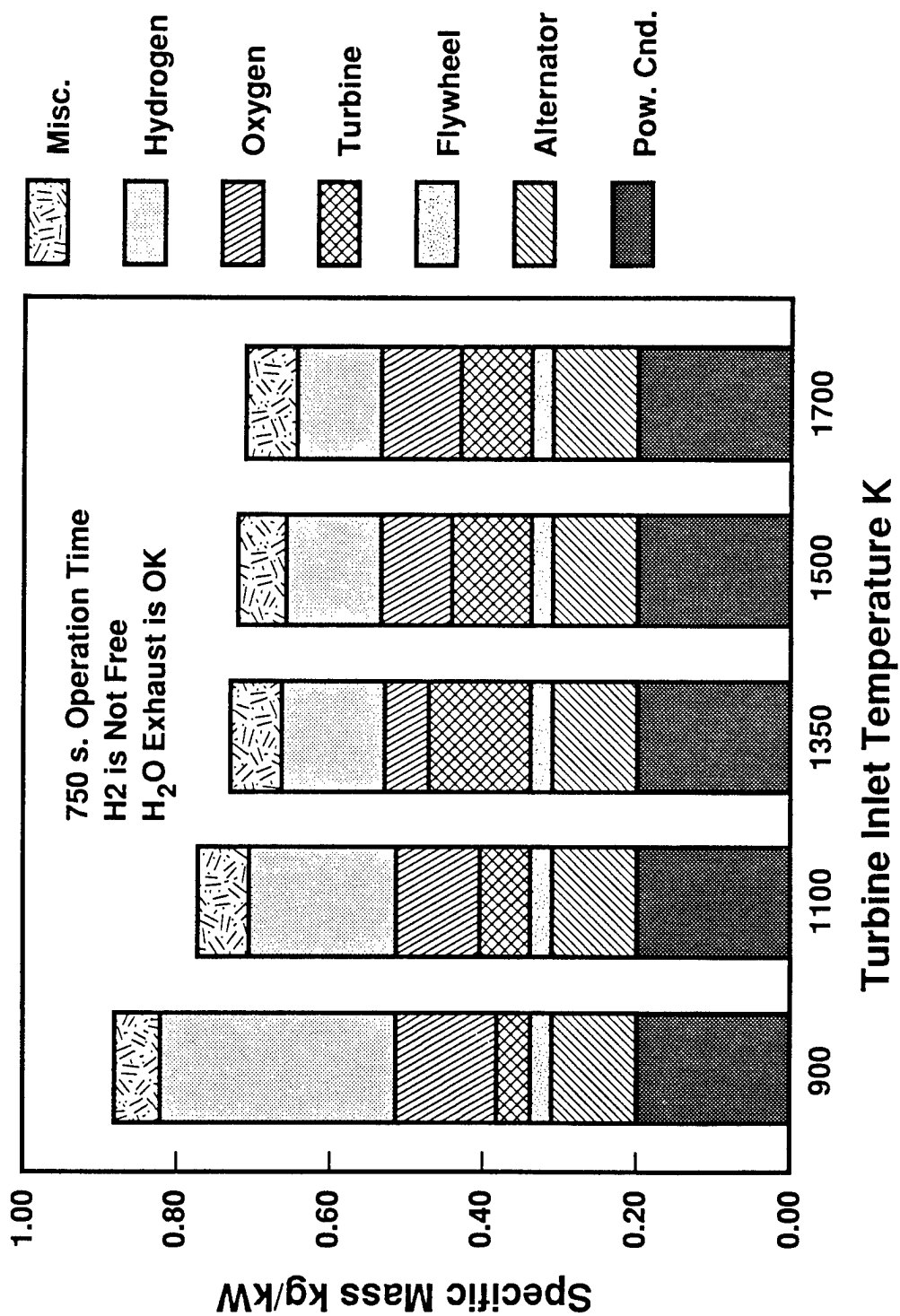


Figure 4. 38.46 MW H₂-O₂ Combustion Reference Power System.

Table 3. Case 2
 38.46 MW H₂-O₂ 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	<u>2.6</u>
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.

