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APPLICATION OF A RESONANT COMBUSTOR TO ARMY AIRCRAFT ENGINE STARTING

By

R. L. Binsley

February 1971

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

CONTRACT DAAJ02-70-C-0001

ROCKETDYNE
A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION
CANOGA PARK, CALIFORNIA

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The report describes a feasibility study of starting an Army aircraft that uses a resonant combustor as the basic power source. Starting of both main engines and auxiliary power units was considered.

This directorate concurs with the findings and conclusions contained herein.

Task 1G162203D14416
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February 1971

APPLICATION OF A RESONANT COMBUSTOR TO ARMY AIRCRAFT ENGINE STARTING

Final Report

Rocketdyne Report R-8384

By

R. L. Binsley

Prepared by

Rocketdyne
A Division of North American Rockwell Corporation
Canoga Park, California

for

EUSTIS DIRECTORATE
U.S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
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13. ABSTRACT

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ABSTRACT

This report describes the results of a 13-month study of the feasibility of starting Army aircraft by means of starting systems utilizing a resonant combustor as the basic power source. Starting of both main engines and auxiliary power units (APU) was considered. Alternative starting techniques were assessed and compared with present techniques. The engine and APU starting techniques that best utilize the unique advantages of the resonant combustor were then studied in more detail. Installation layouts of these systems were prepared to allow assessment of the characteristics and application problems of these systems.

FOREWORD

This report was prepared by Rocketdyne, a division of North American Rockwell Corporation. It summarizes work done in the period beginning 1 September 1969 and ending 30 September 1970 under Contract No. DAAJ02-70-C-0001, Task 1G162203D14416. This contract was administered by the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory (USAAVLABS), Fort Eustis, Virginia. Mr. Graydon Elliott was the technical monitor for USAAVLABS. The work was performed by Mr. R. L. Binsley under the cognizance of Mr. R. S. Siegler, Project Engineer, and Mr. V. R. Degner, Manager.

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SUMMARY

Rocketdyne has conducted a study to determine the applicability of a resonant combustion unit for starting of Army aircraft engines. This study is based on the Army's need for multiple-start attempts without external recharge at -65°F. A resonant combustor can provide hot gas to drive a turbine which, in turn, produces torque to drive the item to be started, a hydraulic pump, etc. After the resonant combustor has been started, it need only be supplied with fuel to continue operation. This resonant combustor and turbine combination is called Resodyne.*

The approach taken in the present study was to determine the requirements for starting of a typical advanced aircraft system. The system chosen for study was a twin-engine, 16,000-lb gross weight utility aircraft. Detailed requirements were established by direct contact with those vehicle manufacturers who had performed studies of an aircraft of this nature. A specific auxiliary power unit (APU)--the Solar T-62T-2A--and a particular advanced engine--Pratt & Whitney ST9--were selected as typical for this application.

The major characteristics of the presently selected starting systems for this aircraft were determined to allow comparison with the resonant combustion system. A number of alternate systems utilizing the resonant combustion approach to starting both APU's and engines were defined. Each system was designed to be self-contained, that is, to work without external power or energy sources. For each of these systems, the major characteristics of weight, reliability, and cost were estimated on a preliminary basis.

APU STARTING SYSTEMS

Table I presents results of the preliminary system comparison for the starting of an APU. Weights for each system were estimated by performing a preliminary sizing process. Relative failure rates and costs were determined for all systems using the same estimating procedure. A major difference among the systems described in Table I is that the present systems are only capable of starting at -25°F. In the case of the present hydraulic system, only one start attempt is possible without an external recharge. A winterized version of the present hydraulic system will start the APU at -65°F, but only one attempt can be made without external recharge. Estimates were also made for a hydraulic starting system capable of providing three starts without recharge at -65°F to allow comparisons on an equal capacity basis.

The Resodyne systems show two versions with weights comparable to those of the present starting systems. All Resodyne systems were sized to provide three starts at -65°F. The direct-start system substitutes the Resodyne for the hydraulic or electrical motor as the torque source on the APU starter pad and utilizes fuel as the energy source rather than the accumulator or battery of the present systems. The Resodyne multiple-start/winterization unit is used as a supplement to the present APU hydraulic starting system. This system has two major functions: it heats the APU lubricating oil to

*Trademark registered

TABLE I. SYSTEM COMPARISON FOR STARTING OF APU'S

System	Starts With 2-Minute Intervals: Number	Starts With 2-Minute Intervals: Temperature (°F)	Weight (lb)	Relative Failure Rate*	Relative Cost
Present Hydraulic	1	-25	24.8	1.0	1.0
Present Winterized Hydraulic	1	-65	45.8	1.37	1.20
Present Winterized Hydraulic	~3	-65	108.8	2.48	1.68
Present Electrical	3	-25	40.0	0.26	0.87
Resodyne Direct Start	3	-65	51.5	2.69	1.38
Resodyne Hydraulic Winterization, Direct Pump Drive	3	-65	98.6	1.39	3.14
Resodyne Hydraulic Winterization, Inertial Energy Storage	3	-65	79.9	1.43	3.14
Resodyne Multiple Start/Winterization	3	-65	58.2	1.44	2.89
Resodyne Electrical Winterization, 3-Minute Initial Start	~3	-65	135.0	2.06	3.34
Resodyne Electrical Winterization, 15-Minute Initial Start	~3	-65	86.0	9.34	2.95

*Assuming 90% of operation above -25°F, 10% below reduce drag and required start energy, and it recharges or tops off the charge in the start accumulator. This system may do either or both of these functions, as required.

To attain three-start capability at -65°F, the multiple-start/winterization system was selected for further study. This system is significantly lighter and more reliable than a three-start version of the present winterized hydraulic system. It is slightly heavier but more reliable than a direct-start Resodyne system. Since the multiple-start/winterization system is an add-on to the present one-start hydraulic starting system, it should integrate easily. It also offers much flexibility with respect to mounting location in the vehicle, since it is not mounted on the starter pad of the APU.

ENGINE STARTING SYSTEM

Table II summarizes the results of comparative study of engine start schemes. In the case of the engine starting schemes, a comparison of present systems with Resodyne systems is complicated by the question of comparable function. The present engine starting systems use the APU as the energy source. The APU performs other vehicle functions as well. If an APU is not present in the vehicle, the present starting systems are incomplete, that is, they have no energy source with which to start the engine. Engine starting systems using a hydraulic accumulator as the energy source have, therefore, been sized both for one and for three starts. These systems provide a better standard of comparison when no APU is present. The accumulator systems are based on use of a fiber glass accumulator with a bladder-type separator that was found to be significantly better than current piston-type accumulators or metallic accumulators with bladder separators.

For multiple starts at low temperature without an APU, the Resodyne hydraulic accumulator recharge is much lighter in weight and more reliable than the best hydraulic accumulator system. A Resodyne direct-start system using a hydraulic power transmission would be somewhat lighter in weight, but much less reliable. Therefore, the Resodyne recharge system was selected for further study.

PRELIMINARY DESIGN STUDY

In the second phase of this contract, layouts of the selected APU and engine starting systems were made. Means were also studied for adapting these systems to a typical aircraft configuration. The layouts showed that the multiple-start/winterization system for APU starting would be slightly heavier than estimated in Table I, while the Resodyne recharge system for engine starting would be approximately the same as shown in Table II. The layouts and integration work disclosed some specific areas that require further investigation, mostly of an experimental nature. These areas include heat exchanger operation and control, interaction of the heat exchanger with the Resodyne, interaction of the Resodyne with exhaust ducting, and interaction of exhaust ducting with the aircraft skin.

TABLE II. SYSTEM COMPARISON FOR STARTING OF ENGINES

System	Starts With 2-Minute Intervals: Number	Starts With 2-Minute Intervals: Temperature (°F)	Weight (lb)	Relative Failure Rate*	Relative Cost
Present Hydraulic	- ***	-65	31.0	1.0	1.0
Present Hydraulic Including APU	∞ ****	-65	126.8	11.12	7.61
Present Pneumatic	- ***	-65	50.0	1.25	1.06
Present Pneumatic Including APU	∞ ****	-65	145.8	10.02	7.80
Hydraulic With Accumulator Energy, Fiber Glass Accumulator	1	-65	124.6	1.41	1.37
Hydraulic With Accumulator Energy, Fiber Glass Accumulator	3	-65	315.0	2.08	2.11
Hydraulic With Accumulator Energy, Piston Accumulator	1	-65	202.1	1.41	1.26
Hydraulic With Accumulator Energy, Piston Accumulator	3	-65	547.5	2.08	1.65
Resodyne Direct With Hydraulic Transmission	3	-65	145.9	4.55	2.09
Resodyne Inertial Energy With Hydraulic Transmission	3	-65	223.4	4.90	2.43
Resodyne Hydraulic Accumulator Recharge, Fiber Glass	3	-65	176.8	1.60**	2.29
Resodyne Hydraulic Accumulator Recharge, Piston	3	-65	254.3	1.60**	2.14
Resodyne Direct With Pneumatic Transmission	3	-65	229.1	3.80	2.13
Resodyne Inertial Energy With Pneumatic Transmission	3	-65	276.9	4.13	2.00

*Assuming 90% of operation above -25°F, 10% below
**50% of starter operating time below -25°F involves Resodyne operation
***Has no energy source
****Assuming APU can be started at -65°F

If multiple starts at -65°F are required, the Resodyne resonant combustion starter appears to be advantageous. For starting an APU, it can be added on to the present hydraulic starting system to give multiple-start and low-temperature capability. For starting an engine with no APU present, a one-start hydraulic accumulator (with a Resodyne for recharging) will provide multiple starts at -65°F.

An experimental program is recommended to demonstrate the ability of the Resodyne to perform satisfactorily as an APU starter in the multiple-start/winterization configuration. The program will demonstrate the feasibility of producing a starter system capable of providing multiple starts without external recharge at -65°F for advanced Army aircraft.

INTRODUCTION

NATURE OF THE ARMY AIRCRAFT STARTING PROBLEM

Trends in the design of advanced Army aircraft, especially helicopters, are in directions of increased engine pressure ratios, increased aircraft self-sufficiency, and improved low-temperature operating capability. Each of these trends has a direct and generally adverse effect on the application of present types of starting systems to advanced aircraft.

The trend toward higher engine pressure ratios is exemplified by the Pratt & Whitney (ST9) and General Electric (GE12) demonstrator engines presently under development. These engines are very compact and lightweight, yet require significant amounts of power (12 or more horsepower) and energy to start. Starting is especially difficult at -65°F and at high altitudes.

Starting at -65°F strains the capability of present starting systems, even for single starts. The increased energy required by the engines at low temperatures coincides with the decreased availability of energy from typical energy storage systems. To be able to start at temperatures below -25°F, current aircraft apparently typically require additional equipment in the form of a "winterization kit."

The requirement for aircraft self-sufficiency means that the start system must be capable of providing multiple-start attempts without use of either ground power sources or manual recharging. Therefore, the starting system must be able to store and control a large amount of energy. A common approach to self-sufficiency is to store the energy in the form of fuel and to convert it to power in an APU. This approach is quite convenient in those cases where the APU is required for other purposes in the aircraft. If the APU is not required to supply power for other purposes, the availability of an alternate starting system would allow the APU to be dropped from the aircraft with a considerable saving in cost.

If an APU is used for engine start, it can easily supply the required starting power and energy. However, starting of the APU presents the same type of problem as starting the engine, except on a smaller scale. The lower power level of the APU means that somewhat less power and energy are required from the starting system. The same limitations in capability of current starting systems still apply.

Clearly, a new approach to Army aircraft starting is desirable. A starting system is desired that can provide multiple-start attempts at low temperatures and is not energy limited. Such a device is the Resodyne resonant combustion-driven starter. The main purpose of the present study is to determine the best manner of applying the Resodyne to aircraft starting and to compare it with present starting system concepts.

DESCRIPTION OF RESODYNE

Resodyne is a device with the potential for providing an essentially unlimited number of starts at temperatures down to -65°F. It can be made either completely or partially self-contained. It can operate on any fuel suitable for the gas turbine to be started. The number of starts without recharging is limited by the amount of fuel and start air stored in the Resodyne system.

Principles of Operation

Resodyne is essentially a resonant combustor combined with a turbine. The resonant combustor produces high velocity hot gases from available ambient pressure air and pressurized vehicle applicable fuel. These hot gases are passed through a turbine wheel producing torque. The turbine torque may be used either as direct starting torque (i.e., substituting for an electric or hydraulic starting motor), or may be used to provide power to drive another device (e.g., hydraulic pump). The basic energy source for the Resodyne is the chemical energy released by combustion of the fuel with the air. This operating principle is illustrated in Fig. 1.

Operation of the resonant combustor is initiated by providing a steady supply of pressurized fuel and an initial burst of start air and spark energy. Once combustion has been initiated, the combustor need only be supplied with pressurized fuel to continue operation. During operation, it continues to induce its own air as part of the combustion cycle. Such a system can easily be made self-sufficient (i.e., independent of all external sources of energy). A description of this combustor cycle may be helpful in understanding the application of the Resodyne.

Figure 2a shows a basic combustor configuration consisting of air valves, a combustion chamber, and tailpipe. (Combustion chamber is slightly ambiguous nomenclature for that part of the combustor between the valves and tailpipe, since combustion also occurs in the tailpipe.) The air valves function as check valves, allowing air to pass only from left to right (into the combustion chamber). Exhaust gases flow out the tailpipe--which may be a single tube as shown in Fig. 2 or any number of parallel flow passages of approximately equal length. Some of the important geometric parameters affecting the performance of the resonant combustor are combustion chamber length, ℓ_c, combustion chamber diameter, d_c (or cross-sectional area if noncircular), tailpipe diameter, d_e (or cross-sectional area if noncircular or multiple), and acoustic length, ℓ (measured from inlet air valves to end of tailpipe).

Figure 2b shows a very simplified version of an analysis technique known as a wave diagram.[1] The abscissa of this diagram is the distance along the combustor measured from the valves. The ordinate of the diagram is time measured from some arbitrary time such as the occurrence of an explosion in the combustion chamber. The solid lines on this diagram represent pressure waves, while the dashed lines represent expansion waves. The circled numbers 1 through 4 represent specific time periods during a complete combustor cycle.

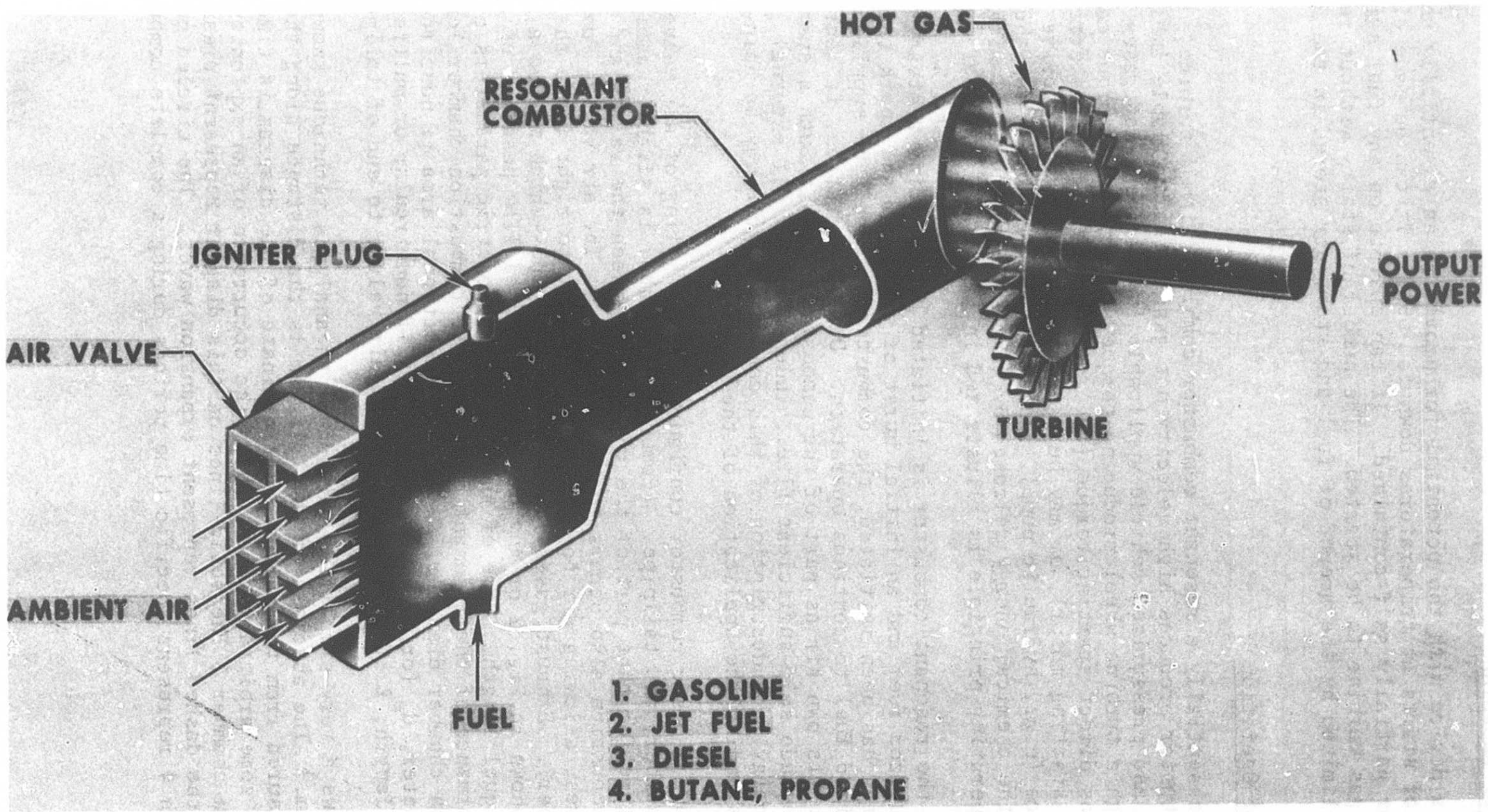


Figure 1. Resodyne Operating Principle.

