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SECONDARY POWER AND ENVIRONMENTAL CONTROL FOR DYNA-SOAR

By Earl M. Donnen
Boeing Airplane Company

INTRODUCTION

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Secondary power is the term applied to all nonpropulsive power used on the Dyna-Soar flight vehicle. It includes electrical power needed for electrical and electronic equipment, power for moving aerodynamic control surfaces while the vehicle is within the atmosphere, and power for attitude control while the vehicle is at altitudes where aerodynamic control surfaces are ineffective. The term environmental control is applied to the provision of properly controlled cooling, heating, pressurization, and atmosphere necessary for the efficient operation of the pilot and the airborne equipment. This discussion will be limited to secondary power and environmental control as applied to (1) the glider portion of the airborne vehicle, and (2) the normal systems as contrasted to emergency systems.

SYMBOLS

I_{sp}	specific impulse, sec
p_1	pressure upstream of nozzle, lb/sq in.
p_2	pressure at nozzle exhaust, lb/sq in.
γ	ratio of specific heats
SFC	specific fuel consumption, lb fuel/lb thrust/hr
$T_1 \ldots T_5$	local temperature, °F

SECONDARY POWER

The selection of the main power source is of primary interest in secondary power. Since all energy must be carried aboard the vehicle,

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weight and volume requirements must be considered on the basis of total energy requirements for the design missions as well as peak-load and transient-load requirements. A total power requirement of 35 horsepower hours is typical of a 2-hour Dyna-Soar flight. Peak horsepower requirements for aerodynamic controls might be as high as 16 horsepower, and electrical requirements as high as 9 kilowatts at various times during the flight. The peak hydraulic loads will occur during the reentry phase, and the highest electrical loads are expected prior to reentry. The types of power sources considered for Dyna-Soar were: (1) open-cycle propellant prime movers, (2) batteries, (3) solar cells, (4) fuel cells, (5) thermionic devices, (6) thermoelectric devices, and (7) nuclear devices. Only the open-cycle propellant prime mover (usually termed an accessory power unit, or APU, when associated with its driven equipment) and batteries of various types were found to be applicable to the Dyna-Soar missions and time scale.

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A typical monopropellant APU system is shown in figure 1. Here, two hydrazine-fueled prime movers, usually turbines, each drive an a-c generator, a hydraulic pump, a fuel pump, and a cooling-system blower. Only one APU is loaded. The other is run at no-load as a standby unit. Thus, a-c electrical power is provided directly from the generator, d-c power being furnished through a transformer rectifier unit. In this particular representation, dual prime movers are supplied from a single fuel system. This same system supplies fuel for the reaction-control gas generator. System integration is represented by the use of the turbine exhaust heat to keep the reaction-control gas generator heated, and use of the fuel as heat sink for part of the hydraulic-system cooling load. Water heat exchangers cool the gas from the blower before it is distributed to cool the electronic equipment as well as to remove that hydraulic oil heat which is above the heat-sink capacity of the hydrazine.

A battery system for Dyna-Soar is not illustrated. However, in a typical system, a multiple-cell battery supplies d-c power directly to the equipment and a-c power through a static inverter. Hydraulic-pump and cooling-blower power is provided by electric motors. Power for the reaction controls must be provided from a separate system.

The results of a weight-trade study of battery and hydrazine APU systems are shown in figure 2. The effect of mission duration on the two systems for the given power level is very apparent. For mission times greater than approximately 30 minutes, the APU system offers a significant weight advantage, even when dual APU prime movers are compared with a single battery. The basic weight, or 100 percent point, is that for a dual APU system on a 2-hour flight. For the same flight, the battery system is approximately 140 percent of the hydrazine APU system weight. Additional significance of the weight-time difference is realized when the design objective of a 4-hour flight is considered.

At this point the battery system is over 200 percent of the hydrazine system weight. For this particular illustration, two-stage turbines, each with a specific fuel consumption of 5.0 lb/hp/hr, and a secondary type, silver-oxide--zinc battery rated at 22 lb/kw-hr (including case and mounting provisions) were used. These values are considered to be representative of equipment which will meet performance, timing, and reliability requirements for Dyna-Soar. The selection of these systems was based on battery and APU investigations which will not be discussed here.

In general, the lower the specific fuel consumption of an APU system, the lower the system weight. For that reason alone, a hydrogen-oxygen bipropellant APU system deserves special consideration. Because of the much higher energy content of the hydrogen-oxygen fuel, the specific fuel consumption obtainable may be 30 to 40 percent of that for hydrazine. In addition, if liquid or very cold hydrogen is used, its heat-sink capability (approximately 2,000 Btu/lb) may be used rather than that of water to absorb waste heat from the power-generating and power-using equipment, as well as aerodynamic heat. A typical system using cold hydrogen and oxygen is illustrated in figure 3. This system is very similar to the hydrazine-fueled system; the main differences are the use of bipropellants instead of a monopropellant, the replacement of water heat exchangers with hydrogen heat exchangers, and the control of fuel flow to satisfy both power and cooling demands. This last difference will require careful system analysis and design to prevent interacting effects between the power and cooling control loops.

The largest drawback to the use of liquid hydrogen is the large heavy tank required because of the low-density extremely cold fluid involved. A development holding much promise for lighter weight and simpler storage is the storage of hydrogen in insulated thin-wall tanks at pressures above critical pressure and at temperatures initially below critical temperature. A vacuum-jacketed Dewar type tank is not required. The hydrogen temperature is increased by heat transfer into the storage tank from ambient air and/or by the controlled addition of heat from electric heaters. The heat input is so controlled that, as fluid is withdrawn, the remaining hydrogen is maintained at a constant pressure. The critical pressure of hydrogen is about 13 atmospheres. Therefore, to be conservative, the hydrogen is stored well above critical pressure at approximately 20 atmospheres (300 lb/sq in. abs). Theoretically, the fluid, which can be called "supercritical," stays as a homogeneous material and will have no liquid-vapor interface. A small fan might be used within the tank to handle any temperature stratification. Thus, the fluid should be expellable in a predictable and consistent condition. Not only does this type of tankage allow controlled expulsion of the fluid, but dense storage as well. A tank volume not much greater than that [redacted]ed for liquid storage should result. This system should be almost as simple as a high-pressure ambient-temperature gaseous storage system and be just as controllable. In addition, the system has a heat-sink capability almost as great as that for liquid storage but does not have the complexity of a helium pressurizing medium and/or a pump system.