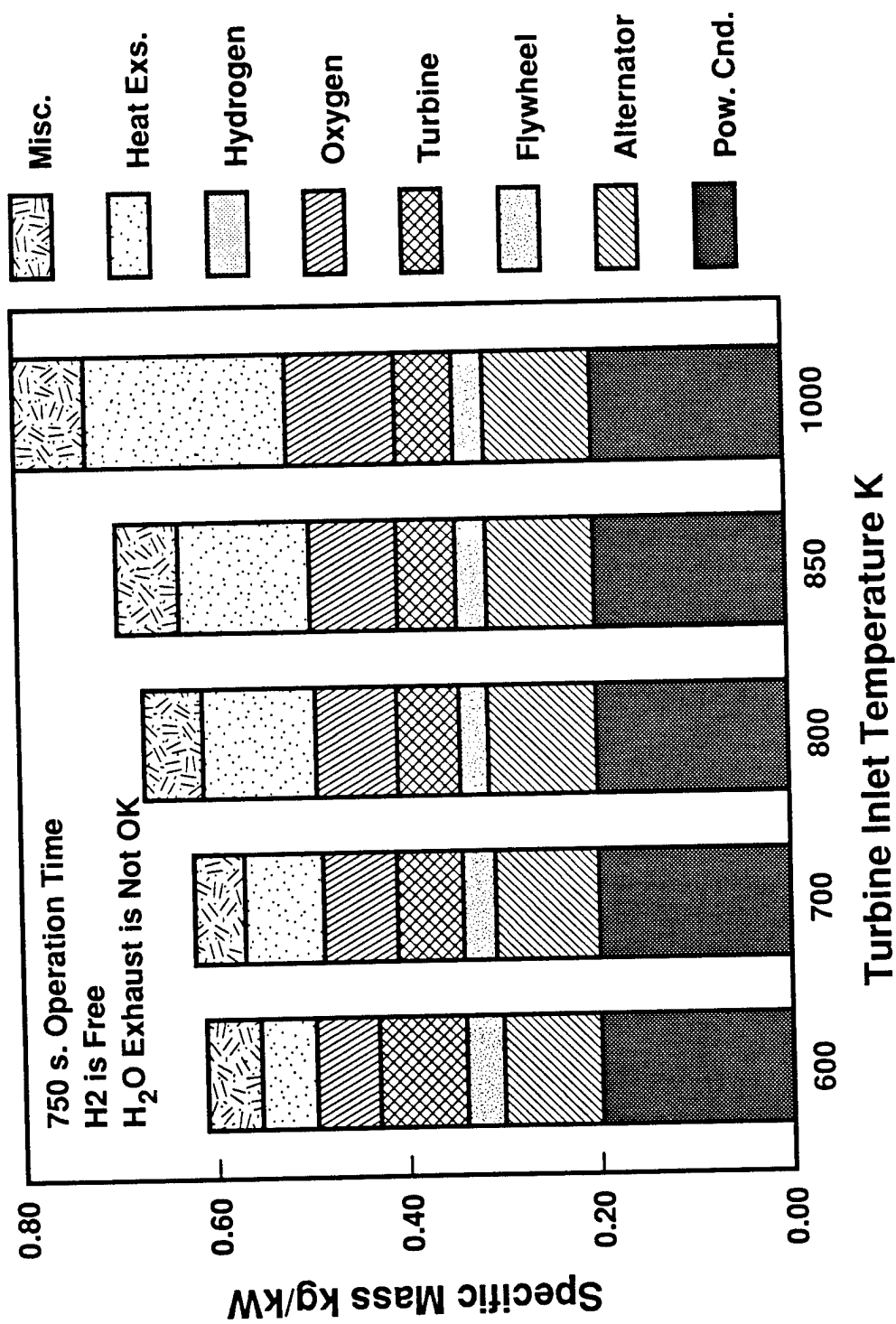


Figure 5. 38.46 MW H₂-O₂ Combustion Reference Power System.

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 (H ₂ & O ₂)	0.41 MW
Refrigeration power (H ₂ & O ₂)	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	<u>2.2</u>
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 (H ₂ & O ₂)	0.3 MW
Refrigeration power (H ₂ & O ₂)	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	<u>3.4</u>
Total	37.4 Mg