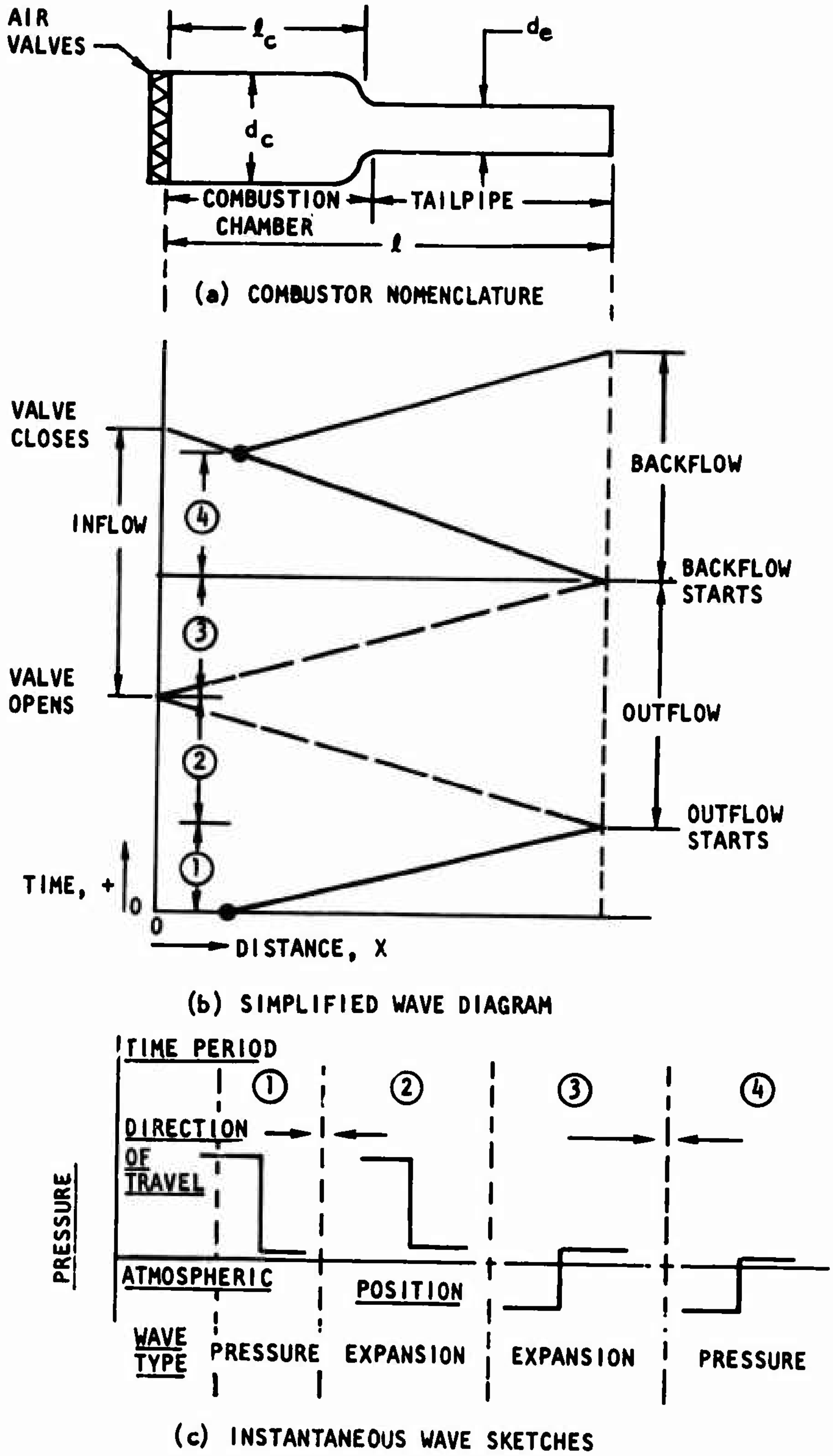


Figure 2. Resonant Combustor Operation.

The significance of the pressure and expansion waves of Fig. 2b may be better understood by referring to Fig. 2c. Each of the four sketches in Fig. 2c represents a plot of pressure versus distance in the vicinity of the respective wave front at an instant of time. The numbered cycle conditions refer to the same time periods as shown in Fig. 2b. Arrows pointing to the right indicate that the wave is traveling toward the open end of the tailpipe, while those pointing to the left indicate wave travel toward the valves. It will be seen then that pressure waves compress the fluid so that the pressure at a given position is higher after the wave has passed. Expansion waves, on the other hand, lower the pressure as they pass.

With the help of these diagrams, a single cycle of combustor operation can now be described. At time zero, the first rapid combustion occurs, sending a pressure wave from the combustion chamber toward the tailpipe. At the end of time period 1, that pressure wave reaches the open end of the tailpipe. As that pressure wave passes out of the open end of the tailpipe, fluid from the tailpipe flows out to the atmosphere. As the wave passes through the open end of the tailpipe, an expansion wave is reflected from the open end back up the tailpipe toward the valves. When this expansion wave reaches the valves, the valves open, allowing a fresh charge of air to flow into the combustion chamber. That expansion wave is reflected from the solid boundary of the valves as another expansion wave, which travels back toward the tailpipe in time period 3. When this expansion wave reaches the open end of the tailpipe, outflow from the tailpipe ceases and backflow into the tailpipe from the outside begins. The expansion wave is reflected from the open end of the tailpipe as a pressure wave which travels back toward the valves during time period 4. This pressure wave precompresses the mixture in the combustion chamber and helps to initiate ignition of the charge. The whole cycle is then repeated with a pressure wave again heading toward the tailpipe.

A cycle corresponds roughly to four trips of waves along the acoustical length of the combustor traveling at roughly the speed of sound in the gas. The frequency of cyclic operation thus will be equal to $a/4\ell$ cps, where "a" is an average speed of sound in the gas. Thus, the resonant combustor in this form acts as a quarter-wave resonator or organ pipe.

A turbine with proper blade shape can now be placed at the end of the combustor tailpipe. The hot gases flowing out of the tailpipe into the turbine rotor will create torque. A complication in this turbine combustor combination is that, during part of the cycle, flow is actually occurring backwards through the turbine rotor into the combustor tailpipe. Proper design such as that described in Ref. 2 can satisfactorily handle this backflow condition.

Development Status

The original development work on the Resodyne concept was begun at Rocketdyne with company funds and was subsequently funded in 1965 under the auspices of what is now the Army's Mobility Engineering Research and Development

Center (MERDC). The original development system[3] utilized two separate resonant combustors each with a single tailpipe driving one turbine disc. The packaging and simultaneous operation of two separate combustors created some development difficulties.

An improved and simplified version, Fig. 3, utilized a single combustor with multiple tailpipes.[4] Specifically, four tailpipes emanating from a single combustor were wrapped in a spiral configuration and directed against a single turbine. The configuration was symmetrical, and was therefore economical and compact compared to the two-combustor version originally conceived. Most of the subsequent development work has been done with this configuration. This includes endurance testing and environmental testing.

An even more compact configuration[5] incorporating spiral-annular tailpipe passages has been evolved. A version of this combustor utilized in a Resodyne demonstrator unit is shown in Fig. 4. While considerable progress has been made with this last configuration, some thermal problems have not yet been satisfactorily resolved.

Other testing and sizing work done by Rocketdyne since development was initiated is summarized in Fig. 5. As indicated, low-temperature, altitude, and multiple fuel operation tests have all been successfully conducted. The Resodyne is developed to a status where multiple tailpipe configurations may be designed and developed to suit any specific application over a wide range of powers.

PRESENT STUDY

The objective of the present study was to determine the applicability of the Resodyne to advanced Army aircraft. The approach taken was to select a typical advanced aircraft system that had been studied at some length. Possible ways of applying the Resodyne concept to this specific aircraft were then considered. Finally, the most promising of these concepts were examined in more detail to determine some of the specific problems and solutions associated with integration of the Resodyne into such advanced Army aircraft.

Aircraft Configuration

The advanced aircraft chosen as typical of future Army systems is a 16,000-lb gross weight twin-engine utility vehicle. Such a configuration has been extensively studied by Lockheed Aircraft, Bell Helicopter, Vertol, and Sikorsky. Each of these manufacturers was surveyed to determine his presently proposed solution to the starting problems and to define starting system requirements for an alternative starting system type such as the Resodyne. Based on these surveys, a definition was obtained of typical present starting systems. These systems are discussed in some detail in the next section. The survey also allowed construction of a composite set of requirements for alternative starting systems. From these designs, criteria were developed for the possible Resodyne systems, which are presented later in this report.

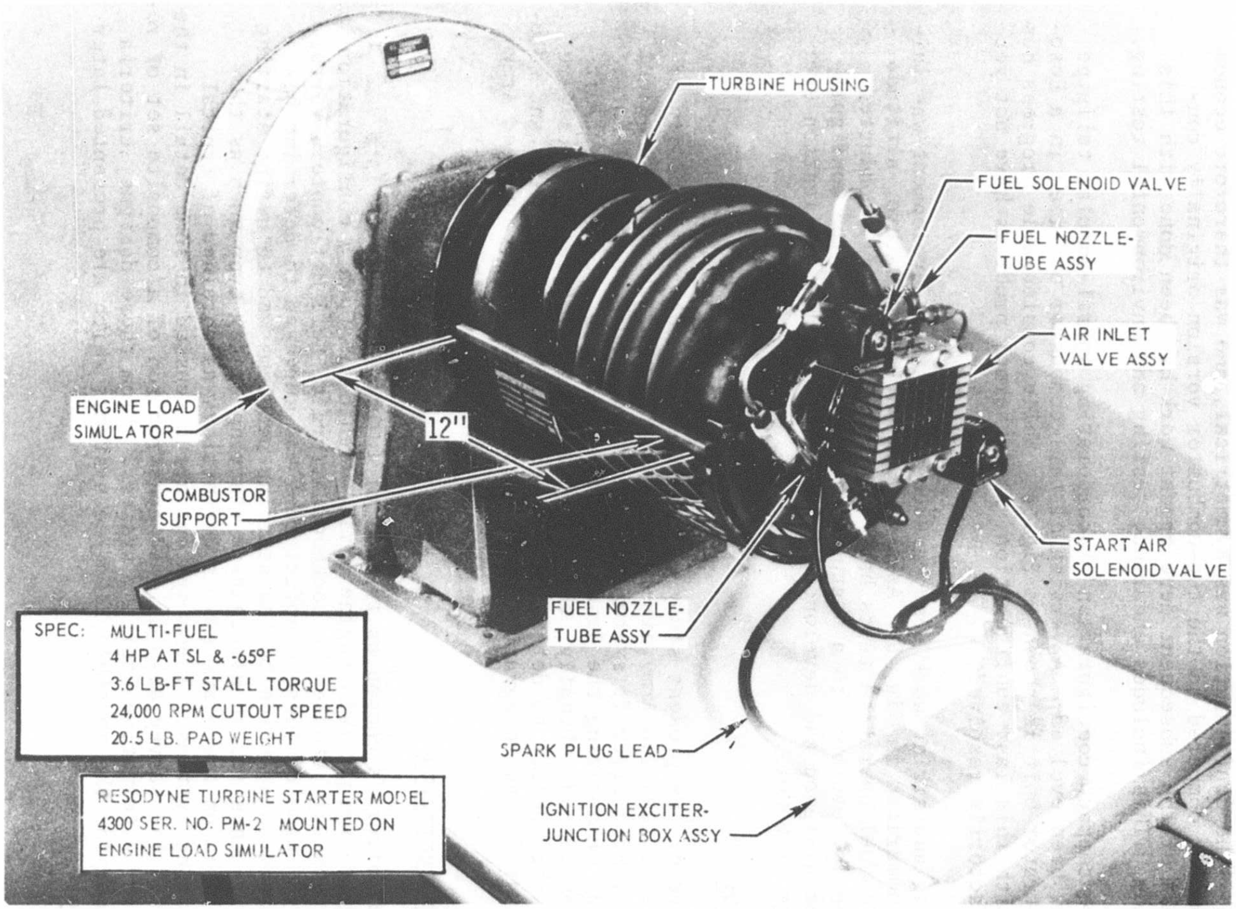


Figure 3. 300-hp MERDC Turbogenerator Starter.

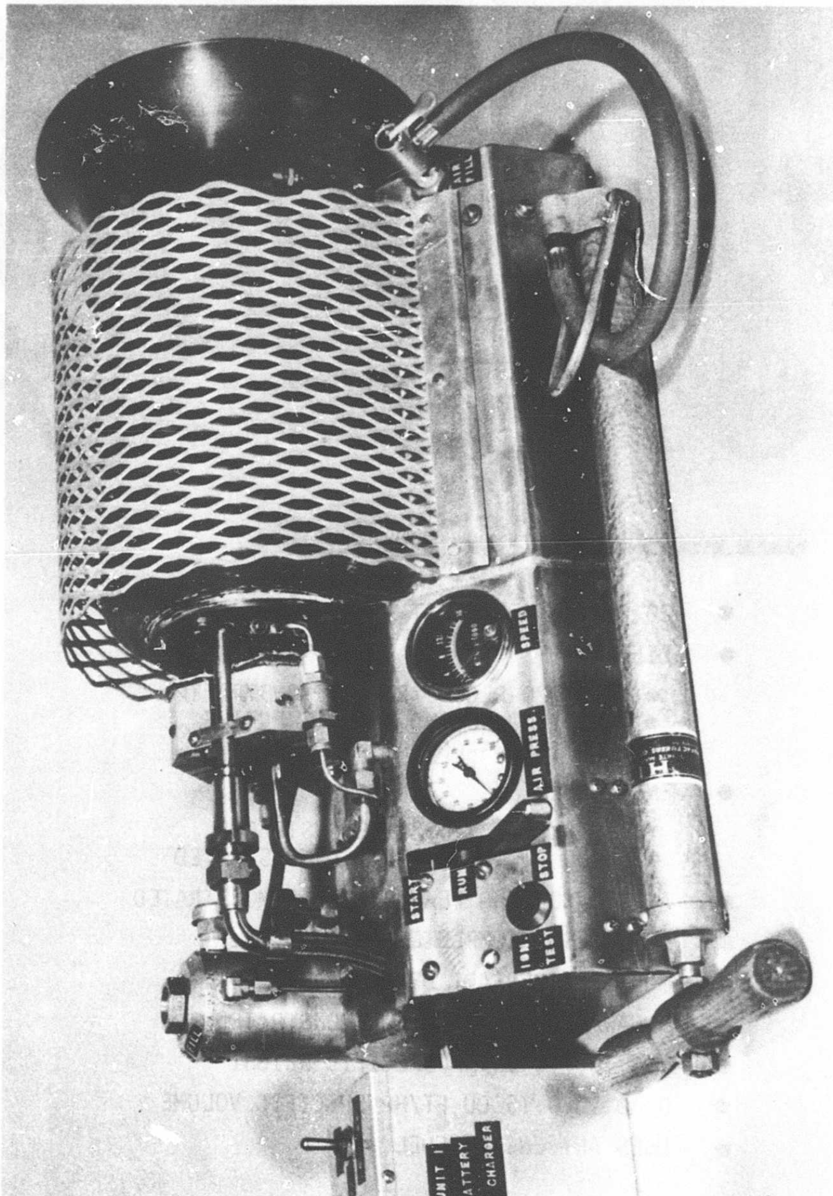
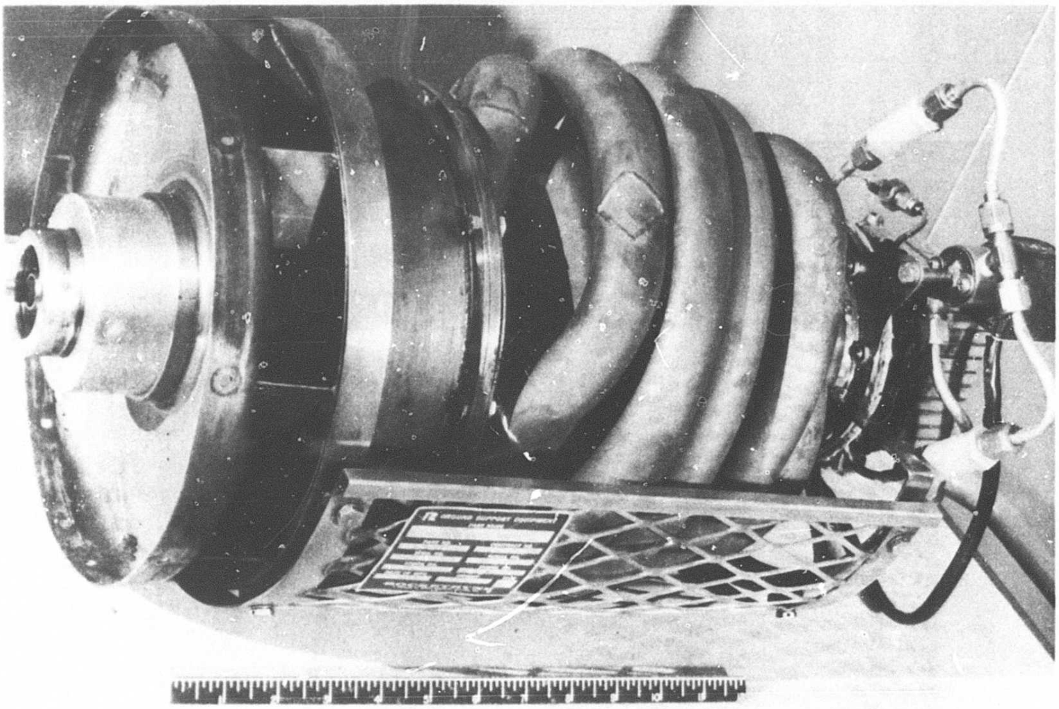


Figure 4. Resodyne Demonstrator Unit.