A weight comparison of the hydrogen-oxygen system, using supercritical storage, and the hydrazine system indicates that, for a 2-hour typical mission, weight savings of approximately 180 pounds can be achieved when the savings in the secondary power system and in the equipment cooling system are considered. The crew compartment cooling system is not included. Although the oxygen is required only for power generation, if it is stored as a liquid or in a "supercritical" state, some heat-sink capacity is provided. This heat-sink capability is relatively small, however, and has not been considered in the weight comparison given.

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ENVIRONMENTAL CONTROL

The two main considerations for environmental control are the pilot and the equipment. The pilot must be provided with a breathable atmosphere controlled to pressures and temperatures which will allow him to perform efficiently. No less important is the provision of a pressurized atmosphere and a temperature-controlled environment for the equipment - upon whose satisfactory operation the pilot and vehicle are so dependent.

In figure 4 is shown a block diagram of one approach to crew compartment environmental control. It represents an atmosphere supply carried in vacuum-jacketed and insulated tanks as a mixture of liquid oxygen and liquid nitrogen. This mixture is in the ratio of 40 percent oxygen and 60 percent nitrogen by weight. In a total pressure of 7.35 pounds per square inch absolute (18,000 feet), the oxygen partial pressure will be 2.6 pounds per square inch absolute (5,000 feet). This mixture is expelled from the tanks as a liquid and is passed through cold-plate cooled electronic equipment where it cools the equipment and is changed to a gas in the process. The proper ratio of oxygen and nitrogen in the gas is thus assured. As breathable atmosphere, it is ducted through essentially two loops - one is through the pilot's pressure or ventilation suit and the other is through the cabin. The pressure suit is not required under normal system operation but is included as a precaution against cabin decompression. A blower circulates the air through the equipment and around the compartment. A water-boiler heat exchanger is in the circuit to remove heat. A back-pressure control on an overboard steam vent regulates the water boiling temperature. In addition, carbon dioxide and water absorbers are shown, since a very low leakage cabin is assumed. Most of the external heat is removed in the water-wall panels on the outside of the pressure shell. This provides a near isothermal boundary around the compartment. The water-wick wall panel is discussed more thoroughly in a subsequent section.

In figure 5 is shown a block diagram of the equipment-compartment environmental control. Liquid nitrogen is vaporized to provide an atmosphere pressurized to 10 pounds per square inch gage in an open-cycle low-leakage rate system. One blower, driven by an APU, circulates the nitrogen through the equipment and around the compartment. The other blower is unloaded to reduce power consumption. The heat picked up from the equipment and that which enters through the exterior insulation is removed by a water-boiler heat exchanger. A combination of water-boiler and hydrazine heat exchanger is used to cool the hydraulic-system oil as it returns from the control-surface actuators and before it enters the hydraulic pump. The water boiling temperature is regulated by a simple orifice in the overboard vent line; therefore, temperature actually varies somewhat with load on the boiler. An investigation of the equipment-compartment cylindrical pressure shell indicated little structural weight penalty in pressurizing to 30 pounds per square inch gage. However, 10 pounds per square inch gage is used as a favorable compromise of compartment leakage rate, blower power required, and cooling effectiveness. The use of hydrogen as a heat sink instead of water is an alternate approach for equipment cooling which was discussed in the section on secondary power.

In order to determine the environmental control systems as illustrated in figures 4 and 5, pilot and equipment requirements are determined and system design approaches studied. For the pilot, the partial pressure of oxygen required, breathing requirements, pressure- or ventilation-suit requirements, allowable temperature range for ambient air and cabin wall surfaces, pressurization requirements, moisture and carbon dioxide concentration limitations, and potential fire hazard are among the more important items to be determined. For the equipment, cooling, pressurization, and temperature range allowable are determined. In addition, an analysis to determine the air temperatures which will surround the crew and equipment compartments is made for the range of flight conditions contemplated. The temperature range and rate of change of temperature have considerable effect on the selection of the environmental control system and a particularly significant effect on the thermal insulation needed for the compartments.

The more important of the crew-compartment studies are studies of (1) system cycle, that is, open as compared with closed, (2) cryogenic cooling as compared with cryogenic plus water cooling, (3) wall cooling as compared with no wall cooling, (4) internal wall cooling as compared with external wall cooling, (5) cabin atmosphere and pressure, (6) crew-compartment humidity, and (7) crew-compartment carbon dioxide.

The determining factor in the selection of the type of cycle to be used for the crew-compartment environmental control system is the compartment leakage rate. The minimum system weight for either open or closed system occurs at a leakage rate of 0.15 to 0.25 pounds per minute. At lower leakage rates, the controls required for humidity, carbon dioxide, and partial pressure of oxygen increase the weight. At higher leakage rates, the penalty is due to the greater atmosphere supply which must be carried.

The primary factors in the study of cryogenic cooling as compared with cryogenic and water cooling are leakage rates and heat load. Water has approximately five times the heat sink of an equal weight of oxygen and nitrogen mixture. The heat loads which can be carried by the cryogenic mixture will depend on the flow rate to meet leakage requirements.