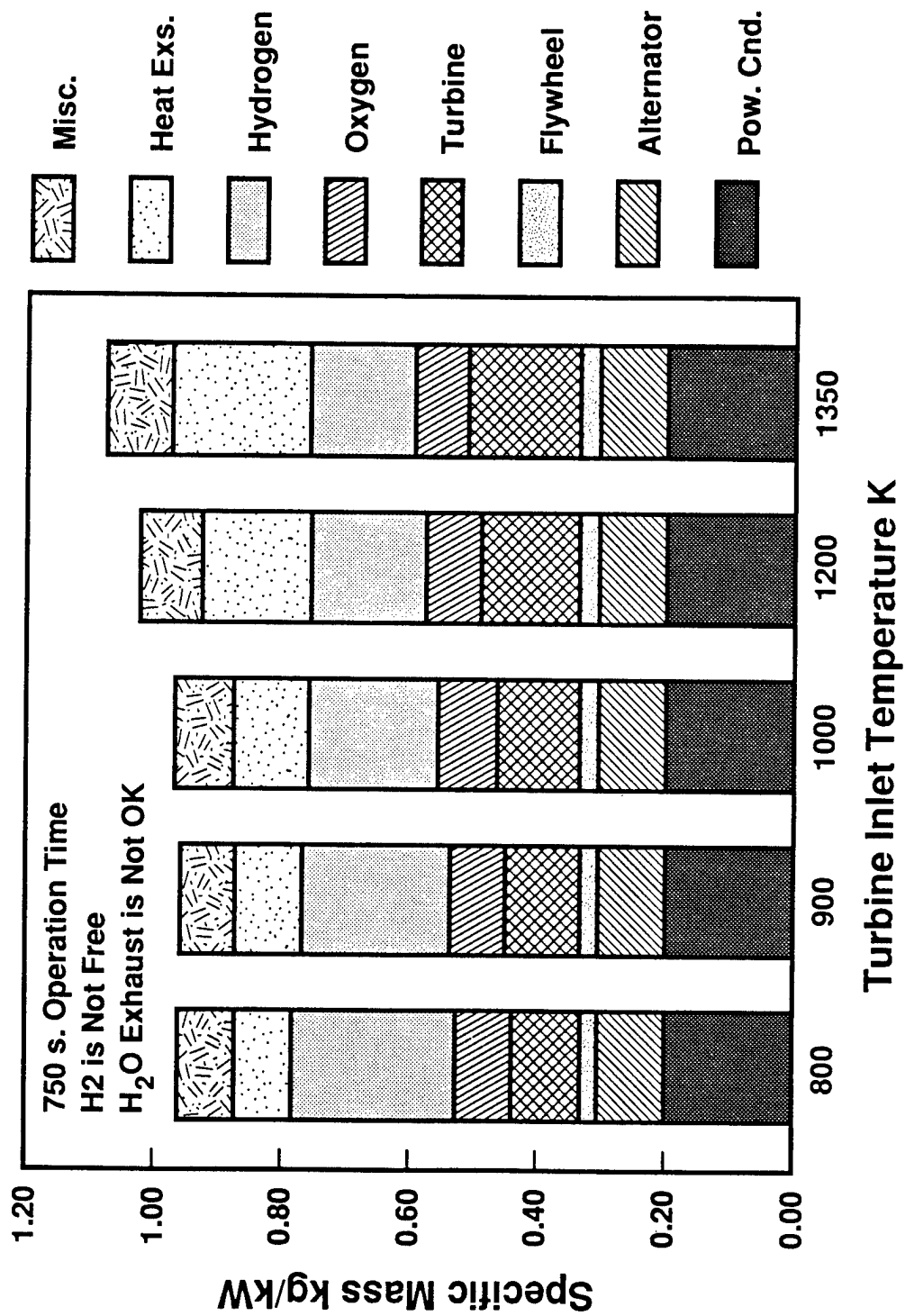


Figure 6. 38.46 MW H₂-O₂ Combustion Reference Power System.

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.