- 20 CU IN. AIR/START AT 60 PSI
- LIFE
  - 500 30-SECOND RUNS DEMONSTRATED
  - 2000 30-SECOND RUNS OBJECTIVE
  - CONTINUOUS-OPERATION OBJECTIVE
- ENVIRONMENT
  - SEA LEVEL, -65°F DEMONSTRATED
  - 8400 FT, 55 TO 85°F DEMONSTRATED
- ACTIVE COOLING FEASIBILITY DEMONSTRATED
- 9000 TESTS COMPLETED
- MULTIPLE RESTART DEMONSTRATED
- RUNAWAY SPEED LIMITS DEMONSTRATED
- 2.3 TO 7.0 LB/HP SPECIFIC WEIGHT
- 0.10 TO 0.15 CU FT/HP SPECIFIC VOLUME
- USES ANY ENGINE FUEL

Figure 5. Resodyne Performance.

Figure 6 shows the general arrangement typical of a version using hydraulic starting of the engines. In this version, the APU can be mechanically coupled to the utility gearbox portion of the main gearbox. Power to drive the utility gearbox and thus the hydraulic pump may be supplied either by the APU or by one or both of the main engines. The alternative APU location sketched in Fig. 6 might be typical of a system with a pneumatic start of the main engines. Ducting would carry the pressurized air from the APU to the engines for start. In this latter case, considerable flexibility is possible with respect to APU-- hence APU starter location. In the former case where the APU is mechanically coupled to the gearboxes, much less flexibility with respect to APU location exists.

All the manufacturers surveyed included APU's in their aircraft. The major stated reason for this was an Army requirement that additional power for ground checkout should be available in specific quantities. The only feasible way to supply this additional power was by means of an APU. In this case then, the particular Army mission dictates the use of an APU in the aircraft system.

The general configuration of the aircraft is also shown in Fig. 6. The other major factors affecting the starter system design are the specific APU and engine characteristics associated with the particular APU and engines used in the vehicle. The following sections discuss the selection of the typical APU and engine and their starting requirements.

APU Selection

The survey of aircraft manufacturers disclosed that the average power to be expected for an APU used on the selected vehicle was approximately 100 hp. None of the manufacturers had made a firm selection of an APU. One manufacturer suggested that a Solar T-62 APU would probably be used. Discussions with a Solar representative produced a suggestion that the T-62T-2A aircraft APU be selected as representative of that which would be used on this vehicle. This APU has a sea level maximum power output of 95 hp with a normal rating of 66 hp at sea level standard conditions.

The T-62T-2A APU does not represent all the possible APU configurations. For example, it does not have bleed air provisions; therefore, it cannot be representative of an APU used with a pneumatic engine system start. In addition, its power output, as well as starting power input, takes place through a 6000-rpm, AND20002, Type XII E pad. This latter characteristic means that, since the main power output is mechanical, an auxiliary pad must be provided for the starter for either the hydraulic or the electrical APU starting system. This implies additional gearing connecting the starting pad to the main power output shaft which provides mechanical power to the helicopter gearbox. Because such an auxiliary gearbox would be required for the present starting systems, its weight was not charged against either the present starting systems or the competitive Resodyne starting systems.

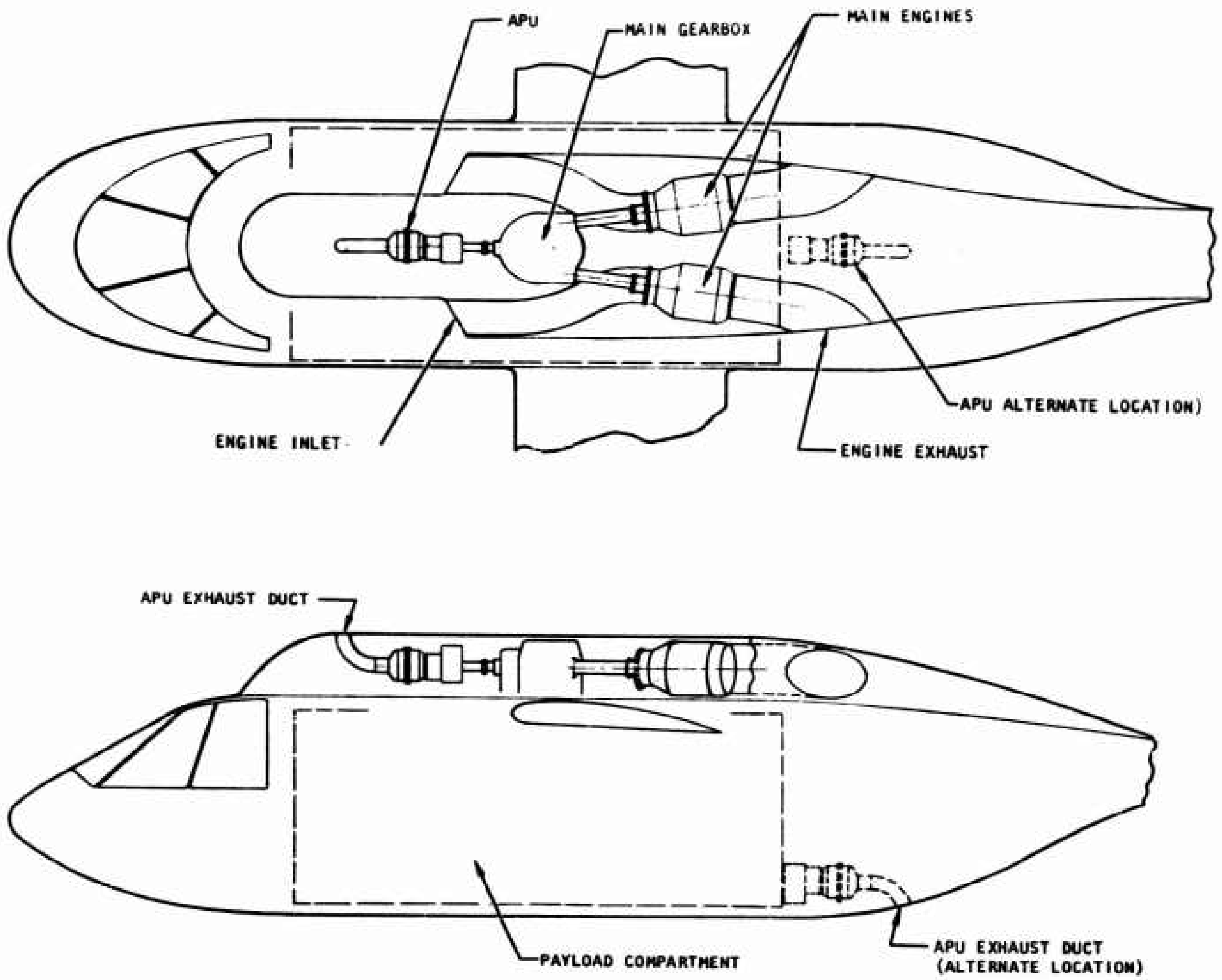


Figure 6. Typical Aircraft Configuration.

This APU was selected for purposes of the present study because the power level of the T-62T-2A is approximately the desired value, its configuration is approximately typical, and starting data are readily available. The drag characteristics of the APU during starts under various temperature conditions are shown in Fig. 7. These data and the polar moment of inertia of 6.1 lb-ft^2 referred to the output pad speed were obtained from Ref. 6.

Engine Selection

Most of the vehicle manufacturers had maintained the flexibility in their preliminary designs of using either the General Electric GE12 engine or the Pratt & Whitney ST9 engine. Demonstrator versions of both these engines are currently under development by their respective companies under contract with USAAVLABS. The engine power levels associated with a 16,000-lb gross weight vehicle are approximately 1500 hp for each of the two engines. This is the power level of the present demonstrator engines.

No compelling reason appeared to exist for selecting one engine over the other. Since data were more readily available on the ST9, it was selected as representative for this study. The ST9 cold-day drag* is shown in Fig. 8. The 10,000-ft drag values were interpolated from the other values shown. The corresponding polar moment of inertia is 9.0 lb-ft^2.

*Letter from J. N. Tulino, Pratt & Whitney Aircraft, to R. Binsley, Rocketdyne, 29 October 1969.

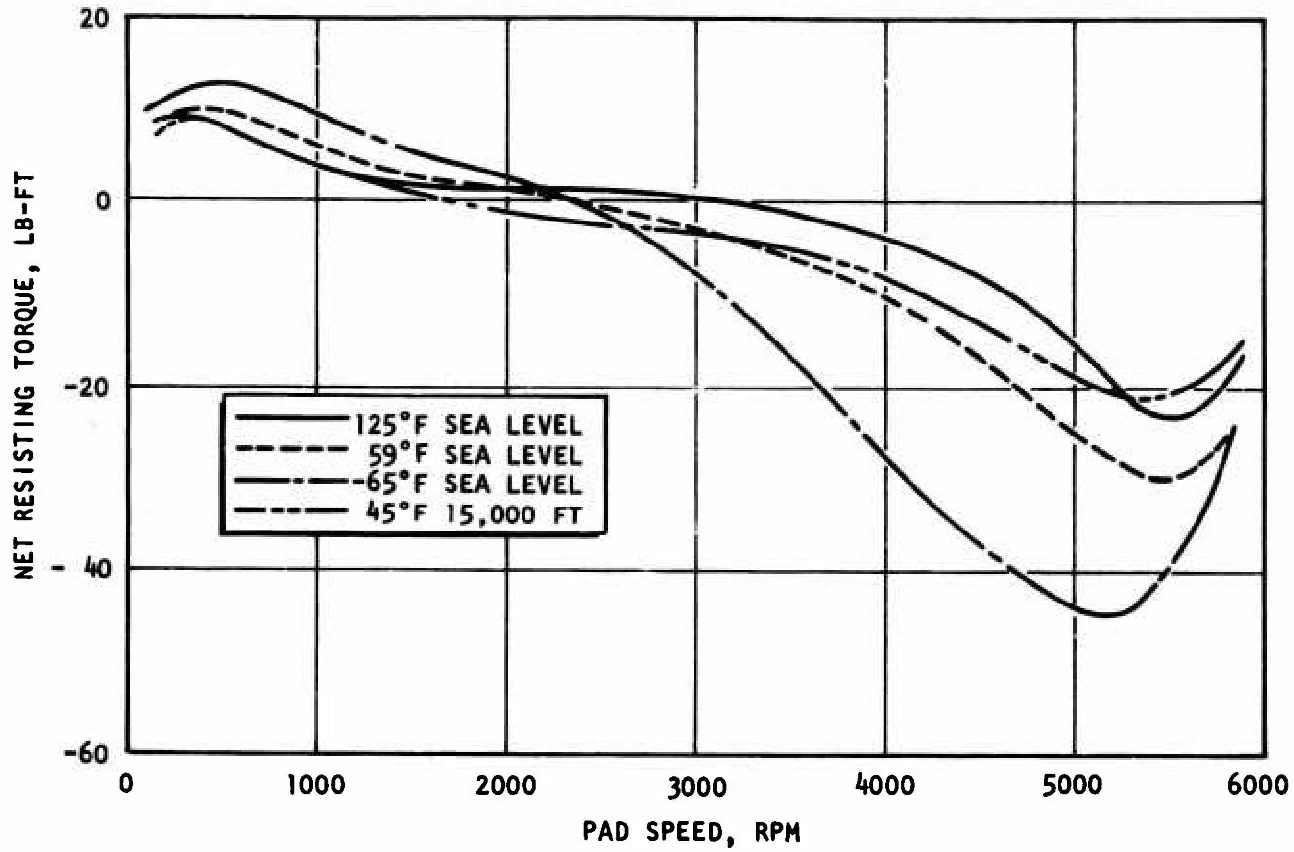


Figure 7. Estimated T-62T-2A Starting Characteristics

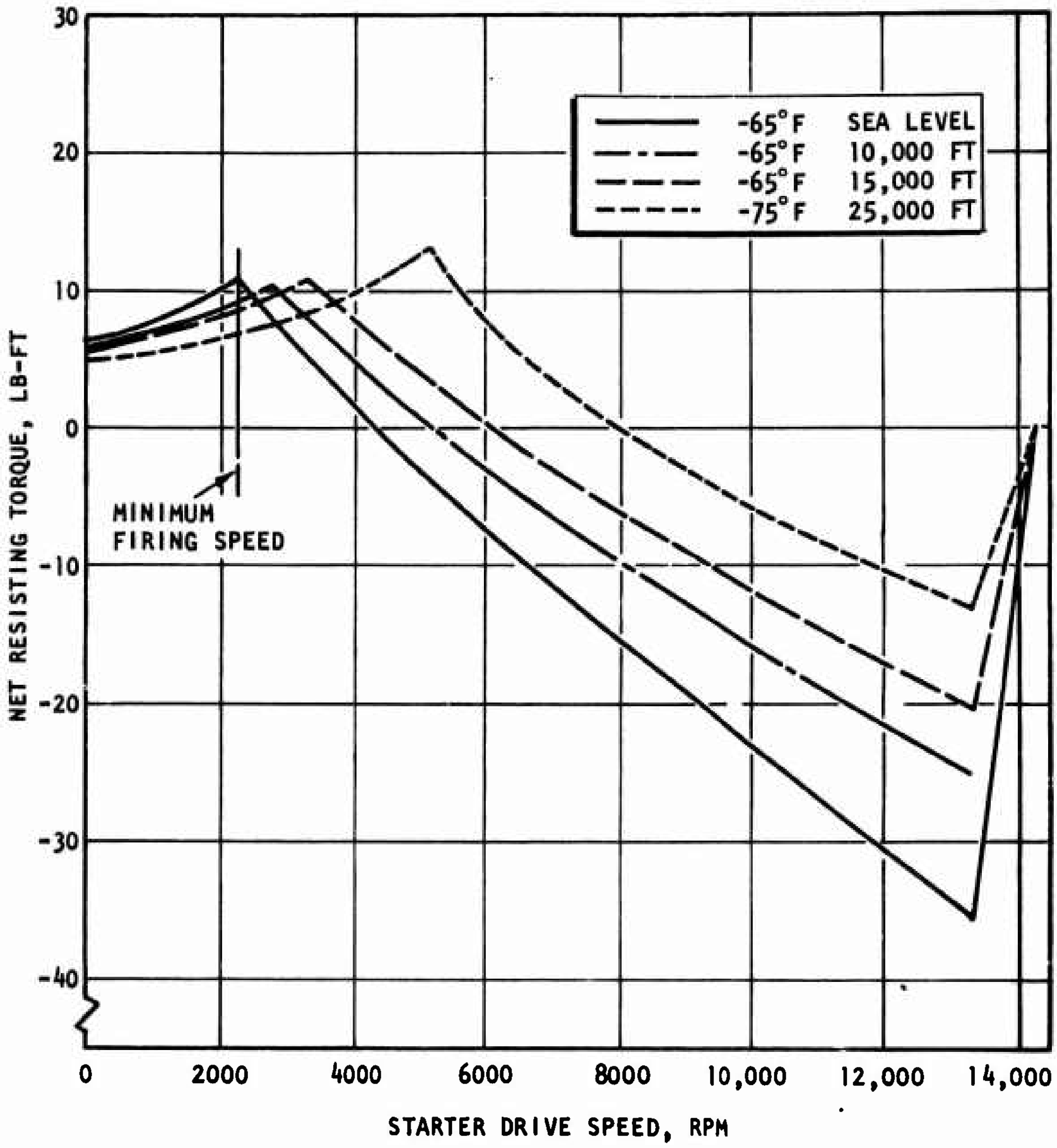


Figure 8. Estimated ST9 Cold-Day Starting Characteristics.