A study of heat transfer through the cabin walls will determine the necessity of removing heat at the walls to keep the inside wall and compartment temperature at tolerable levels for the pilot and equipment. If wall cooling is necessary, several approaches can be used; for example, (1) cabin air can be circulated through wall panels and then through a water-boiler heat exchanger for cooling, (2) internally or externally located panels can be filled with water, or (3) water can be circulated through wall panels or tubing. Careful consideration particularly must be given not only to the heat-removing capability and weight, but also to the reliability.

Cabin atmosphere and pressure level are determined primarily from consideration of human factors, structural weight, and fire hazard.

Similar studies are made for equipment-compartment environmental control. Without the pilot's requirements to consider, however, the results are often very different, particularly in regard to atmosphere composition, temperature, and pressure level.

EFFECT OF UTILIZATION SYSTEMS

The secondary power and environmental control systems perform essentially service functions; that is, they exist only to enable other systems, such as flight control, communications, guidance, and data acquisition, to perform their assigned jobs. Because of this service

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role, their size and cost, in addition to the efficiency of their particular design, are greatly dependent upon the demands of the utilization systems and upon the efficiency with which the utilization equipment makes use of these services. The following are a few examples. These examples actually represent good "horse-sense" design consideration but illustrate the point and are too frequently given inadequate attention.

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(1) The flight control system requires that hydraulic fluid be provided at flow rates and pressures which will actuate the control surfaces to meet vehicle stability and control requirements. If, however, hydraulic power is requested which represents maximum control surface rate and hinge moment at highest "q" conditions and for maximum "g" maneuver and is represented as a continuous demand on the hydraulic system, even though not actually required, the hydraulic system installed to meet this demand would be considerably oversized for actual flight requirements. Not only would the hydraulic pumps, transmission lines, accumulators, reservoirs, and the control-surface actuators be overly large, but also a larger APU and fuel system, a larger heat exchanger, and more water for cooling would be required. All this is in addition to structural provisions for the greater than necessary volume and weight which result.

(2) In electronic equipment, emphasis is usually given to compact packaging and efficient arrangement of components for electronic reasons. Too often, however, the benefits of this packaging are lost to the vehicle because of prohibitively high cooling requirements. To be more specific, certain items of electronic equipment can be adequately cooled with an airflow rate of 4 pounds per minute per kilowatt at an inlet temperature of 70° F. Other equipment of the same type requires as high as 10 to 12 pounds per minute per kilowatt at 70° F. This requirement naturally is reflected back into blower, heat exchanger, and ducting size as well as additional fuel to provide for additional power. A detailed check of some of these packaging practices has shown that cooling requirements can be greatly reduced by simple rearrangement of components with the aim of more efficient heat transfer and still not impair the performance of the component.

(3) Other items which can unfavorably affect the overall vehicle in terms of excessive secondary-power and environmental-control provisions are (a) excessively close frequency and voltage control for electrical supply system, (b) too low temperature and too high pressure-drop requirements of electronic equipment, and (c) greater than needed attitude resolution for reaction control at high altitude.

On a conventional jet airplane (such as the Boeing B-52 or the Boeing 707) where secondary power is extracted from the main engines (either by a shaft or by compressor bleed air) and pressurized air for

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breathing and cooling are also extracted from the engine by bleed air or by ram air, the preceding considerations are also valid. However, the penalty of additional power extracted from the main engines, additional ram air, and additional weight is a minor reduction in range. The effect of added secondary power and environmental-control weight has added significance on Dyna-Soar, however, where weight is the determining factor in whether the vehicle can be boosted into the desired flight trajectory with a given booster.

DEVELOPMENT TESTS

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Two development tests of special interest in secondary power and environmental control for Dyna-Soar are (1) a hot-gas system for reaction controls, in which hydrazine is decomposed in a centrally located gas generator, and (2) passive water-wick panels for providing a heat barrier around crew and equipment compartments. Both of these developments are of a feasible or exploratory nature and are not developments of completed flight hardware.

HOT-GAS SYSTEM

Development studies of reaction-control-system requirements indicated the need for a system with very rapid response characteristics. These requirements, in conjunction with vehicle considerations for low weight, low fuel consumption, and compatibility with the high temperature environment associated with a radiation-cooled structure, pointed up the attractiveness of a hot-gas reaction control system. The feasibility of an on-off gas type of reaction control system was demonstrated on a three-degree-of-freedom flight simulator. Compressed nitrogen gas was used for these tests, pending the development of a hot-gas supply system. A central hot-gas system using a monopropellant showed promise of meeting the basic requirements with a minimum weight penalty.

The purpose of these hot-gas development tests was twofold: (1) to establish the feasibility of maintaining hot-gas supply pressure and temperature under simulated operating conditions using hydrazine and (2) to obtain gas-supply-system design parameters for future system designs.

An operational mockup of a hot-gas reaction control system was set up. (See fig. 6.) It initially contained a pressurized fuel supply, a gas generator, relief valve, and three combination on-off valves and thrust nozzles; that is, one nozzle each for pitch, yaw, and roll. A

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volume of distribution piping equivalent to that required for supplying gas to an additional 3 nozzles was provided. A fuel-metering valve was later added to provide a constant system gas pressure regardless of demand. The injector for the gas generator in this system mockup was water-cooled. This cooling prevented the heat "soak-back" from the gas generator from causing premature decomposition of the hydrazine in the fuel line. The equipment used does not represent flight hardware but rather development hardware for demonstrating feasibility of approach.