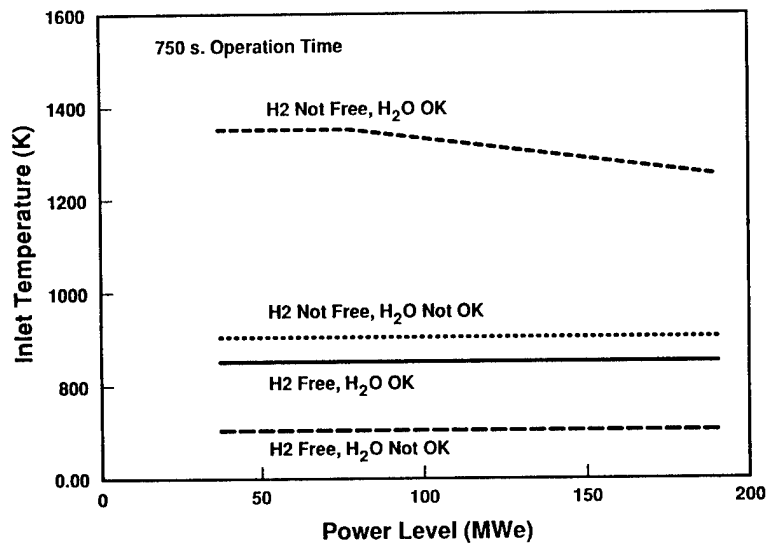


Figure 7. Optimum Turbine Inlet Temperature Depends Weakly on Power Level.

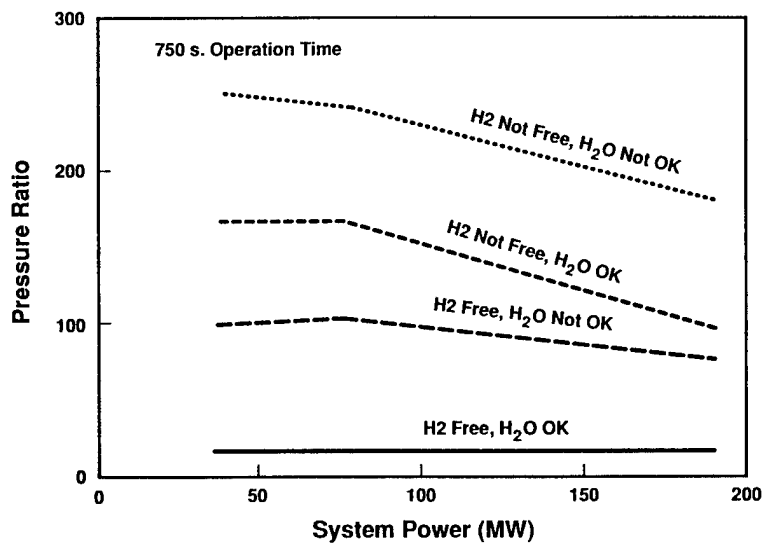


Figure 8. Optimum Turbine Pressure Ratio Depends on Power Level.

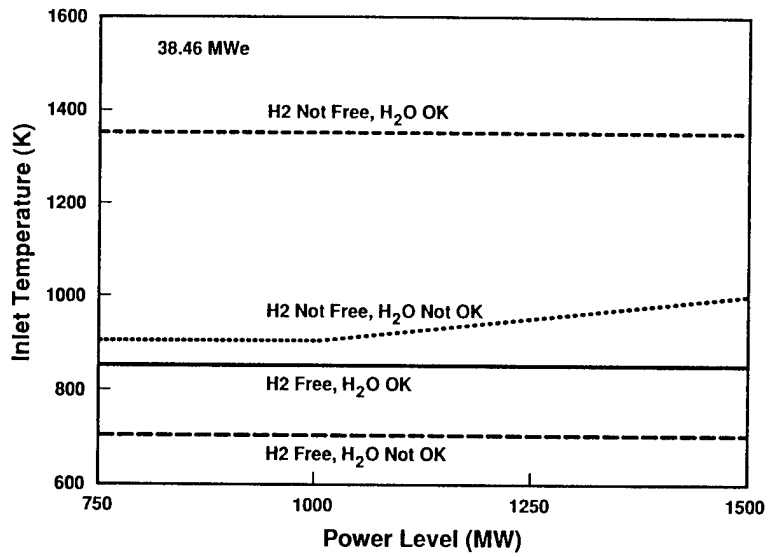


Figure 9. Optimum Turbine Inlet Temperature Depends Weakly on Operation Time.