PRESENT STARTING SYSTEMS

APU STARTING

The survey of vehicle manufacturers disclosed that two basic kinds of systems were being proposed for starting the APU: (1) hydraulic, using a hydraulic accumulator as the primary energy source; and (2) electrical, using a battery as the primary energy source. All these systems were designed for starting at temperatures down to -25°F. To operate either the hydraulic or electrical systems at temperatures below -25°F, it would be necessary to add a "winterization" kit to the system. A brief discussion of the present hydraulic and electrical starting systems and their possible winterization kits follows.

Hydraulic APU Start System

The present hydraulic start system is shown schematically in Fig. 9. Energy stored in the accumulator is released to the hydraulic start motor on the APU when the start valve is opened. After a normal start, the hydraulic accumulator is recharged by the pump in the vehicle utility system. After an unsuccessful start attempt, manual recharging of the accumulator is required for another attempt.

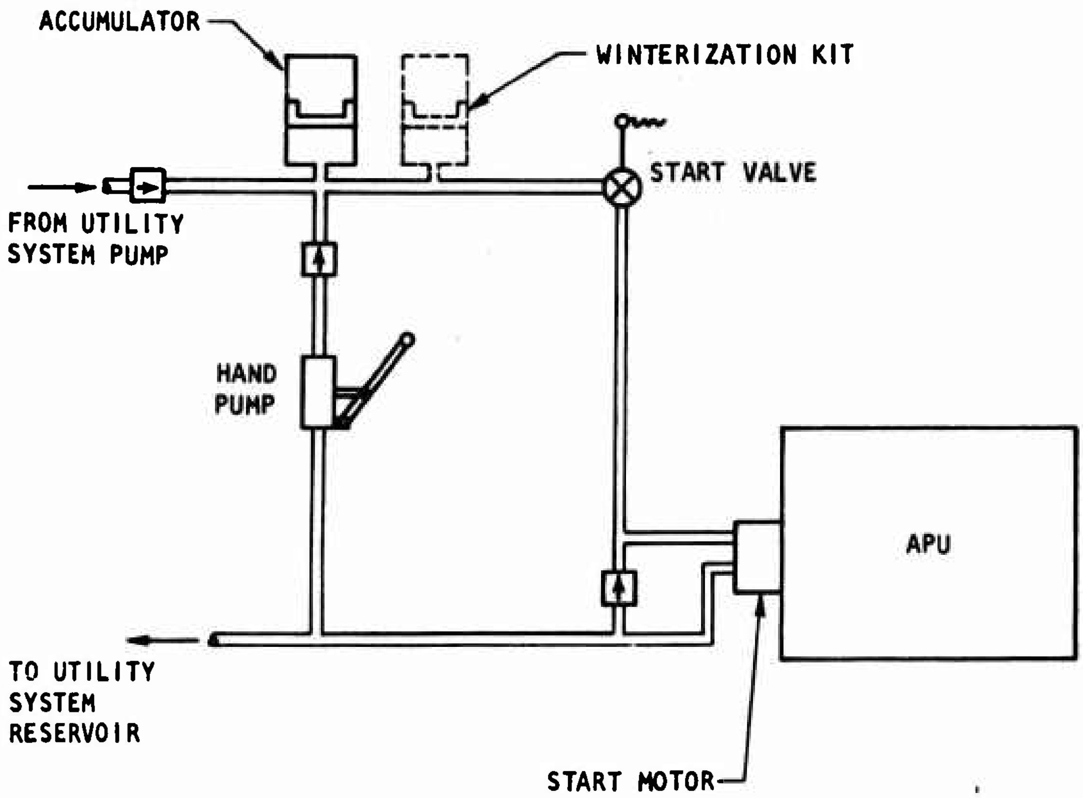


Figure 9. Present Hydraulic APU Starting System.

The weights of a typical hydraulic APU start system for a 100-hp APU are shown in Table III. The weights of the fixed-displacement hydraulic motor, start valve, and hand pump are self-explanatory. The accumulator and reservoir weights represent the additional capacity that must be placed in the system because of the use of a hydraulic start for the APU. In other words, if the APU were not started hydraulically, the accumulator could be 30% (5.8 lb) lighter and the reservoir could be about 1 lb lighter.

This total APU weight represents the weight chargeable to a hydraulic APU start system capable of a single start followed with a manual recharge if the start were unsuccessful. Manual recharging would require 286 double strokes of the hand pump. Thus, the time required for the manual recharging would be approximately 5 to 10 minutes. The system as shown will start down to -25°F.

TABLE III. HYDRAULIC APU START SYSTEM* WEIGHT

Hydraulic Motor	10.0 lb
Accumulator (30% Chargeable)	5.8
Start Valve	2.0
Additional Reservoir	1.0
Hand Pump	2.7
Plumbing and Fluid	3.3
Total	24.8 lb

*-25°F single start and manual recharge

If it is necessary to start at -65°F, a winterization kit must be provided. This essentially consists of additional accumulator capacity (i.e., additional stored energy). Data* indicate that a winterization kit for consistent starting at -65°F consists of an additional accumulator. The weights corresponding to the additional 200-cu in. accumulator and corresponding increased reservoir capacity are summarized in Table IV. A manual recharge would now require twice as many strokes and at least twice as much time as for the basic unwinterized system. A saving in weight (about 10 lb) might be realized if only 300 cu in. of capacity were utilized, since data* indicate that consistent starting can be attained with this capacity. The weight saving would be at the expense of increased cost and/or decreased reliability compared to the system in Table IV.

TABLE IV. PRACTICAL WINTERIZED HYDRAULIC APU START SYSTEM* WEIGHT

Basic Hydraulic Start System	24.8 lb
Additional Accumulator (wet)	19.4
Additional Reservoir	1.6
Total	5.8 lb

*-65°F single start and manual recharge

Electrical APU Starting System

The present electrical APU starting system is shown schematically in Fig. 10. At its simplest, it consists of a battery energy source, an electric start motor, and a relay for connecting the battery and motor.

* Personal communication from L. Blinman, Solar Division of International Harvester, Inc., 20 October 1969.

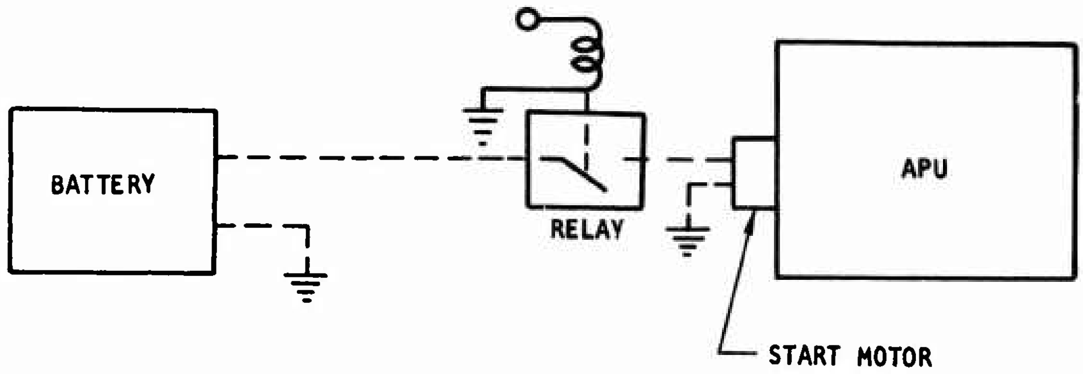


Figure 10. Present Electrical APU Starting System.

The weights of these components are summarized in Table V. The 17 lb for the motor corresponds to the lightest currently available starting motor (with relay) suitable for the T-62. The 25 lb represents the additional battery weight necessary to handle an electrical start system. If the APU were not started electrically, the vehicle would require, typically, a battery capacity of 20 amp-hr at 24 volts which would weigh about 55 lb. To start electrically, an additional 11 amp-hr of capacity is required as a minimum. In practice, the next battery size is 34 amp-hr, which weighs an additional 25 lb. The present electrical starting system is only suitable for temperatures down to -25°F. Means of winterizing the present electrical starting system for operation to -65°F have not been well defined. Therefore, no weight estimates are available. Some possible approaches are discussed later.

TABLE V. APU ELECTRICAL START SYSTEM* WEIGHT

Motor	17.0 lb
Battery Additional	25.0
Cables and Connectors	3.0
Total	45.0 lb

*-25°F starts

ENGINE STARTING

Two basic kinds of engine starting systems were used by the vehicle contractors surveyed--hydraulic and pneumatic. In both cases, the APU served as the basic source of hydraulic or pneumatic energy. Once one engine has been started using the APU, it is then possible to start the second engine using power either from the APU or from the running engine. A detailed description of these systems follows.

Hydraulic Engine Start System

A typical hydraulic engine starting system is shown in Fig. 11. Here the utility system hydraulic pump that provides the energy for operating either engine start motor is mounted on the accessory gearbox. With neither engine running, the accessory gearbox is driven by the APU through a clutch. This

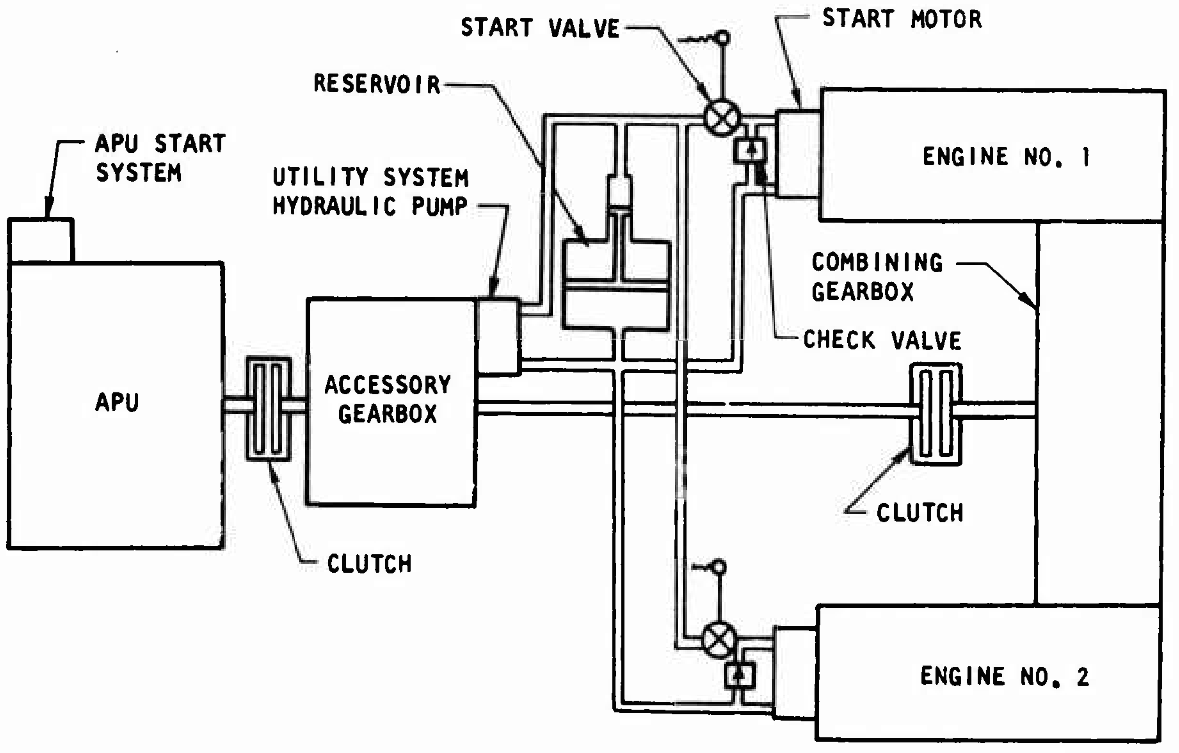


Figure 11. Present Hydraulic Engine Starting System.

arrangement allows the APU to drive accessories when neither engine is running (e.g., during ground checkout). It also allows the APU to be completely disconnected from the system and shut down when one of the engines is running. This latter is possible because the accessory gearbox may also be driven by means of a shaft from the combining gearbox that connects the two engines to the rotor.

The weights of a typical hydraulic engine starting system are shown in Table VI. These weights represent the weight that could be removed if the engine were not started hydraulically. The weights in Table IV represent only the bare weights associated with the hydraulic pump, hence the hydraulic start system; the weight charged should be somewhat higher. Specifically, the T-62T-2A has a dry weight of 71 lb. This does not include the APU starting system which, if done hydraulically, would add 24.8 lb, nor does it include the utility system hydraulic pump

TABLE VI. HYDRAULIC ENGINE START SYSTEM* WEIGHTS

Starter Motors (2)	16.4 lb
Circuitry	2.0
Plumbing	8.7
Fluid	2.5
Supports	1.4
Total	31.0 lb

*-65°F starts, exclusive of energy source

or the clutch and mechanical elements used to connect the APU to the accessory gearbox. The total weight of the engine starting system is greater than 125 lb.

Pneumatic Engine Start System

The basic pneumatic system is shown schematically in Fig. 12. Again, the APU can be mechanically connected to the accessory gearbox through the clutch.

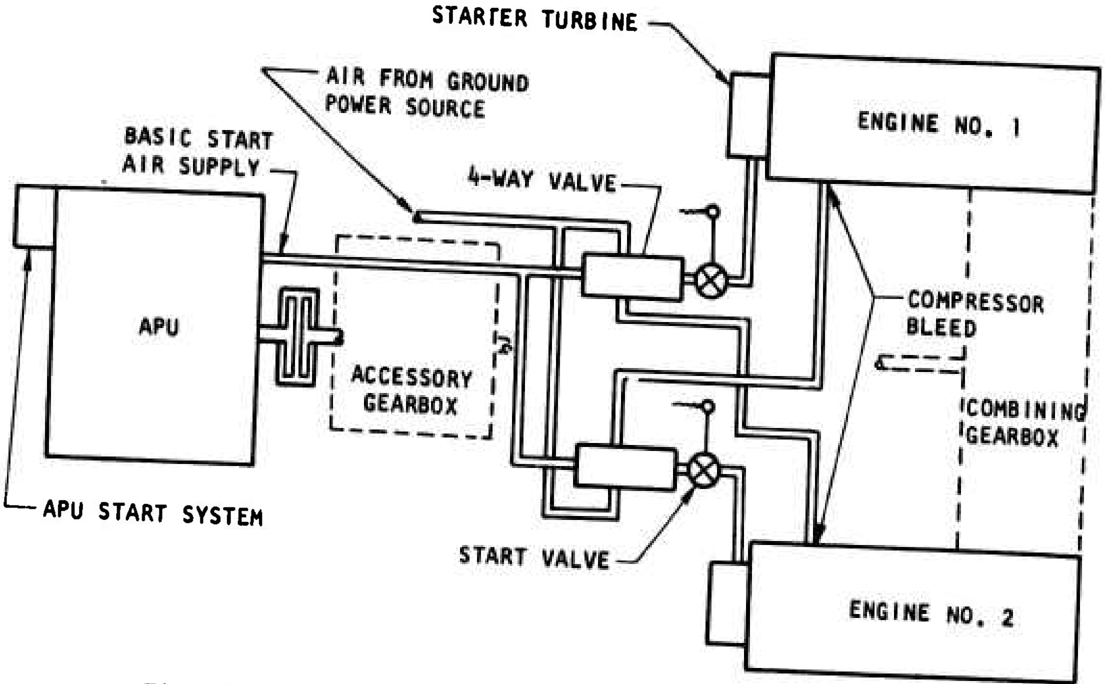


Figure 12. Present Pneumatic Engine Starting System.

The actual engine starting, however, is done using air bled from the APU and put through the starter turbine mounted on the engine. Alternatively, air can be supplied for engine starts from a ground power source or by cross-bleeding from the other engine when it is running. The four-way valves allow selection of the appropriate air source.

TABLE VII. PNEUMATIC ENGINE START SYSTEM* WEIGHTS	
Starter Turbines (2)	26 lb
Four-Way Valves (2)	13
Ducting	11
Total	50 lb

*-65°F starts, exclusive of energy source

The typical weights of the pneumatic engine starting are summarized in Table VII. Again, the weights represent that amount which could be removed if the engines were not started pneumatically. If the weights of the APU and its starting system were considered, an additional weight of more than 97 lb would be added, giving a total greater than 145 lb.

POSSIBLE RESODYNE SYSTEMS

STUDY CRITERIA

To make valid comparisons of alternative starting systems, the comparisons must be made on a standardized basis. Thus, each system should be designed to function in the same environments. Ground rules for estimation of major comparison parameters (e.g., weight, reliability, and cost) should be the same for all systems. The following sections briefly describe some of those major criteria developed for this study.