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Tests in which the valves were cycled manually for various reaction jet pulse lengths and also in which the valves were cycled automatically in conjunction with a computer program which simulated flight operation conditions were made. Computer studies of the reaction control system have shown that "thrust" demand will be short in relation to "no thrust" demand. Since the gas system will thus be dead-ended for a large percentage of time, the temperature of the gas at the nozzle will be considerably less than at the gas generator. Low ambient temperatures at the nozzle plus the dissociation of the ammonia in the gas reduce the temperature. In order to pursue the effect of temperature reduction on specific impulse, tests were made with insulated piping at a regulated gas-generator pressure of 160 pounds per square inch gage. Under full flow condition, this pressure represented a nozzle inlet pressure averaging 120 pounds per square inch gage. Oscillograph traces of pressure show this drop from a system pressure of 160 pounds per square inch gage to 120 pounds per square inch gage to be almost instantaneous with the valve opening. In figure 7, the average nozzle-exhaust temperature after system warm-up is plotted against duty cycle. Pulse durations of 0.020 and 0.400 second were used. Good agreement of temperature data was obtained for the same duty cycle for different pulse durations. Duty cycles are not expected to approach the 40 percent mark except for a brief period required for vehicle stabilization at separation from the booster, and for a brief period for orienting the vehicle for reentry. A duty cycle of less than 1 percent would be typical of most of the high-altitude flights.

Figure 8 illustrates the effect of the previous temperature data on the effective specific impulse I_{sp} at the nozzle. Since reduced specific impulse means more fuel for a given total impulse, it seems to indicate that adequate consideration of temperature drop in a system must be given along with duty cycle to minimize fuel requirements for various flights. However, as shown in figure 9, when the same basic data are plotted in terms of specific fuel consumption (SFC), or pounds of fuel used per pound of thrust in one hour of operation, a somewhat different impression is obtained. For the longer duty cycles, higher temperatures at the nozzle and, therefore, higher effective I_{sp} are maintained. For the shorter duty cycles, the temperature at the nozzle

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and the effective I_{sp} are reduced. At these shorter duty cycles, the difference in SFC is so small as to make questionable the payment of the weight penalty for duct insulation. This curve also illustrates the desirability of a short duty cycle to achieve minimum fuel consumption.

In addition to design data obtained, the important conclusions which were reached as a result of this testing were:

(1) A central hot-gas system using hydrazine is technically feasible

(2) The hydrazine-gas generator can be operated in a self-sustaining manner for substantial periods of time with no gas being exhausted from the system. The operation is self-sustaining without the use of oxidizers or external heat

(3) A simple fuel-metering system to maintain a constant system gas pressure can be built as flight hardware

(4) A hot-gas valve with adequately fast response time can be built as flight hardware

(5) Careful consideration must be given to fuel-injector cooling, or possibly the elimination of the need for injection cooling, in the design of flight hardware.

WATER WICK PANELS

If, for a particular vehicle design, it is determined that cooling of a cabin or equipment compartment wall is necessary, it is desirable that the cooling means be a passive system, that is, be independent of pumps, blowers, or other active devices. For pilot protection in particular, it is necessary that the wall cooling be also independent of cabin pressurization. One promising approach to satisfying this requirement is the use of the water wick panel.

In figure 10 are illustrated two approaches to the water wick panels - each intended to serve as a nonstructural heat barrier between the outer skin and the cabin. The first is the tube-type panel where a water-absorbent or wicking material is placed in tubes and the tubes are filled with water. The tubes are placed next to the cabin shell with a layer of aluminum foil next to the tubes and 2 inches of insulation on the outside of the foil. The insulation is held in place with a thin sheet of steel. The steam exhaust is collected in a manifold and vented overboard. In a flight configuration, the back pressure would

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be regulated to control the boiling point at high altitude to approximately 70° F.

An earlier tube panel configuration did not include the aluminum foil over the tubes. However, a computer analysis showed that an appreciable amount of heat would flow around the tubes and cause severe temperature gradients in the cabin pressure shell. The addition of the foil causes a short which shunts the heat through the water-filled tubes and practically eliminates the temperature gradient in the pressure shell. At the same time, the percentage of aerodynamic heat allowed to flow to the cabin is reduced from approximately 30 percent to 2 percent.

The second configuration shown is termed a vapor-cooled insulation type. In this configuration, the wicking material is held against the pressure shell by a semipermeable membrane. This membrane will pass water vapor but not water at the design operation conditions. The water vapor passes through the insulation layer and out through the perforated steel retention sheet. The steam is vented overboard from the space between the outside skin and the panel.

Several materials were tested for suitability as a wick. One of the better materials is fiber glass in a mat of unbonded "B" fibers. Figure 11 illustrates the water-retention capability of three samples of varying height. The significant point of these data is that, for this material, the practical water wicking limit is approximately 8 inches. The average wetness ratio, or pounds of water per pound of wick, drops off rapidly above this wick height.

Another important consideration in choice of wick height is the water-retention ability of the wick under acceleration loads. Centrifuge tests of a saturated wick showed that water retention is markedly affected above an acceleration of 4g. Individual panel design must, therefore, account for boost accelerations and provide panel sizes which will permit the wicking action to redistribute the water in a reasonable time. More testing will be required to establish the specific sizes required.

The next illustration (fig. 12) shows the test results at 140,000 feet of a vapor-cooled-insulation type of panel. Heat lamps were used to raise the temperature of the perforated steel shield to 1,600° F. The temperatures at various points through the panel at its center are plotted against time. The wick material reached 100° F in 53 minutes when the water had been almost expended. In figure 12 is shown the temperature distribution in the water wick at 140,000 feet over a 12-inch by 18-inch panel. The significance of wick height is again illustrated. Those temperatures measured in the lower half of the panel are considerably lower than those measured at the top of

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the panel because the water-retention capability of the wick is reduced at these upper locations, as previously shown in figure 11.

The exhausting of steam through the insulation has two main advantages: (1) the weight of a steam-collecting manifold is eliminated, and (2) the superheating of the steam as it passes through the insulation lowers the insulation temperature and, therefore, reduces the insulation conductivity. An analysis indicates that approximately 20 percent less water is required for a given heat input because of the vapor-cooled insulation.