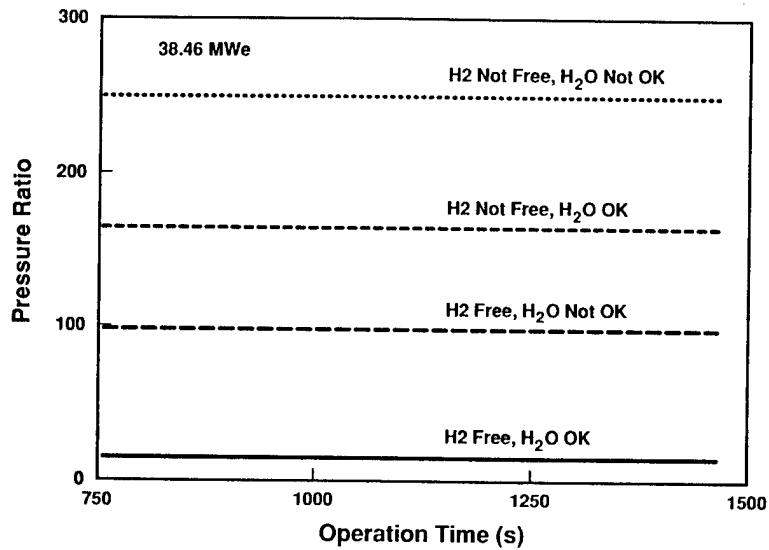


Figure 10. Optimum Turbine Pressure Ratio Is Not Sensitive to Operation Time.

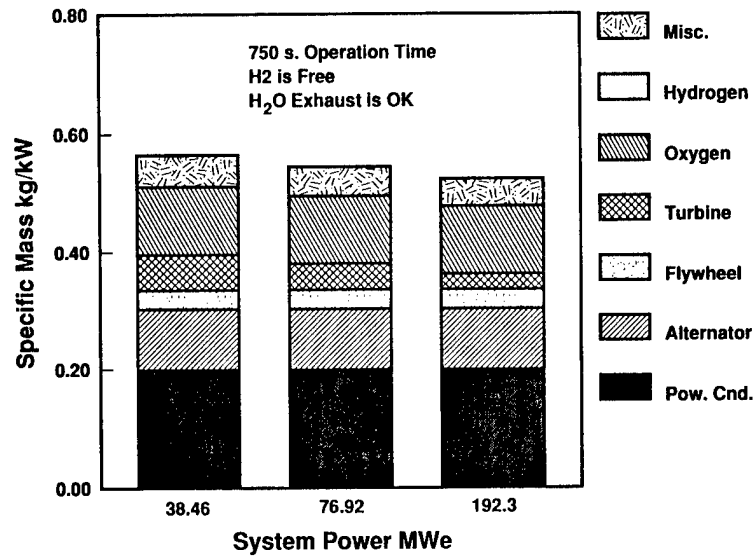


Figure 11. H₂-O₂ Combustion Reference Power System -- 750 s. Operation Time; H₂ is Free; H₂O Exhaust is OK.

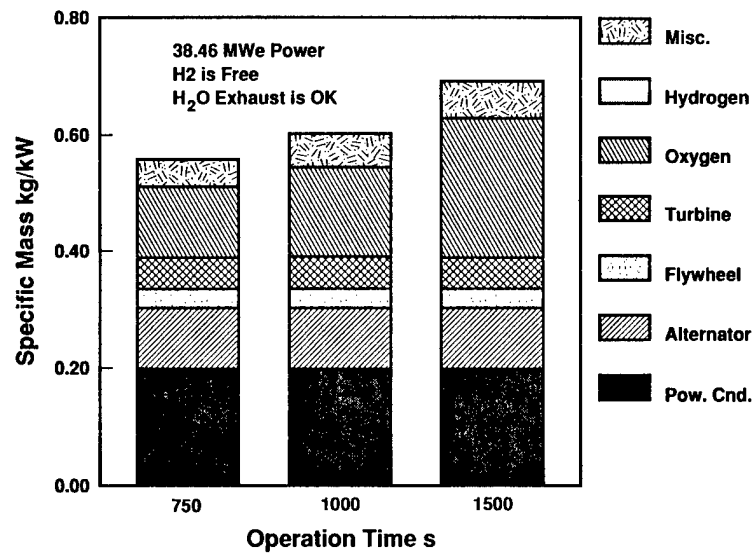


Figure 12. H₂-O₂ Combustion Reference Power System -- 38.46 MWe Power; H₂ is Free; H₂O Exhaust is OK.