Environment

A mission requirement for the typical aircraft system being studied is that the engines be capable of restarts at the maximum operating altitudes. If, under these conditions, one engine can be started using energy supplied by the other engine, the basic starting system need not be capable of supplying starting power at these high altitudes. Thus, designing the basic starting system to supply its power only at lower altitudes fixes the means of transmission of starting power for the engines as being either hydraulic or pneumatic. This is the same as for the present starting systems described previously.

For this study, the basic starting systems including the Resodyne were to be designed to be capable of supplying engine starting power at altitudes up to 10,000 ft. The low temperature to be expected under this condition is -65°F. Typically, then, this 10,000-ft, -65°F condition is the worst design requirement for the engine starter. This altitude requirement is a severe one for an air-breathing device such as the Resodyne. Thus, favorable results in the comparison under such severe conditions would make a strong case for future application of Resodyne.

The requirement that the engine be started using the basic starting system means that the APU must be able to start and operate at 10,000 ft, -65°F. Therefore, the APU starting systems must also be designed for these same conditions. The APU is not restricted, however, in the means by which the starting power is transmitted from its starter to the APU.

The case of an engine start without an APU as an energy source creates difficulty with regard to system comparisons. No vehicle manufacturer had prepared estimates of or even defined such a starting system. Therefore, it was necessary to size at least one such system as part of the present study. The specific system chosen as most likely to be applied if neither an APU nor the Resodyne were used was the hydraulic energy storage system using an accumulator. This system is described in the Engine Starting section of this report.

Reliability and Cost

Reliability Goals. At this time, firm reliability goals have not been established by the vehicle contractors. Some apportionment of the overall vehicle reliability goals down to the major subsystem level has been accomplished, however. Based on the data that were obtained, a typical set of reliability and maintenance goals has been established (Table VIII).

TABLE VIII. TYPICAL RELIABILITY AND MAINTENANCE GOALS

	Failures per 10^6 Flight-Hr	Failures per 10^6 Starts*	Unscheduled Maintenance-Hr per 10^6 Flight-Hr
APU Complete	6300	2100	65,000
APU Starter System	1200	400	8,000
Engine Starter			
Without APU	1100	550	2,000
Including APU	7400	3700	67,000

*Assuming two engine starts per flight-hour, three APU starts

The reliability goals are expressed in terms of maximum numbers of failures allowed in 10^6 flight-hours. Similarly, the maintenance goals are expressed in terms of unscheduled maintenance man-hours per 10^6 flight-hours. The APU start system goals were arbitrarily broken out of the typical complete APU goals. In the case of the engine starter, reliability and maintenance are expressed in two ways--the smaller numbers are for the engine starting system without an energy source, and the larger numbers are for the engine starting system plus the APU.

The data presented in Table VIII do not represent specific system requirements, nor do they represent the results of extensive analysis. They do, however, indicate the order of magnitude of the desired levels of reliability and maintenance for starter systems for a twin-engine helicopter.

Reliability Estimates. In comparing the alternative starting systems, it is necessary to make estimates of the expected reliability (or failure rate) for each system. At the present level of system definition, it is not feasible to prepare highly detailed reliability estimates. It is feasible, however, to compare systems by estimating the reliability of each, based on a common set of ground rules and common reliability data.

In preparing these estimates for comparative purposes, it was assumed that all components of each system had independent, exponentially distributed failure rates. Two basic sources of data[7,8] were used. Reference 7 represents the data collected by a single company with an extensive reliability effort. These data were utilized by taking the mean generic failure rate and applying an installation environmental factor of 100 for aircraft in flight.

Reference 8 represents a compilation of data from a number of aircraft and missile programs. For the present study, only the data that applied to post-World War II aircraft programs were used. No application factor was applied to these data, since they represent actual flight experience.

Each of the competing starting systems was broken into major functional components. From the data tabulations,[7,8] failure rates for those components were established. Because considerable variation existed in the reported failure rates for the same component (say a hydraulic pump) from the various sources, it was decided in each case to use the most optimistic value (i.e., lowest failure rate). This is equivalent to assuming that the starting system is made up of highly developed components, thus comparing all systems on the basis of their long-range potential. For those few cases where data were not available for a specific component type, data for nearly identical part types were used.

Component failure rates were added for each system to obtain an estimate of the number of system failures per flight-hour. Differences in operating modes for the various systems were assumed to be small enough to permit this addition. Because it was also assumed that the exposure to failures only occurred during actual starter system operation, and because some of the starting systems have different periods of operation, the data were converted to failures per start. In the case of the electrical winterization system where the first start may take from 3 to 15 minutes, this is an especially important fact. The estimates of reliability of engine starting systems with an APU were based on the assumption that the APU would attain the exact failure rate goal shown in Table VIII.

Because the absolute levels of failure rates for starting systems are of limited validity, data were expressed as a ratio of failure rate compared to a reference value. The reference value chosen for both engine and APU starting is the estimated failure rate for the present hydraulic system.

Cost Estimates. Cost estimates for the various starting systems considered in this study were prepared, where possible, from quotations obtained on parts identical or similar to those expected to be used. Where such estimates could not be obtained, such as for the labor of assembly and test, estimates of the man-hours required were used to obtain dollar estimates. The cost of installation of the various starting systems in the vehicle was not considered. Therefore, these cost figures are only relative costs and are presented as such in the later comparison tables. All costs are compared to the references values, as was done for reliability. The approximate reference costs for the starting systems are $1000 for the APU and $2000 for the engines.

Specific Resodyne Criteria

Multiple-Start, Self-Contained System. Although current starting systems do not have this capability, the Resodyne systems were designed to provide three start attempts without recharging and to be completely self-contained. Self-containment of the Resodyne is quite simple except for the electrical power required for combustion ignition. This electrical power can be supplied either by a battery or by a hand-cranked generator. For this study, it was assumed that small nickel-cadmium batteries would be used as the energy source. It was further assumed that when the vehicle was subjected to the extremely low temperatures, the batteries would be removed from the vehicle and stored in a controlled environment such as living quarters or a crew member's pocket.

Resonant Combustion System Controls. There are many possible ways in which the energy to start and operate a resonant combustor device can be stored and controlled. The ground rules of the present study place major restrictions on the energy storage and control possibilities. One of the simplest forms that the system can take is shown schematically in Fig. 13. With this system, energy is stored in three forms: chemical, pneumatic, and electrical. The fuel contains chemical energy that is released upon combustion with air in the resonant combustor. The fuel is stored in an accumulator under a pressure that is maintained pneumatically. Fuel enters the accumulator through a filter and check valve. The accumulator is refilled by the main engine or APU fuel pump during normal engine or APU operation. In an emergency, it could be replenished by a hand pump.

Air for initiating combustion in the resonant combustor is stored in an air bottle. The air enters the system through a filter and check valve. The stored air is replenished by bleeding a small amount of air from the APU or engine compressor discharge during normal APU or engine operation. In an emergency, the air bottle could be recharged using a stock automobile tire pump. This air and fuel storage in bottles is shown to be feasible in the Resodyne demonstrator unit shown in Fig. 4.

Electrical energy is supplied by small nickel-cadmium batteries. Such batteries are included to make the resonant combustor starter system completely independent of the vehicle electrical system. Thus, if the vehicle should not have a battery, or if the battery should not be able to produce significant power at -65°F, the starter can still function. This is accomplished by having the starter batteries removable so that they can be kept in a room temperature environment until ready to use. The batteries selected weigh less than 1 lb and, thus, can be readily carried in a pocket or stored indoors. They have proved effective in the demonstrator unit shown in Fig. 4. The batteries can be readily recharged by a small portable charger indoors. In fact, the batteries, when not in use, can be stored in the charger.

The energy control system is comparatively simple. It involves a single, three-position lever in the vehicle cockpit. This position information may

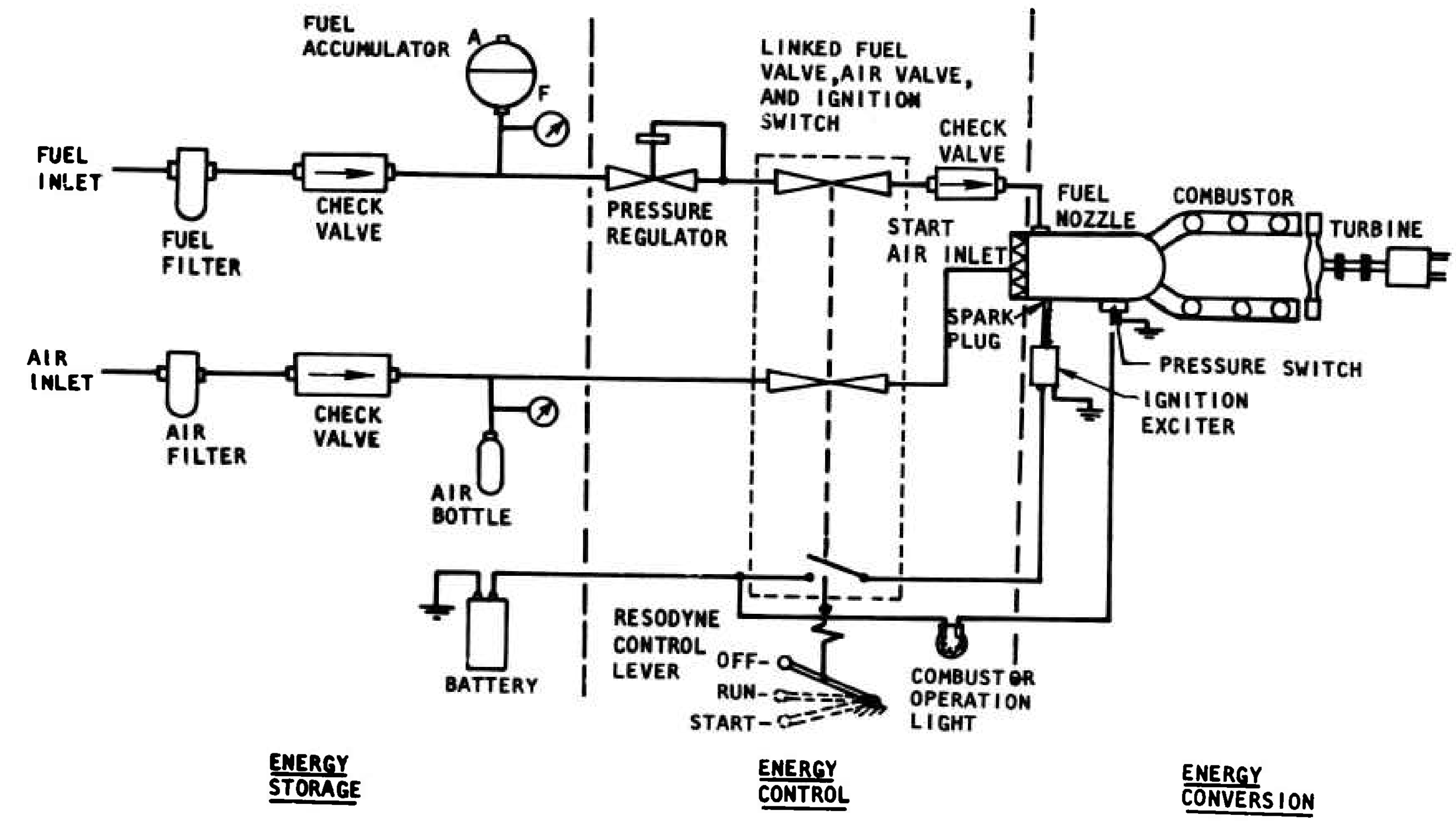


Figure 13. Resonant Combustor System Controls.

be transmitted to the resonant combustion starter either electrically or mechanically through a flexible cable. The simplest approach appears to be the use of the push-pull cable to mechanically actuate the mechanically linked ignition switch and start air and fuel valves. The additional self-actuated control elements are the fuel pressure regulator and the fuel line check valves. The pressure regulator regulates fuel pressure to a constant value with the input level varying as the fuel accumulator bleeds down. The check valve in the fuel line is close-coupled to the fuel nozzle to minimize the amount of fuel that can drip into the combustion chamber following combustor shutdown.

The operation sequence may now be described. With the battery, air bottle, and fuel accumulator fully charged, the pilot puts the starter control lever into the "start" position. This opens the fuel valve admitting fuel to the resonant combustor, opens the air valve admitting start air to the resonant combustor, and closes the switch connecting the battery to the ignition system.

Operation of the combustor is sensed by the pressure switch and displayed on the operation light. When the combustor is operating, the pilot returns the control lever to the "run" position. In this position, the ignition exciter circuit is opened, stopping the sparks, and the start air valve is closed, stopping the start air flow. The fuel valve remains open and fuel flow continues at the regulated pressure. When the resonant combustion unit has completed its particular function, the resonant combustion control lever is moved to the "off" position, shutting off the fuel and putting the unit into the recharge mode.

The control scheme just described is basically a simple manual control. By use of more control elements, it is feasible to have the logic of the start sequence controlled automatically. The pilot's input would thus be reduced to only a "start" and a "stop" command.

Other significant variations are possible. For example, the battery that must be kept warm and recharged externally may be replaced by a hand-operated generator. Such a generator would make the Resodyne completely self-contained with a weight penalty of approximately 1 lb.

Other control elements in a Resodyne system will vary as the systems for utilizing the turbine power vary. These are discussed later in more detail as each possible system is discussed.

Installation. For safety, it was assumed that all exhaust gases from Resodyne units would have to be ducted overboard from the vehicle. Since the Resodyne is fairly sensitive to exhaust duct losses, this dictates placing Resodyne units close to the vehicle skin to minimize duct length. Appropriate sealing techniques should be used to prevent any leakage of the hot gases into the compartment in which the Resodyne is located.

Because Resodyne tailpipe surfaces can attain temperatures of 1800°F during extended operation, all Resodyne systems were assumed to require protective grills. A protective grill such as that shown on the lower part of the Resodyne in Fig. 3 prevents any crew member from accidentally coming in contact with the hot surface.

Rotor Burst Protection. One of the criteria desired for any starting system is complete containment of all parts in the event of a catastrophic failure of some portion. Especially difficult is containment of the fragments of a high-speed rotor in the event of a blade or disc failure. A major question to be answered then is the amount of weight that must be added to a starter system to contain a possible burst of a turbine or flywheel.

A program is currently under way at the Naval Air Propulsion Test Center, Aeronautical Engineering Department, Philadelphia, to experimentally verify rotor burst protection criteria. This program, as well as related analysis work at the Massachusetts Institute of Technology, is sponsored by NASA. These programs promise to fill a large gap in current knowledge of protection of high-speed rotating machinery. At the time of the analysis work of the present study, results from this Rotor Burst Protection Program (RBPP) were not sufficient to permit unequivocal calculation of required containment weight by refined or even by rule-of-thumb calculations.

Because it was necessary to prepare containment weight estimates for this present study, a preliminary analysis was undertaken of the RBPP test data. Rotor burst data from the first 34 tests[9,10] are plotted in Fig. 14. Since one would normally assume that the containment weight required per unit disc would be a function of kinetic energy of the disc, this ratio was plotted as a function of the product of disc weight and tip speed squared, a rough measure of kinetic energy. The dark points in the figure are four cases where the turbine had an actual rotor shape. The opened points were flat discs. For a given product of disc weight and tip speed squared, these latter flat discs would have higher actual kinetic energy levels. Thus, if the scale could have been made in terms of actual kinetic energy, those flat disc points would tend to move to the right relative to the contoured rotor cases. Independent of the details, however, the data plotted in Fig. 14 show that the ratio of containment weight to disc weight is apparently not strongly affected by the kinetic energy level of the disc at burst. Because of this, it appears only slightly optimistic to assume that with future improved design techniques, it will be possible to contain bursts with containment weight equal to the disc weight. This assumption was used in the present study.