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Tests were made at sea level to establish the feasibility of the tube-type panels. Test panels were constructed with two rows of 8-inch water tubes. Heat lamps were used to raise the temperature of the outside steel sheet to 2,000° F. (See fig. 13.) After 22 minutes of operation, the temperature on the inside surface of the acoustical insulation had not exceeded 105° F, even though the water boiled at 212° F, as compared with 70° F to 80° F boiling temperature at high altitude.

There are other approaches to the application of water to passively cooled panels. However, these tests firmly establish that the water-wick configurations described here are feasible designs directly applicable to Dyna-Soar.

CONCLUDING REMARKS

Feasible systems and two significant developments in secondary power and environment control for the Dyna-Soar vehicle have been presented. Additional studies and developments along with the latest vehicle requirements will establish the actual systems configurations.

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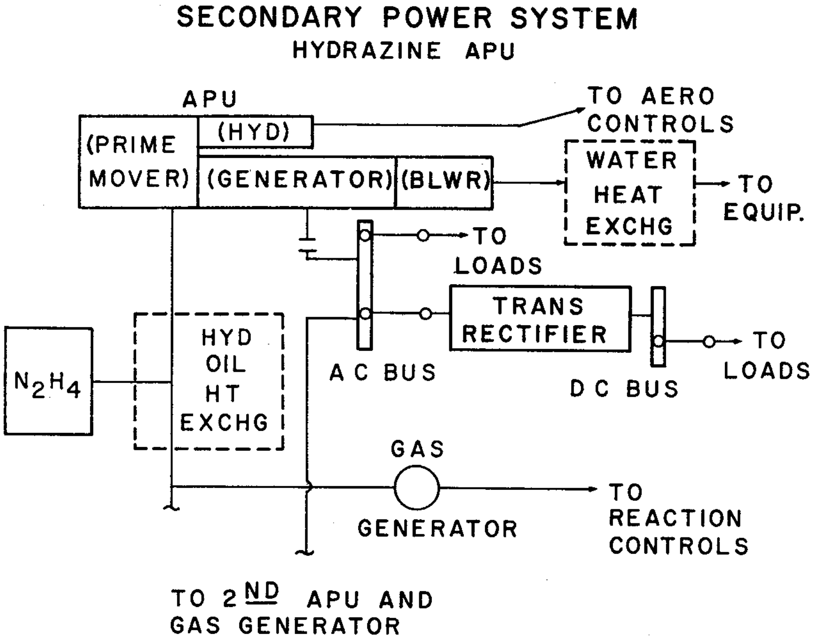
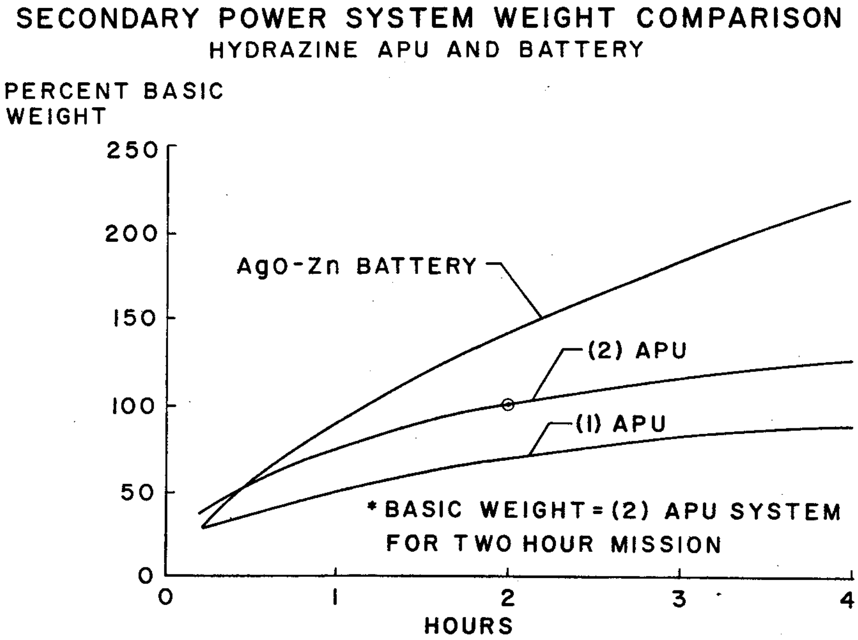


Figure 1



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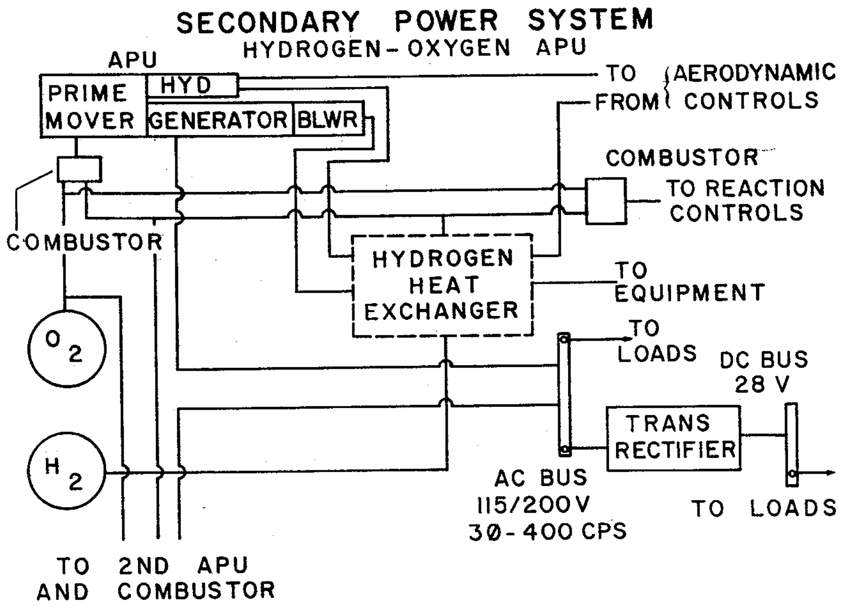