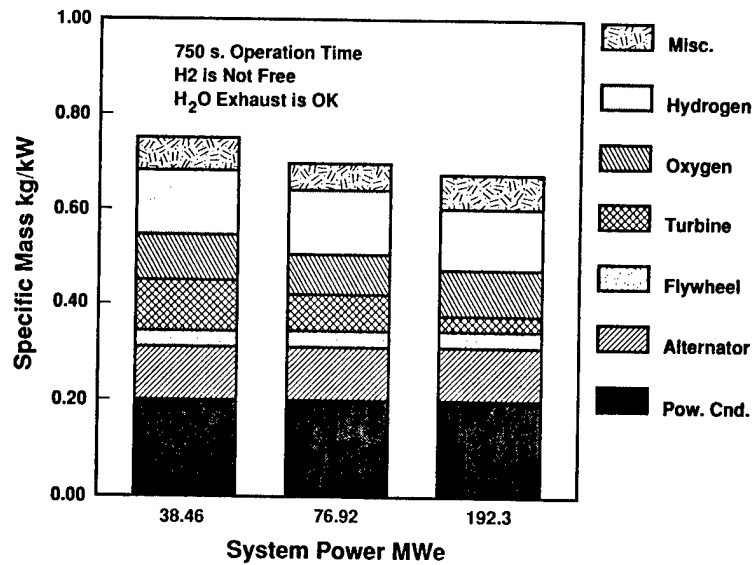


Figure 13. H₂-O₂ Combustion Reference Power System -- 750 s. Operation Time; H₂ is Not Free; H₂O Exhaust is OK.

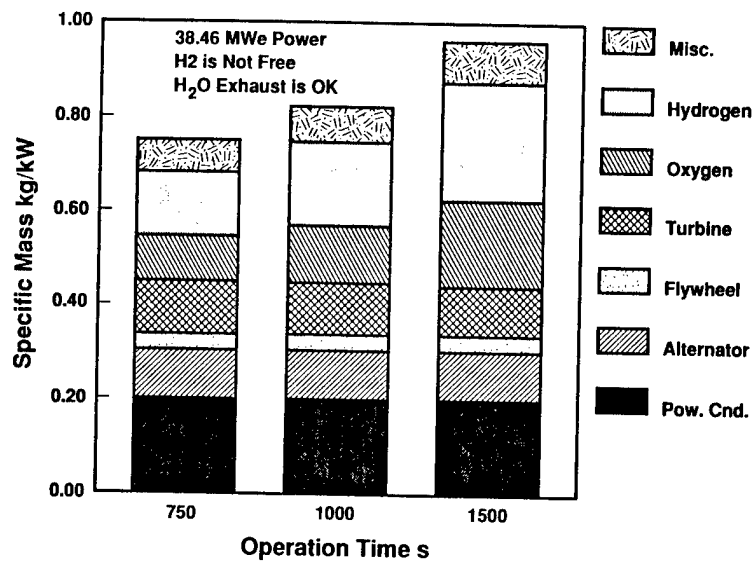


Figure 14. H₂-O₂ Combustion Reference Power System -- 38.46 MWe Power; H₂ is Not Free; H₂O Exhaust is OK.

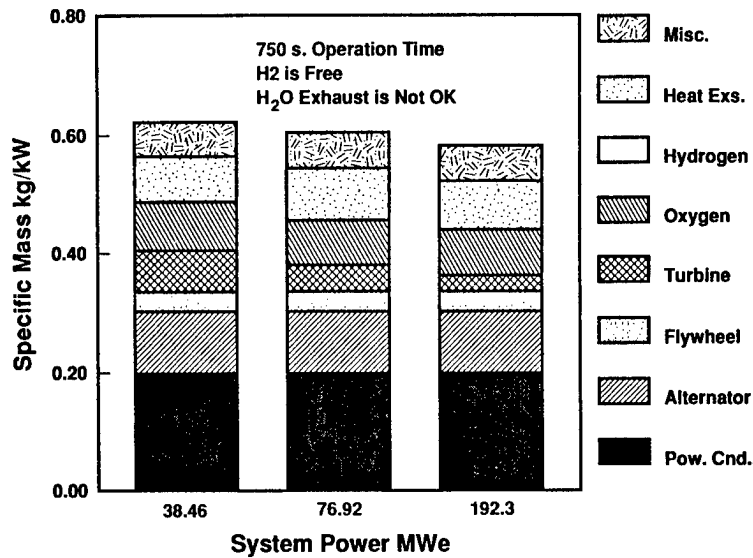


Figure 15. H₂-O₂ Combustion Reference Power System --
750 s. Operation Time; H₂ is Free; H₂O Exhaust is
Not OK.