APU STARTING

Direct Drive

The simplest approach to applying the Resodyne to an APU start is the direct-drive system wherein a Resodyne provides starting torque directly at the starter pad. This concept is shown schematically in Fig. 15. When a more

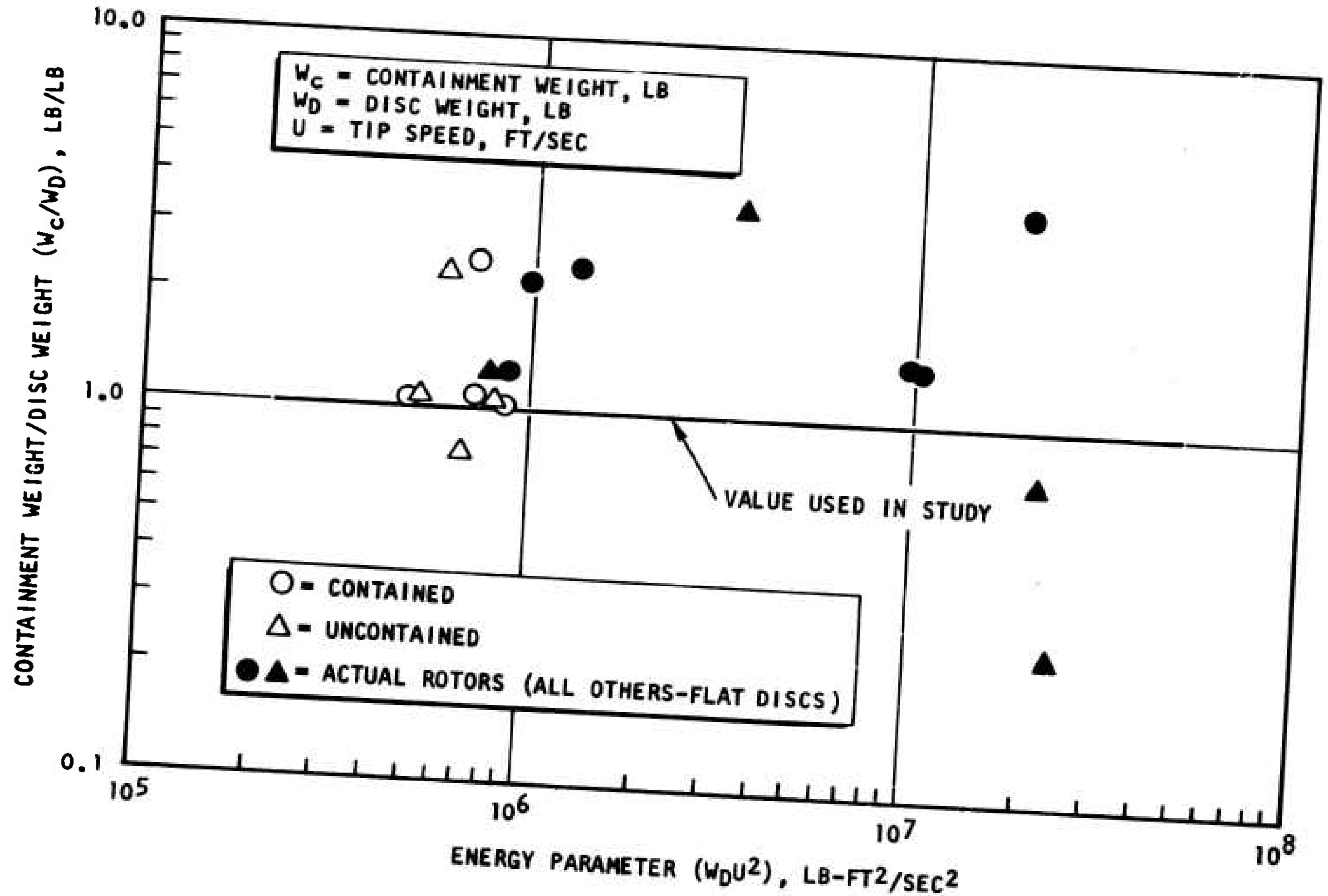


Figure 14. Summary of RBPP Tests (Rotor Data Only).

detailed look is taken at the problem of direct start, it becomes apparent that several physical configurations are possible. These are related primarily to the ducting of exhaust gases and to the manner in which the shaft power is directed from the turbine to the starter pad on the APU. Three major configurations have been considered and are discussed below.

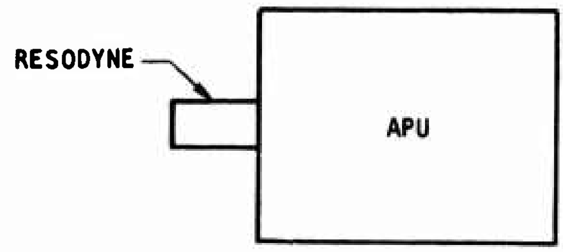


Figure 15. APU Starting System (Direct-Drive Resodyne).

Exhaust Scroll Configuration. This configuration, shown schematically in Fig. 16, takes the power directly from the turbine to the starter pad on the APU gearbox. The turbine exhaust gases are collected in a scroll and ducted a short distance to the vehicle skin. The Resodyne combustor configuration is the multiple-pass configuration, which gives the most compact package.

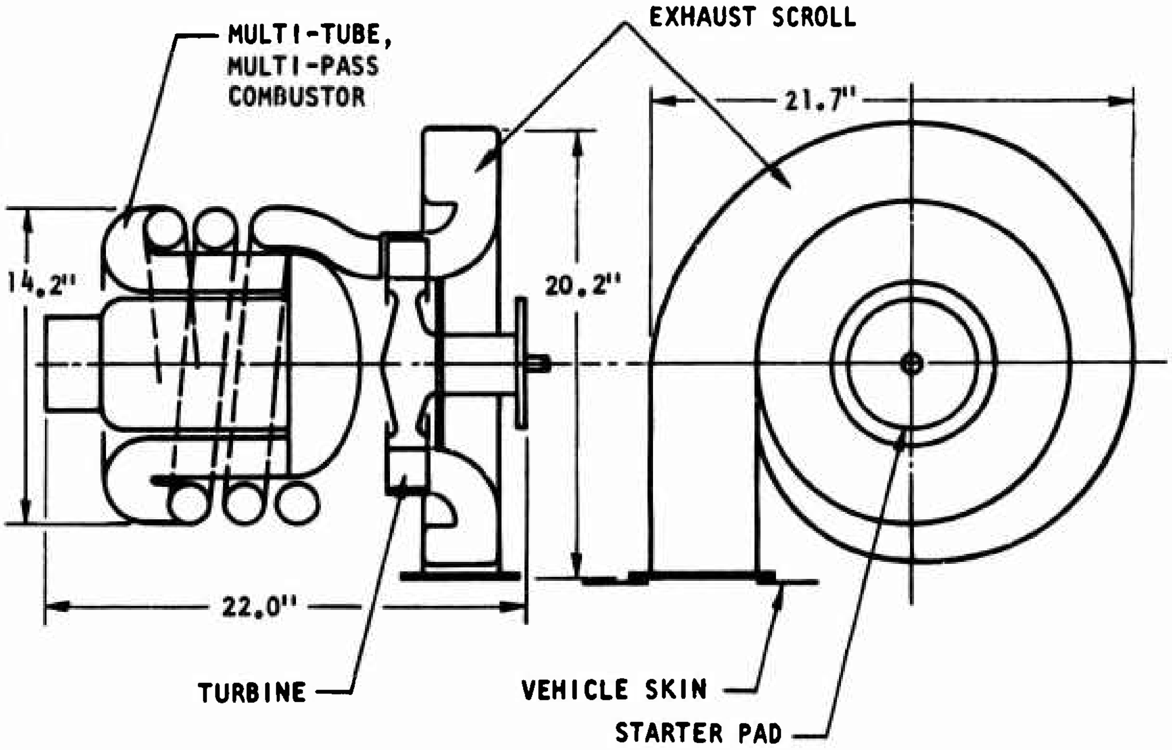


Figure 16. Resodyne for APU Direct Start (Exhaust Scroll Configuration).

The major difficulty with this exhaust scroll configuration is that the use of the exhaust scroll introduces additional losses into the Resodyne system. Therefore, it is necessary to use a larger size combustion chamber and turbine than would otherwise be required without the exhaust scroll. The total weights of such a system are shown in Table IX.

TABLE IX. RESODYNE APU DIRECT START (EXHAUST SCROLL CONFIGURATION)	
Basic Resodyne	38.5 lb
Turbine Containment	11.0
Support Structure	3.2
Controls and Battery	3.0
Air and Fuel Bottles	1.0
Exhaust Scroll	7.7
Total	64.4 lb

Inlet-Side, Right-Angle Drive. This configuration places the turbine immediately adjacent to the skin of the vehicle so that a very minimum of exhaust ducting is required. The negligible losses associated with this ducting mean that the minimum-size Resodyne can be used. Figure 17 shows schematically the manner in which the shaft power is brought out through a right-angle gear drive between two turns of the spiral exhaust tailpipes.

The weight of the inlet-side, right-angle drive system is summarized in Table X. The weight of the basic Resodyne has been decreased approximately 20% compared to that of the exhaust scroll configuration. The weight of the total system, however, has been reduced by over one-third. This is due both to the reduction in Resodyne and related weights and to the removal of the exhaust scroll weight. These weight reductions are partially offset by the addition of the right-angle drive gearbox. The Resodyne configuration used in this case is the most elemental single-pass of the tailpipes.

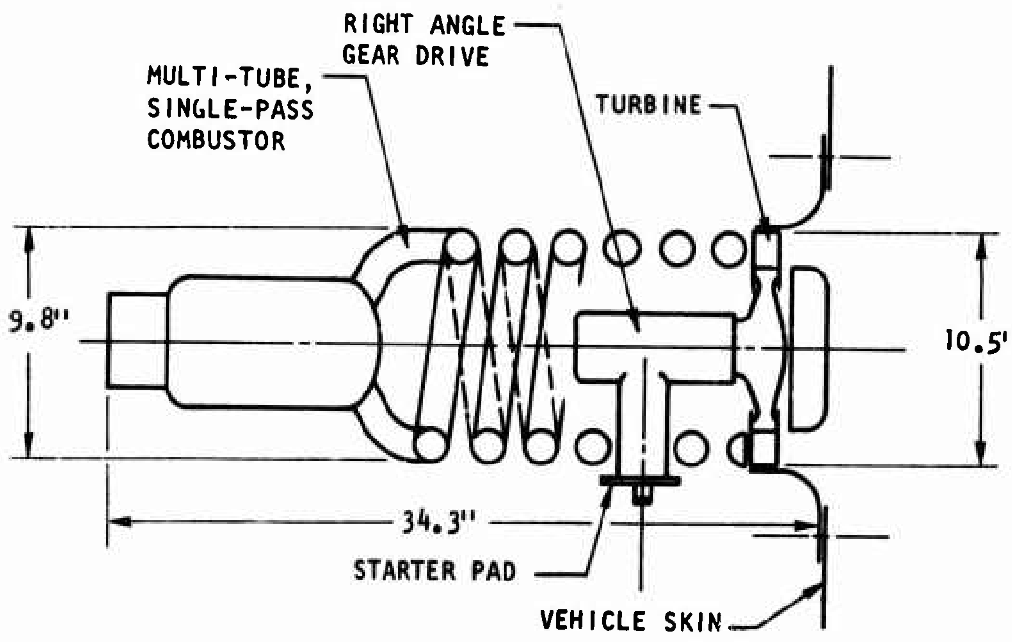


Figure 17. Resodyne for APU Direct Start (Inlet-Side, Right-Angle Drive).

The total weight of this inlet-side, right-angle drive system is nearly competitive with that of the winterized hydraulic system. This system, of course, has the capability for three -65°F starts compared to the single-start, manual-recharge capability of the basic winterized hydraulic system.

TABLE X. RESODYNE APU DIRECT START (INLET-SIDE, RIGHT-ANGLE DRIVE)	
Basic Resodyne	31.7 lb
Turbine Containment	9.3
Gearbox	3.8
Support Structure	2.8
Controls and Battery	3.0
Air and Fuel Bottles	0.9
Total	51.5 lb

Exhaust-Side, Right-Angle Drive. This system, shown schematically in Fig. 18, is to some extent a hybrid of the two previous systems. It has a fairly close-coupled turbine for minimum exhaust duct losses but it takes the shaft power out through a right-angle drive, located in the turbine exhaust region. With this configuration, the starter output pad comes out too close to the vehicle skin, thus introducing possible difficulties in mating with the APU. The Resodyne combustor, on the other hand, can again revert to the more compact multiple-pass configuration.

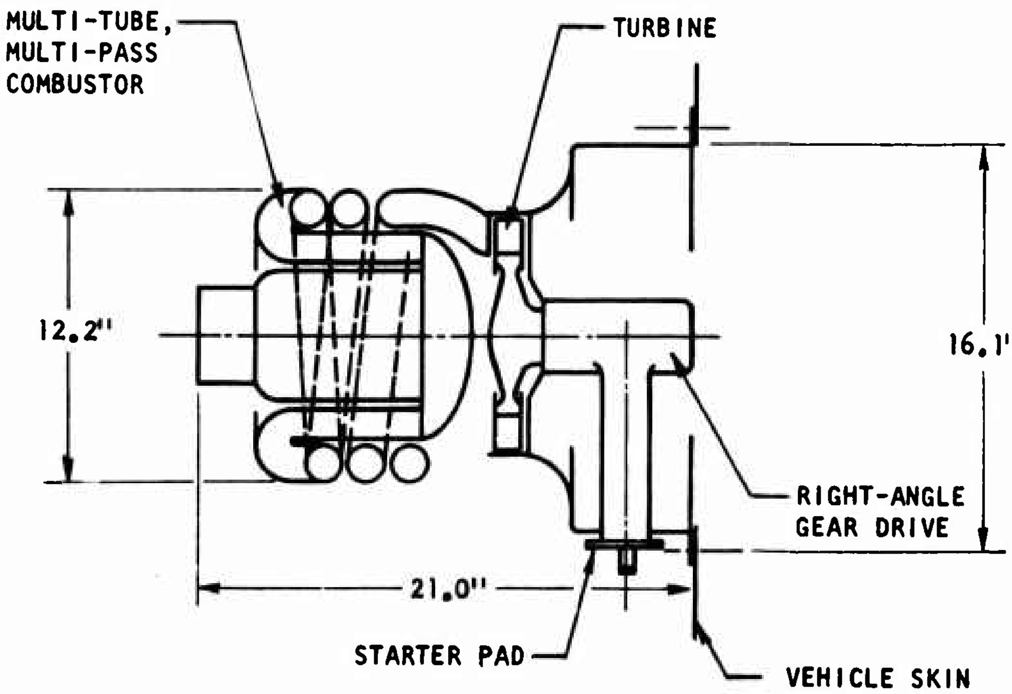


Figure 18. Resodyne for APU Direct Start (Exhaust-Side, Right-Angle Drive).

The weights of the system are summarized in Table XI. The basic weights are nearly the same as those of the inlet-side, right-angle drive case.

The major difference is in the gearbox weight. To extend outside the turbine exhaust ducting, the right-angle gearbox must be larger. The turbine exhaust ducting has been sized to allow full advantage to be taken of the backflow characteristics of the turbine (i.e., a shaped exhaust flare adapts the turbine to the final exhaust duct). The exhaust duct has a diameter 1.7 times that of the turbine. The slight additional difference in weight is due to the exhaust ducting associated with this configuration

TABLE XI. RESODYNE APU DIRECT START (EXHAUST-SIDE, RIGHT-ANGLE DRIVE)

Basic Resodyne	32.5 lb
Turbine Containment	9.3
Gearbox	5.1
Support Structure	2.8
Controls and Battery	3.0
Air and Fuel Bottles	0.9
Total	53.6 lb

Hydraulic Winterization

A Resodyne-driven winterization kit for a hydraulic APU start system has two potential functions: (1) adding flow capacity to the system, thus, increasing the apparent stored energy of the basic accumulator and (2) heating the APU lubricating oil to reduce the torque required to start the APU. The additional capacity effect will be considered first, then the combined effect of additional capacity and oil heating. The two basic systems to be considered are direct pump drive by a Resodyne and inertial energy storage with a Resodyne power source.

Direct Pump Drive Flow Supplement. The Resodyne-driven hydraulic winterization system is shown in its simplest form, the direct hydraulic pump drive, in Fig. 19. This system is nearly identical to the present APU winterization system except that the Resodyne-driven hydraulic pump is substituted for the accumulator. The additional difference from the present winterization kit is that the hydraulic system reservoir is tied into the system. The hydraulic pump is not capable of pumping unless given adequate pressure on the inlet or suction side. The reservoir is pressurized by use of high-pressure fluid from the pump outlet side.

Sizing of the hydraulic pump is based on the following considerations. A total fluid quantity corresponding to an accumulator total volume of 300 cu in. has been shown to be satisfactory for consistent starting. The basic system accumulator has a capacity of 200 cu in. total volume. Thus, the pump must provide a flow equivalent to that which would be provided by 100 cu in. of accumulator capacity. The hydraulic motor capacity of 0.95 cu in. per revolution combined with a cutout speed of 4200 rpm produces a maximum flow rate at cutout of 18 gpm. The assumption that motor and APU speed increase linearly with time allows one to calculate a start time of 4.65 seconds, based on 161 cu in. of fluid from the accumulator. To provide one-third of this volume from the pump would require a pump having a flow rate of 3.3 gpm. This is shown in Fig. 20.

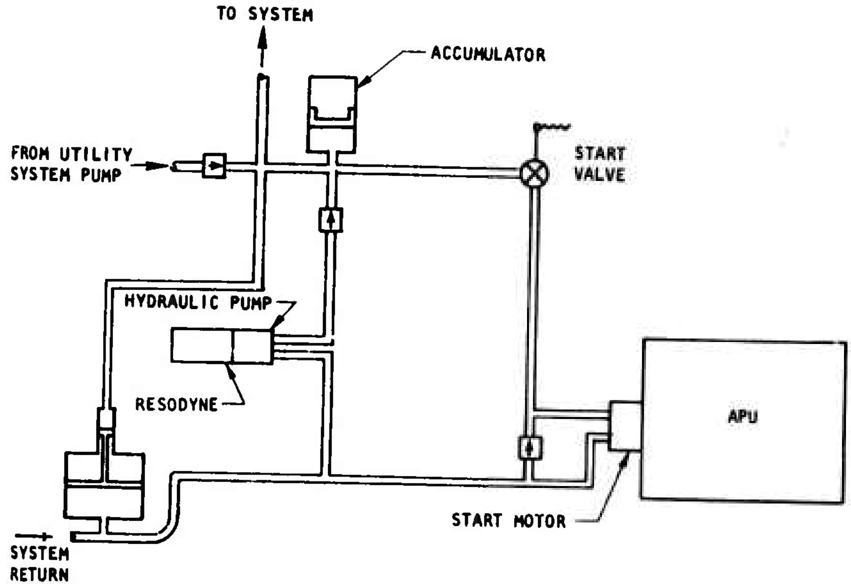


Figure 19. Resodyne APU Hydraulic Winterization (Direct-Pump Drive Flow Supplement).