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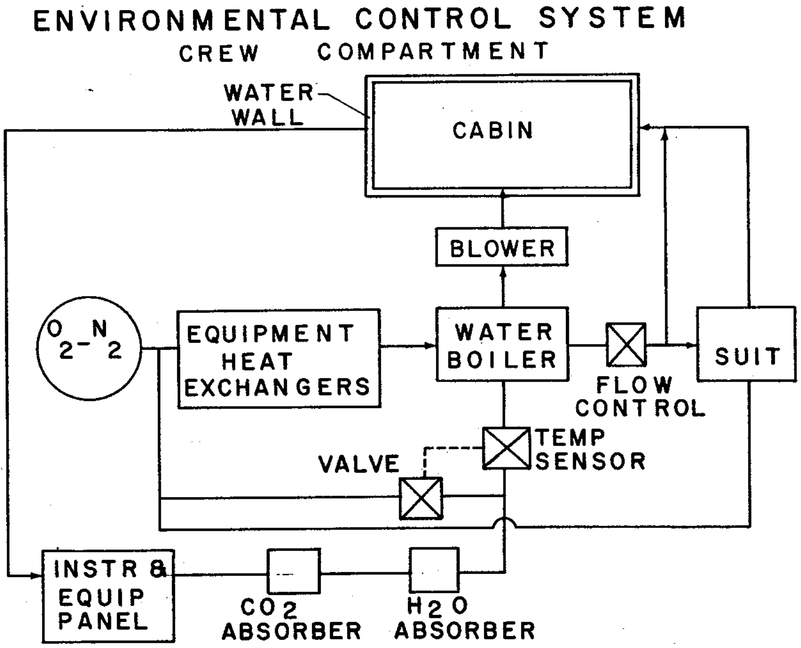

Figure 4

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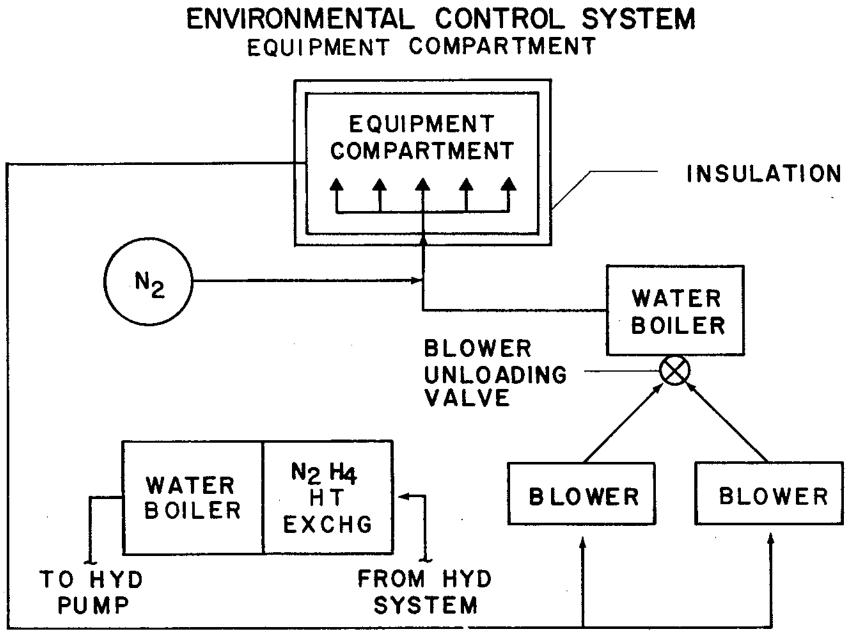