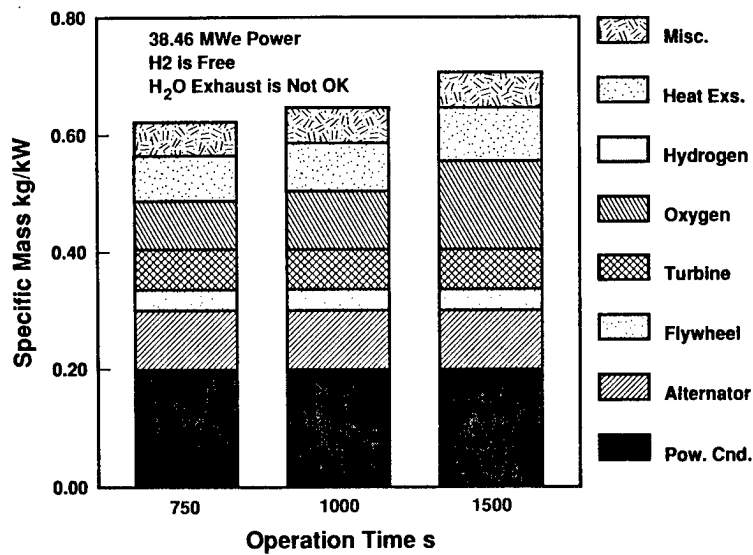


Figure 16. H₂-O₂ Combustion Reference Power System --
38.46 MWe Power; H₂ is Free; H₂O Exhaust is Not
OK.

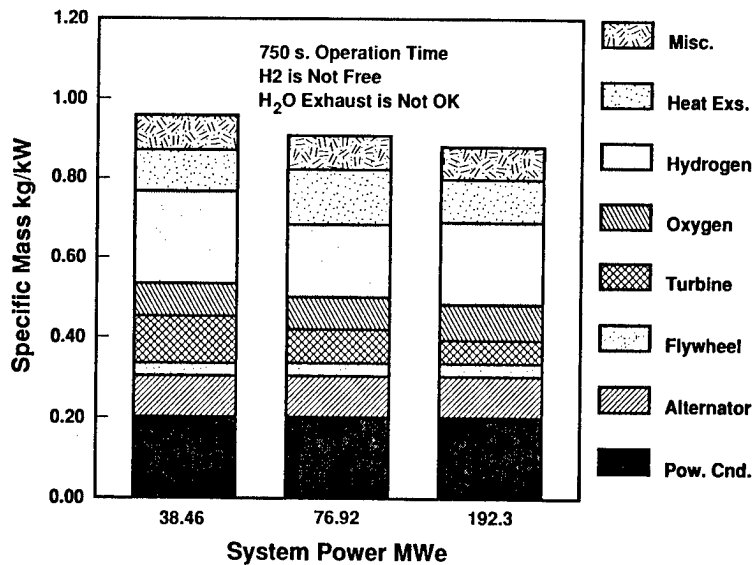


Figure 17. H₂-O₂ Combustion Reference Power System -- 750 s. Operation Time; H₂ is Not Free; H₂O Exhaust is Not OK.

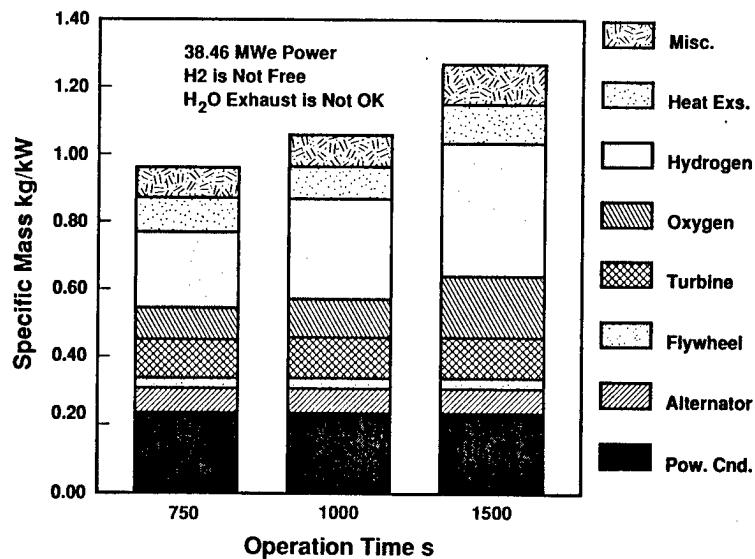


Figure 18. H₂-O₂ Combustion Reference Power System -- 38.46 MWe Power; H₂ is Not Free; H₂O Exhaust is Not OK.

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