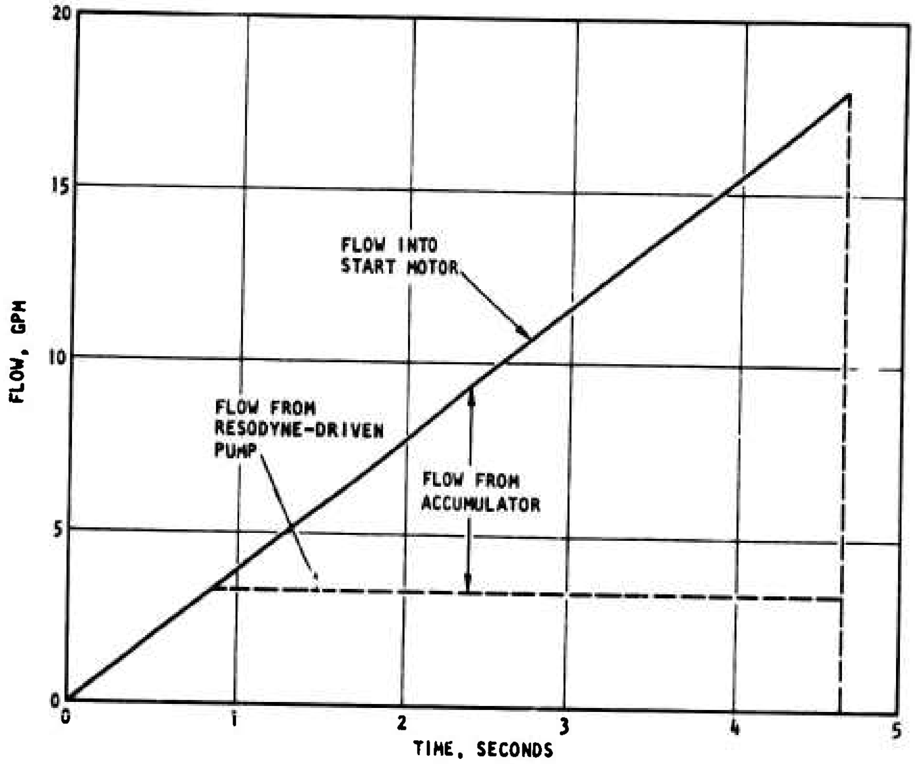


Figure 20. Flow During Hydraulic Start of APU With Flow Supplement.

The pump then has a theoretical flow of 3.44 gpm and a shaft hp of 6.68. If a Vickers PV3-022 pump is considered, it would run at 3620 rpm to deliver this flow. The Resodyne to deliver this power weighs 45 lb. Total weight of such a system is shown in Table XII. Since this system is only supplementing the basic hydraulic start system with a single accumulator, it is necessary to add the weight of that basic system to the Resodyne weights to get the total weight of a hydraulic start system with Resodyne winterization. Since this total weight is nearly 100 lb, this system will not be considered further.

TABLE XII. RESODYNE APU HYDRAULIC WINTERIZATION (DIRECT PUMP DRIVE)

Resodyne	45.0 lb
Turbine Containment	14.0
Gearbox	5.3
Support Structure	4.0
Controls and Battery	3.0
Air and Fuel Bottles	0.6
Hydraulic Pump	4.6
Basic Hydraulic Start System (less hand pump)	22.1
Total	98.6 lb

Inertial Energy Storage Flow Supplement. Because the power requirement to supplement the basic system accumulator was so large, the whole Resodyne system for direct pump drive was excessively large. Therefore, it is desirable to consider the inertial energy storage system as an alternative. This system is shown schematically in Fig. 21. Here the Resodyne is used to store energy in a flywheel over a 2-minute period. During the normal start, the stored energy is withdrawn from the flywheel to drive the hydraulic pump which supplements the basic system accumulator.

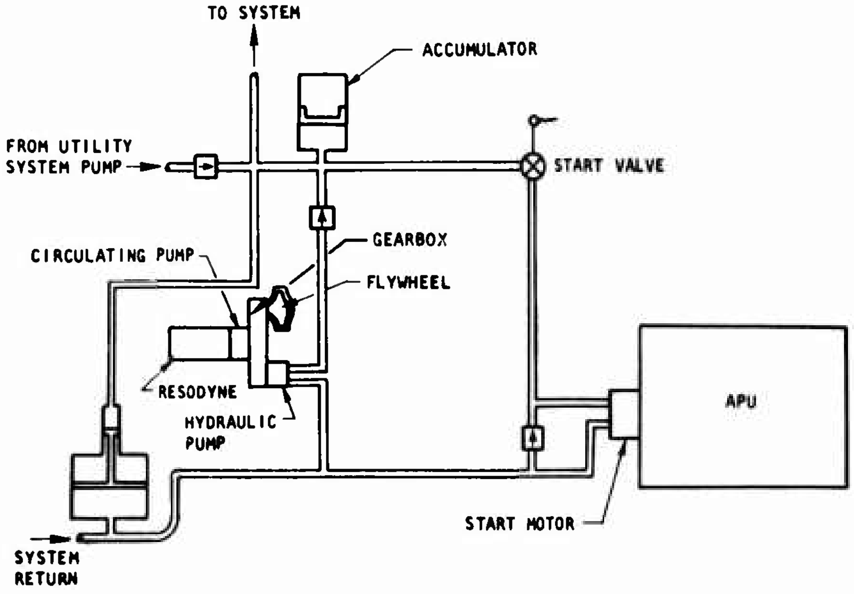


Figure 21. Resodyne Hydraulic Winterization (Inertial Energy Storage Flow Supplement).

As may be seen in Table XIII, the weight of the Resodyne itself is considerably reduced with this system over that of the direct pump drive. Unfortunately the weight of the gearbox and flywheel assembly now becomes significant.

TABLE XIII. RESODYNE APU HYDRAULIC WINTERIZATION (INERTIAL ENERGY STORAGE FLOW SUPPLEMENT)

Resodyne	18.0 lb
Turbine Containment	4.8
Gearbox (lube, scavenger, and vacuum pumps)	15.7
Support Structure	1.6
Controls and Battery	3.0
Air and Fuel Bottles	1.3
Hydraulic Pump	4.6
Flywheel Assembly (including containment)	8.8
Basic Hydraulic Start System (less hand pump)	22.1
Total	79.9 lb

The cause for the additional gearbox weight may be seen in the schematic of Fig. 21. The total gearbox consists of a right-angle drive and a step-up to the flywheel and a step-down to the hydraulic pump. The combination plus the necessity for gearbox lube and scavenge pumps and a vacuum pump for the flywheel casing causes the total weight to be high. Again in this inertial energy storage system, it is necessary to add the weight of the basic hydraulic start system to obtain a total weight. The total weight of the system, while lower than that of the direct pump drive, is still considerably higher than that of the present (single start) winterized hydraulic system.

<u>Multiple Start/Winterization</u>. A large portion of the torque required to start an APU, especially at the lower speeds, is viscous drag. At low temperatures, especially, the high oil viscosity causes high resistance to motion. If the oil in the APU could be heated prior to the start attempt, the amount of energy to start the APU might be significantly reduced.

For an electrically started APU, heating the oil would apparently be of little value because the main problem is heating of the battery, which must be done internally for rapid starting. Heating the APU oil, while it might reduce the energy required for a start, would only add a small safety factor to an electrical winterization starting system.

A hydraulic system with APU oil heating offers somewhat more promise. Such a system is shown schematically in Fig. 22. In this system, the Resodyne-driven hydraulic pump functions to top off the accumulator charge and to recharge the accumulator in the event of an unsuccessful start. The APU oil is circulated through an exhaust heat exchanger by the recirculating pump. The design time for oil circulation and heating is 2 minutes.

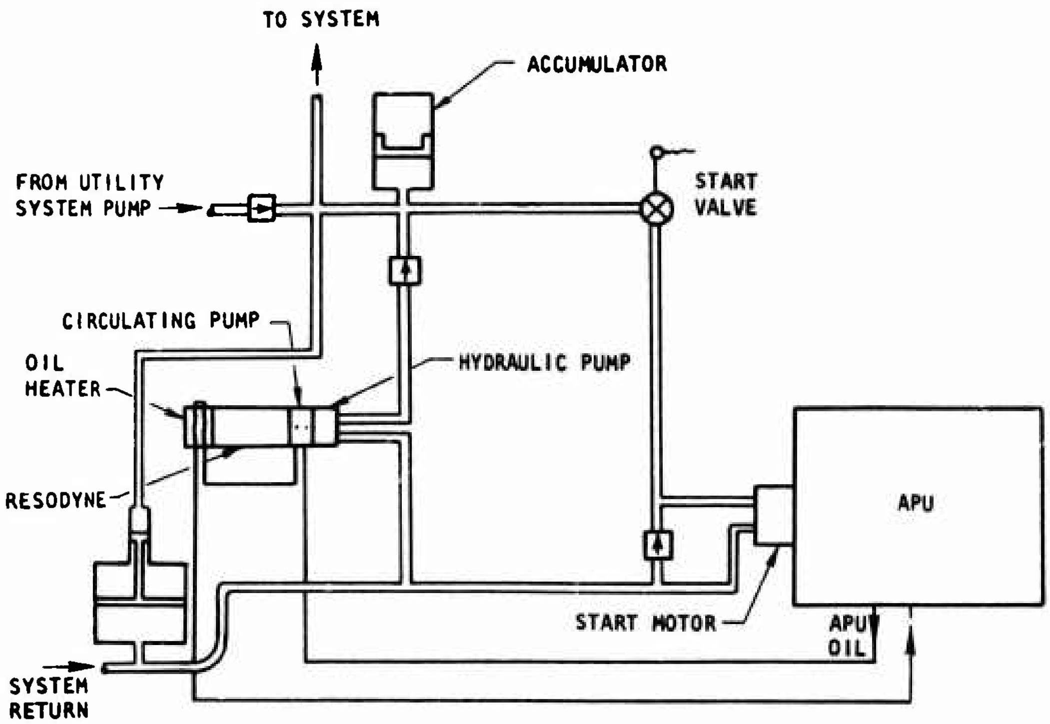


Figure 22. Resodyne APU Hydraulic Winterization (Multiple-Start/Winterization).

Sizing of this hydraulic system is based on several assumptions. It has been assumed that enough heat must be transferred to heat 5.8 lb of oil to 135°F and 17.8 lb of aluminum gearbox to 35°F, both from a temperature of -65°F. This heating results in a total heat requirement of 990 Btu. If this heating is done over a 2-minute period, a heat rate of 8.25 Btu/sec or 29,700 Btu/hr results.

The energy required to start the APU if the oil has been heated must also be estimated. It is assumed that the APU drag with heated oil corresponds to that for a +125°F ambient temperature at low APU speeds and to that for a -65°F ambient temperature at high APU speeds, as shown in Fig. 23. This assumption results in a peak power requirement of approximately 2.2 hp for the heated oil case compared to roughly 3.7 hp required if the APU and oil are both at -65°F. Thus, to a first approximation, the APU with heated oil requires approximately one-third less power and energy than the completely cold unit.

The net result of this reduced power would be a system that could start using the basic hydraulic start system accumulator. The basic system 200-cu in. total volume accumulator would give a satisfactory start. In addition, the hydraulic pump would have the capability both of topping off the accumulator prior to start and of fully recharging the accumulator in a short time in the event that the APU failed to start.

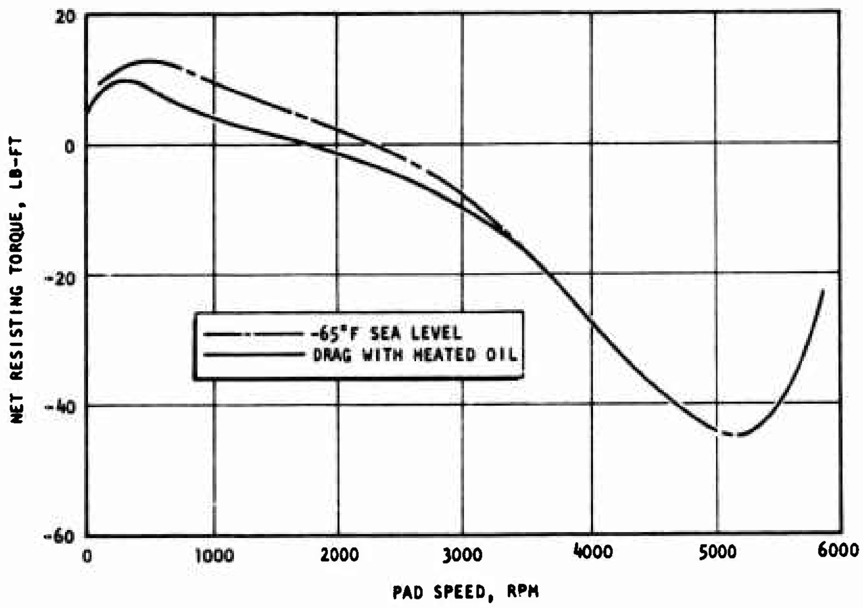


Figure 23. Effect of Oil Heating on Estimated T-62T-2A Cold-Day Starting Characteristics.

The basic Resodyne has been sized to provide minimum hydraulic pump flow and power plus the power to drive the circulating pump. The corresponding system weights are shown in Table XIV. The total weight of this system is very close to that of the direct-start Resodyne systems. Thus, it appears competitive. From the overall system point of view, this approach allows an add-on unit that provides both winterization capability and multiple-start capability.

TABLE XIV. RESODYNE APU HYDRAULIC MULTIPLE START/ WINTERIZATION	
Resodyne	15.5 lb
Turbine Containment	3.9
Gearbox	3.8
Support Structure	1.4
Controls and Battery	3.0
Air and Fuel Bottles	1.1
Hydraulic Pump	2.3
Circulating Pump	1.5
Heat Exchanger and Fluid	3.6
Basic Hydraulic Start System (less hand pump)	22.1
Total	58.2 lb

Electrical Winterization

An electrical winterization system works by ensuring that the battery is at a temperature equal to or higher than -25°F and has sufficient charge to permit a start of the APU. The possible system variations are based on the manner in which the heat is applied to the battery (i.e., internal or external and on the source of energy for the heat, again, internal or external).

External Battery Heating, External Energy Source. The most obvious approach to winterization of an APU electrical start system using the Resodyne is to use external heating supplied by an external energy source. This is shown schematically in Fig. 24. Some preliminary calculations have been made of the rate at which heating might occur. It appears that for a typical battery, it would require approximately 1/2 hr for the battery to be heated from -65° to -25°F. One of the major reasons for this long time for heating is the necessity for limiting the surface temperature of the battery to about 240°F. This limit is required to avoid damage to the battery. Because this is far beyond the desired heating time, this system was not given further consideration.

External Battery Heating, Internal Energy Source. An alternative system, shown in Fig. 25, is that using internal energy from the battery to provide continuous heat externally. With this system, it is possible to maintain the battery at a temperature high enough to produce full battery output. The typical amount of power required to maintain the temperature stable for 1 hr is 1.25% of the rated capacity. Thus, over a 24-hr period, approximately 30% of the battery capacity would be discharged. Typically, a daily recharge would be required to keep a battery heated in a -65°F environment. Also, typically, approximately 10 amp-hr of charging would be required for a 34 amp-hr rated capacity battery.

Figure 26 shows the weight of a recharging system driven by a Resodyne and capable of recharging 8.4 amp-hr in the stated times. Again, to reduce the recharge system weight to a reasonable value, say 50 lb, requires a recharge time of approximately 12 minutes. This is not such a bad system, however, since the 12 minutes is not part of the start time but is, rather, a normal maintenance time. Normal start can be obtained very rapidly since the battery is maintained at a temperature that allows it to discharge most of its rated capacity. The total weight of such a winterized electrical start system would be 95 lb, and thus not very competitive.

Internal Battery Heating, Internal Energy Source. The final winterization system considered (Fig. 27) is that involving internal heating using internal energy from the battery. Internal heating is accomplished by shorting the battery. This is the fastest means of heating the battery, but it still requires at least 3 minutes to get the battery up to a useful temperature level. Attaining a useful temperature level drains a significant portion of the battery's capacity. Therefore, it is necessary to replace a portion of this capacity. The weight shown in Fig. 26 represents the weight of a Resodyne-driven recharge system capable of replacing the fraction of the capacity drain from a typical 34 amp-hr battery in self-heating from -65° to -25° F.