Figure 5

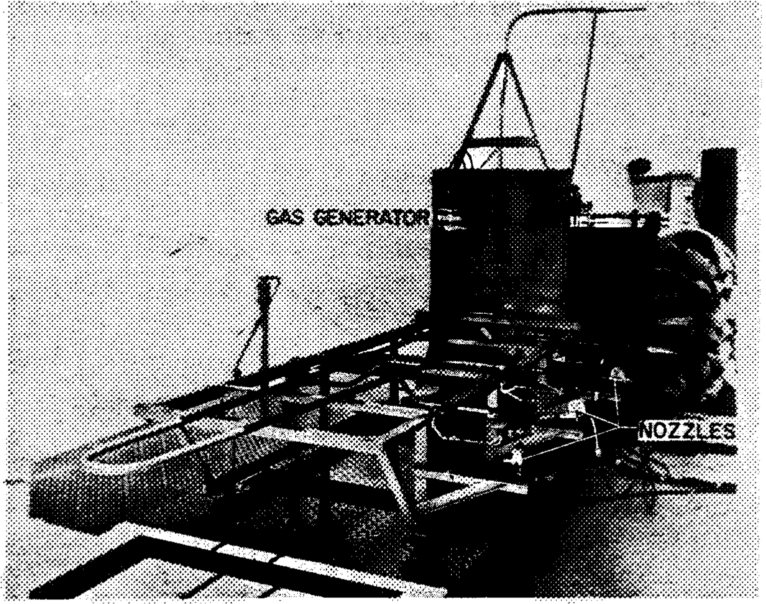

Figure 6

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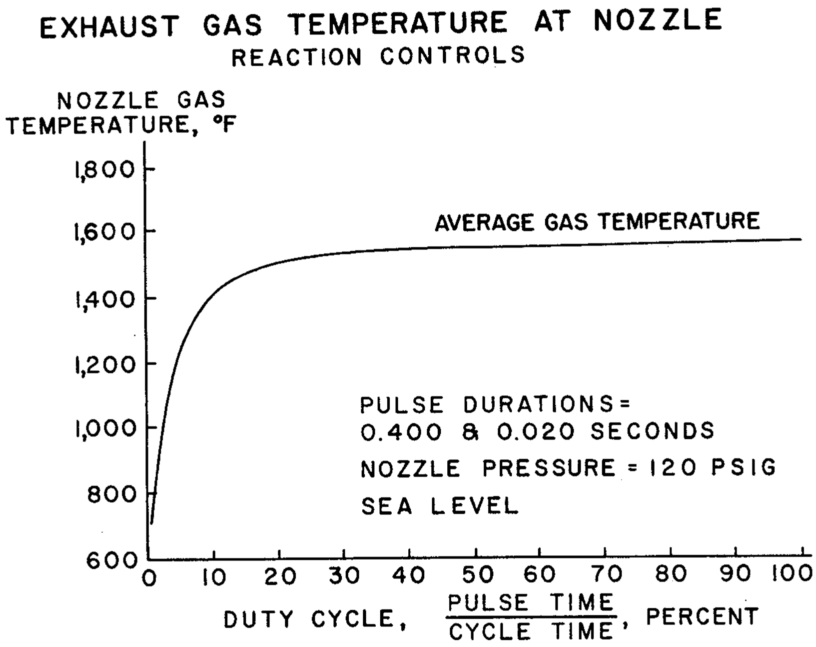

Figure 7

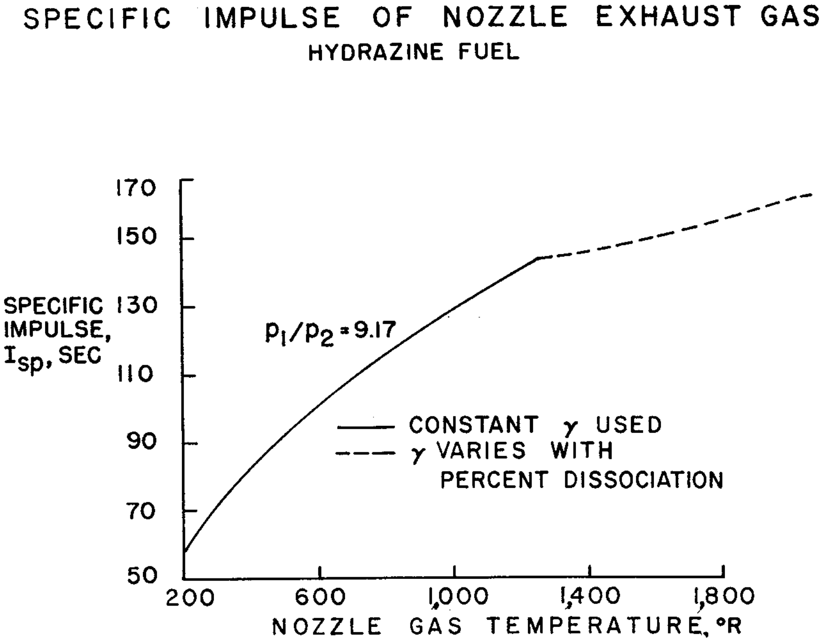

Figure 8

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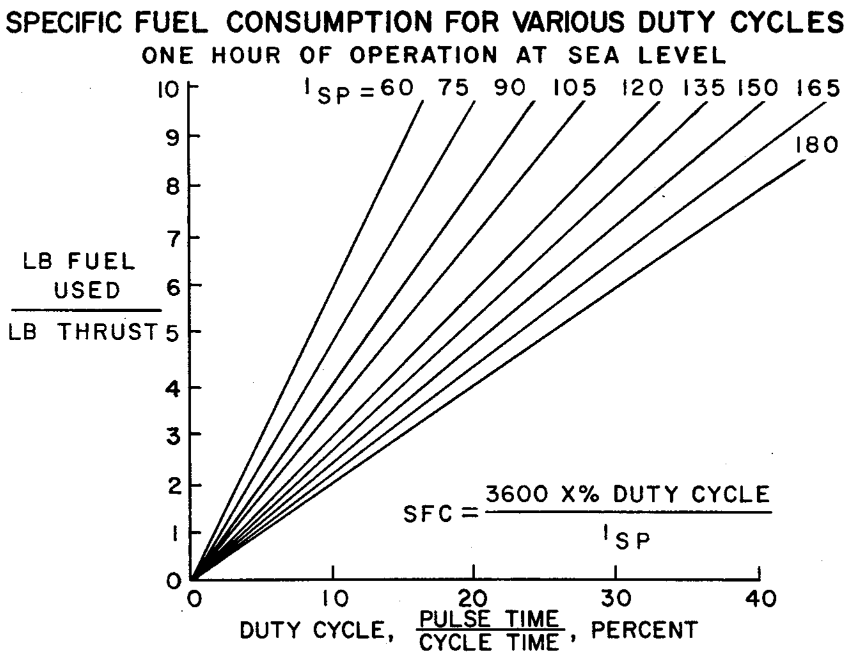

Figure 9

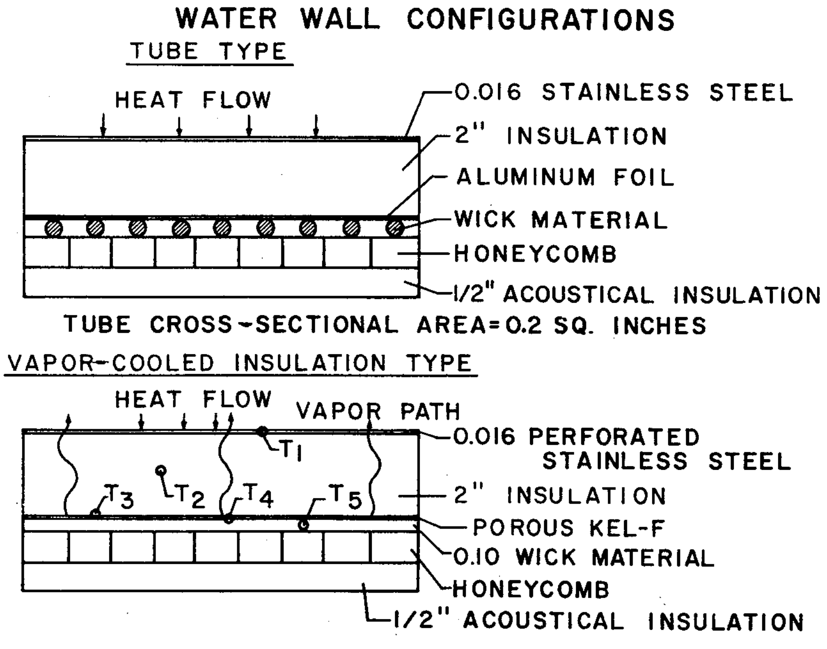

Figure 10

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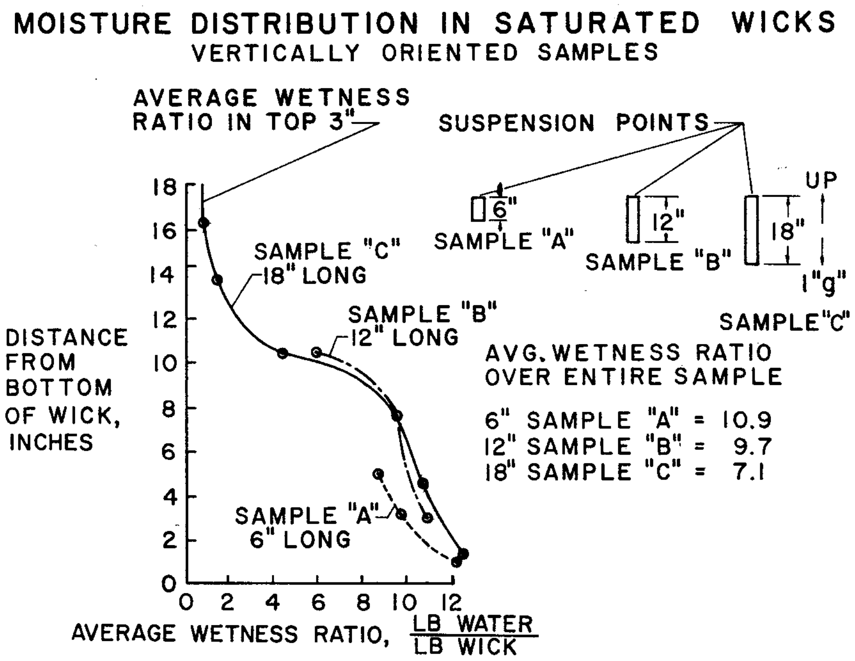

Figure 11

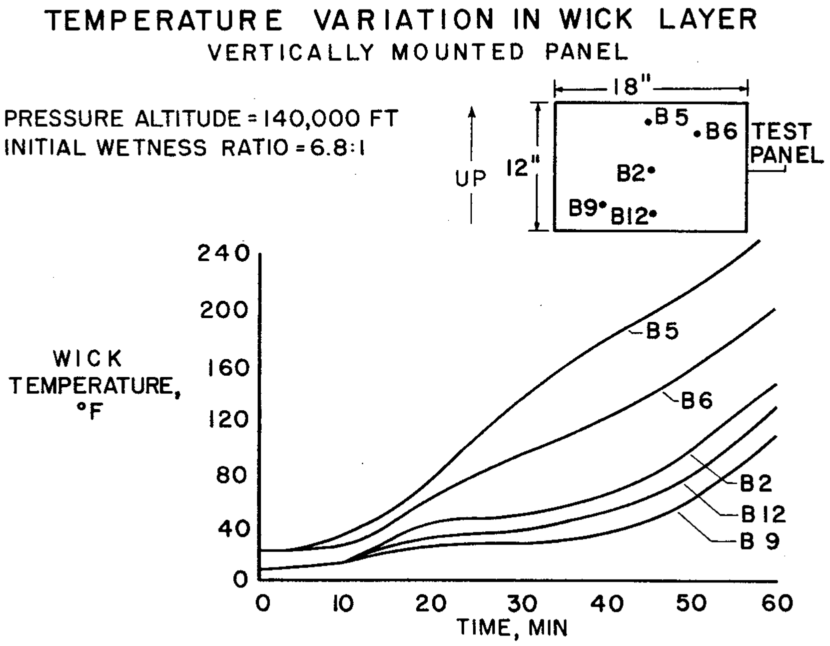

Figure 12

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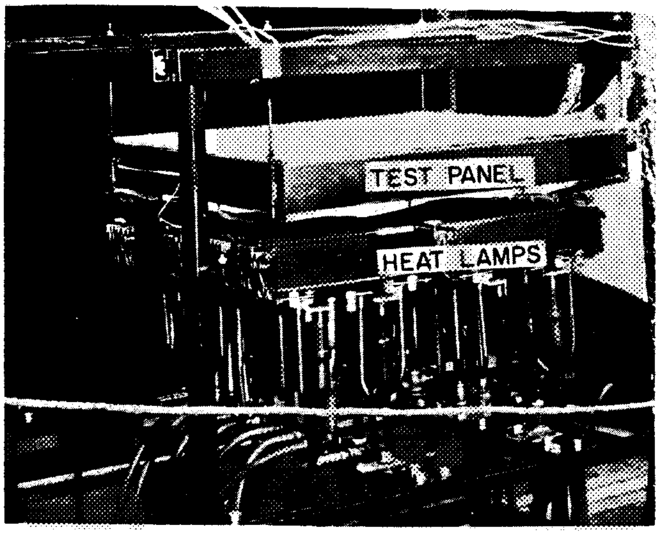

Figure 13