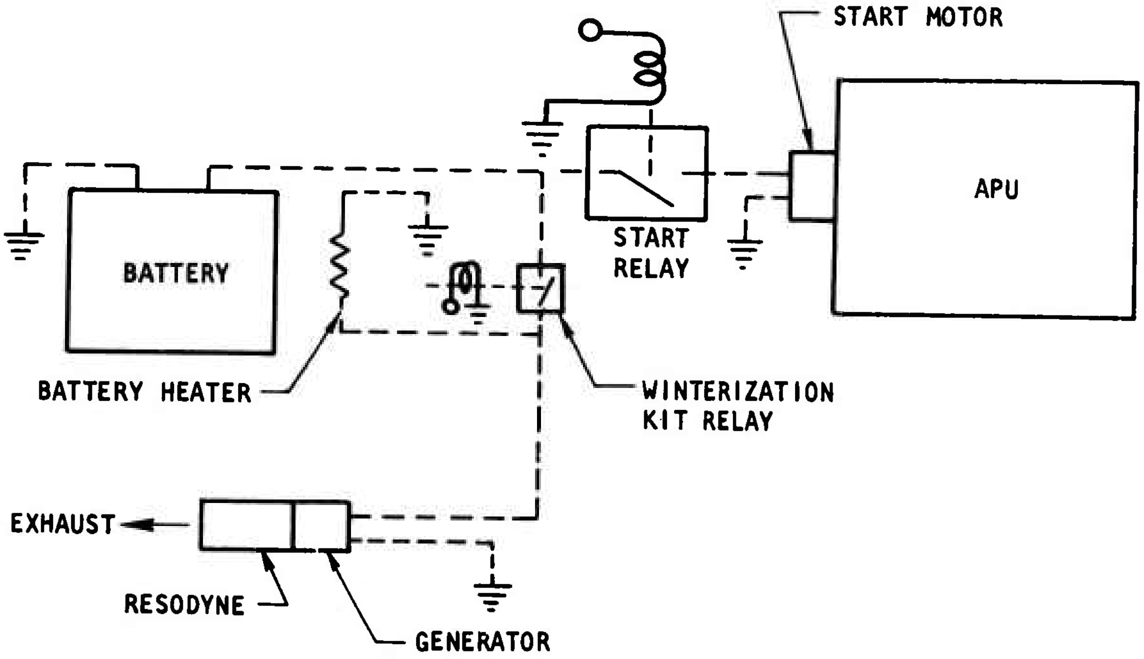


Figure 24. Resodyne APU Electrical Winterization (External Battery Heating, External Energy Source).

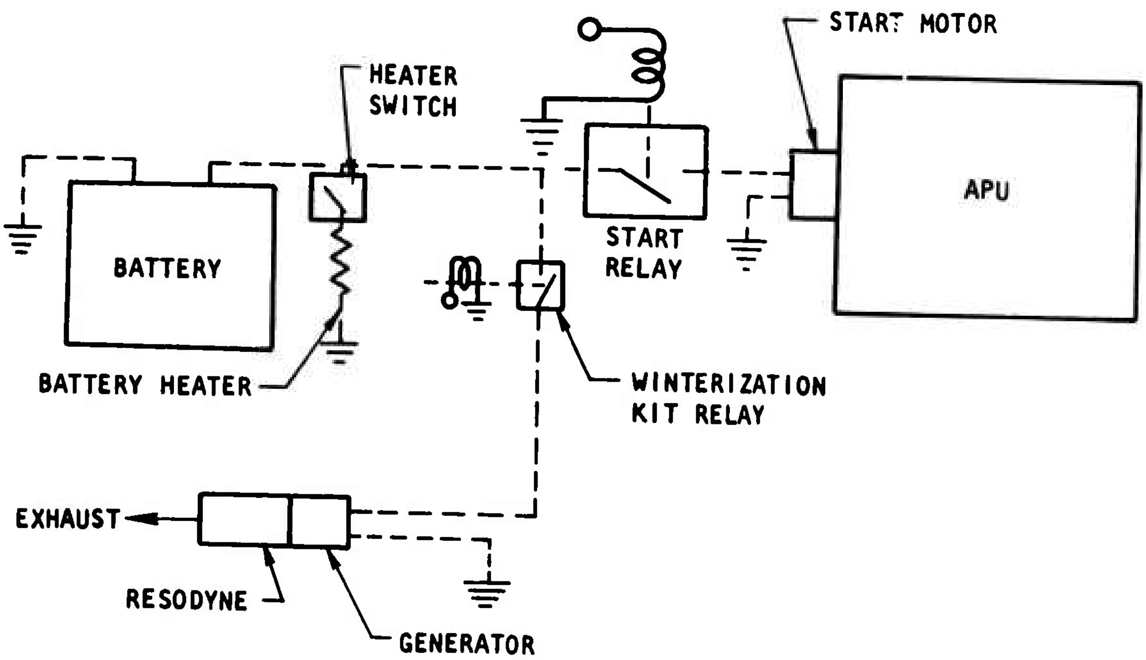


Figure 25. Resodyne APU Electrical Winterization (External Battery Heating, Internal Energy Source).

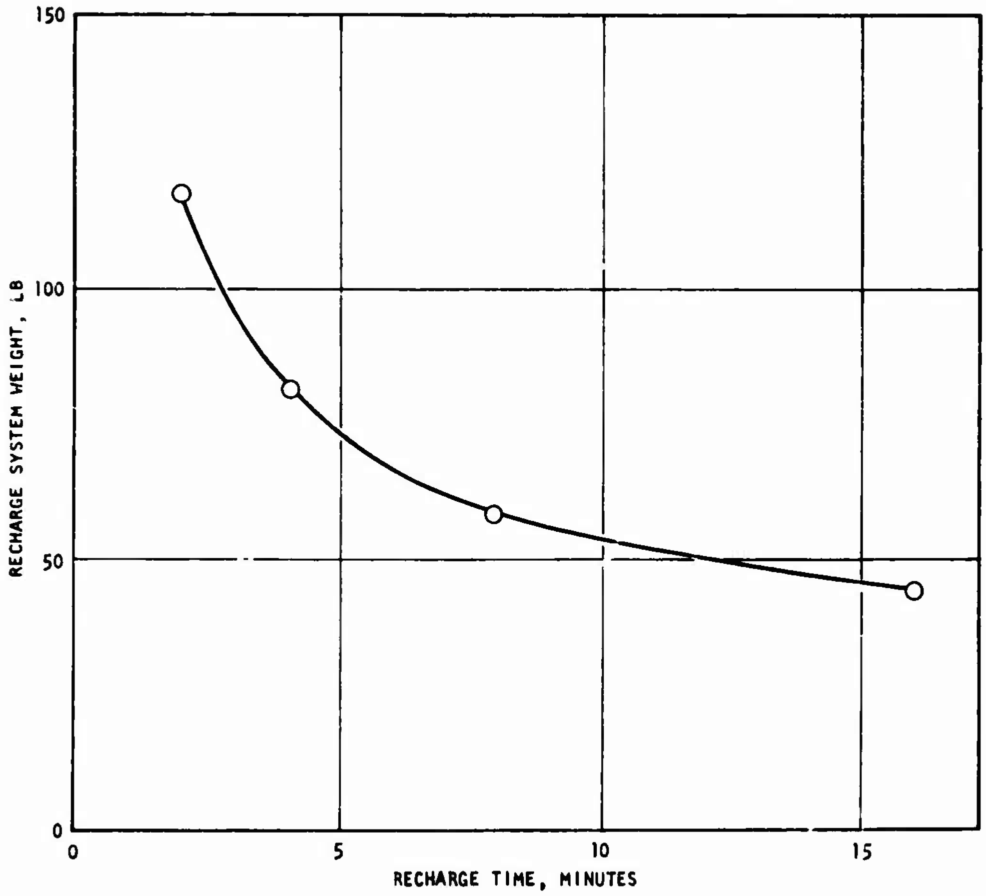


Figure 26. Effect of Recharge Time on Recharge System.

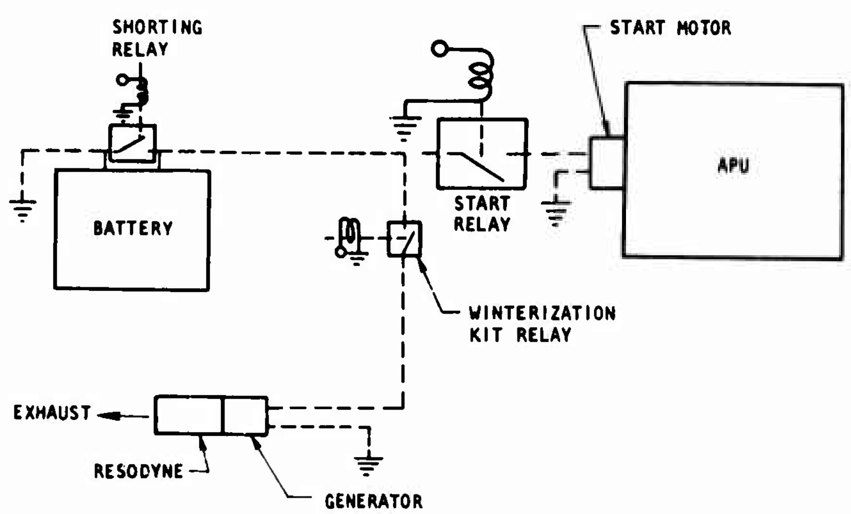


Figure 27. Resodyne APU Electrical Winterization (Internal Battery Heating, Internal Energy Source).

Table XV presents the weight of systems capable of starts within 3 and 15 minutes of command. It is assumed that this recharging can take place while the battery is being heated. The systems are still quite heavy.

TABLE XV. RESODYNE APU ELECTRICAL WINTERIZATION (INTERNAL BATTERY HEATING, INTERNAL ENERGY SOURCE)

3-Minute Initial Start	
Basic Electrical System	45 lb
Resodyne Recharge	95
Total	140 lb
15-Minute Initial Start	
Basic Electrical System	45 lb
Resodyne Recharge	46
Total	91 lb

System Comparison

Table I summarizes the results of the present study of alternate APU starting techniques. The estimated weight, relative failure rate, and relative cost for each system are shown. Two other important parameters are also shown for each system: the minimum temperature at which the system will function and the number of start attempts that may be made without recharging the starting system externally.

The present electrical starting system is not capable of starting at temperatures below -25°F. A winterized hydraulic system which can start at -65°F weighs nearly twice as much as the basic hydraulic system which is only suitable for use at -25°F. This winterized hydraulic system is only good for one start attempt without manual or other recharging. A winterized hydraulic system large enough for three start attempts without recharging would weigh over twice as much as the one-start winterized hydraulic system. In addition, it would have a relative failure rate nearly twice that of the one-start system. Among the Resodyne systems, the electrical winterization does not appear attractive. For short-time recharging, it is excessively heavy. For long-time starting, it is still heavy and burdened by an extremely high relative failure rate.

The two hydraulic winterization systems that substitute Resodyne-powered devices for an additional accumulator are also rather heavy. The inertial energy storage is somewhat lighter than the direct pump drive version but otherwise offers no advantage.

The two most promising APU starting systems powered by resonant combustion devices are the direct-start and the multiple-start/winterization kit. The direct-start system is the lightest in weight as well as the lowest in cost. It is almost as low in cost as the single-start winterized hydraulic system presently used. On the other hand, the direct start has the highest failure rate of the nonelectrical Resodyne systems. The failure rate is approximately twice that of the alternative Resodyne-powered systems because, with the direct start, the Resodyne must operate each time the APU is started. The alternative systems for winterization are only operated when required (for example, by low temperature). Even the comparatively high failure rate of the direct Resodyne APU starting system, however, is comparable to that of a three-start Resodyne APU starting system. Thus, for three starts, the direct Resodyne system has a comparable failure rate, somewhat lower cost, and less than half the weight of the winterized hydraulic system. One further mechanical facet of the direct system is that it requires that the APU be so oriented in the vehicle that the exhaust from the Resodyne may be directly through the skin of the vehicle. Mounting the APU away from the skin would require ducting for the Resodyne exhaust, and this could easily wipe out any advantages of the Resodyne system.

The full winterization system is somewhat heavier than the direct Resodyne and is also more expensive. However, it does have a significantly lower relative failure rate because the winterization system is only required to operate for a fraction of the APU starts. Its failure rate is comparable to that of the present winterized hydraulic system. Since this system as a winterization system would only be added to vehicles that are intended for use in low-temperature environments, the cost factor is de-emphasized.

One other significant advantage to the multipe-start/winterization system is that it does not require any specific orientation or location of the APU. It is only required that it be possible to mount the Resodyne comparatively close to the APU and with its exhaust through the vehicle skin. This is a much less stringent requirement than that of fixing the APU orientation. Of the systems considered, the multiple-start/winterization Resodyne system appears to offer the greatest flexibility for aircraft use. It will definitely provide a multiple-start, low-temperature capability demanded while in addition offer multiple-start capability at higher temperatures, which essentially does away with the requirement for manual recharging of the APU starting system. Because of this flexibility in potential, the full winterization system was selected for further study in the second phase of this program.

ENGINE STARTING SYSTEMS

Direct Engine Start With Hydraulic Transmission

This system (Fig. 28) is similar in concept to the reference hydraulic starting system. In the reference system, the APU drives the utility system hydraulic pump. In the present system, a Resodyne drives the hydraulic pump. The Resodyne resonant combustion unit is a power-limited device.

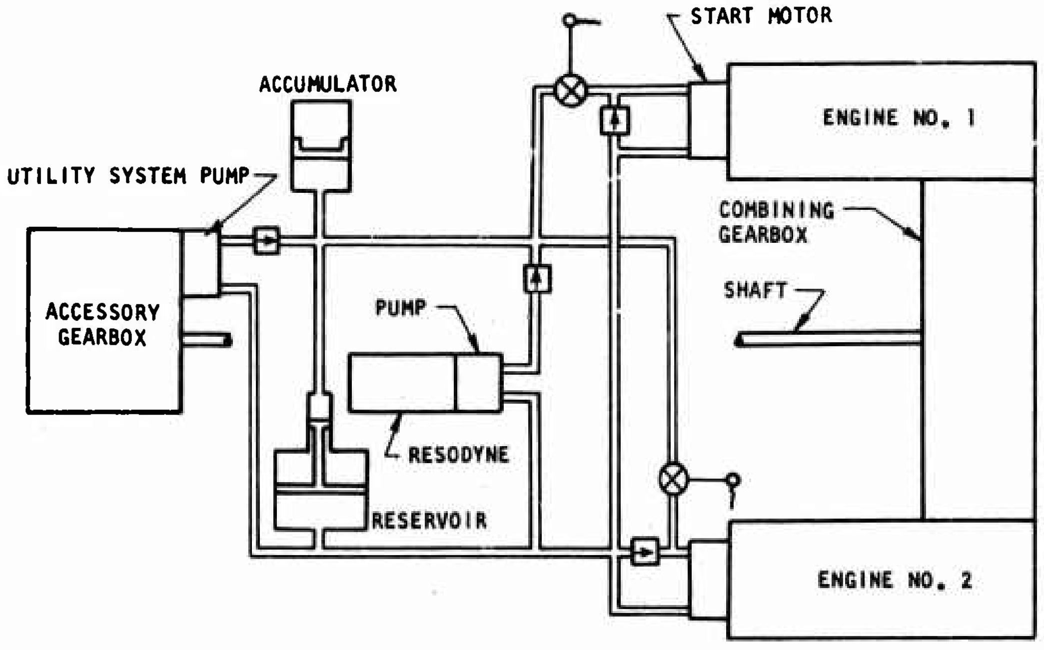


Figure 28. Resodyne Direct-Start Hydraulic System.

To use a minimum feasible size Resodyne, it is necessary to carefully select the hydraulic system components. The combination that appears to be most appropriate is the fixed-displacement hydraulic starting motor and the variable-displacement pump with a constant power feature. Several pump and motor sizes were examined. Best performance was obtained with a 0.44 cu in. per revolution motor combined with a 0.44 cu in. per revolution pump. The pump must be operated at a nominal speed of 10,000 rpm with a constant power cutoff adjusted to be effective at a flow rate corresponding to a motor speed of 3000 rpm. Under these circumstances, the pump input power, which must be produced by the Resodyne at altitude, is 11.7 hp.

Weights of alternate versions of the system are shown in Tables XVI and XVII. Table XVI presents the weight of the system with the gearbox and hydraulic pump in the exhaust area. Table XVII presents data with a right-angle drive on the turbine inlet side and the pump external to the combustor diameter. As before the latter configuration is somewhat lighter.

Resodyne Inertial Hydraulic Engine Starting System

In this system (Fig. 29), energy for the start is stored in a flywheel, which drives the hydraulic pump. Energy from the Resodyne is used to "charge" the flywheel. The starter motor is a fixed-displacement device while the pump is a variable-displacement. In the search for a minimum weight system, two types of pump pressure compensation were examined--constant pressure and constant power. The constant power case is really only

TABLE XVI. RESODYNE HYDRAULIC ENGINE START (DIRECT PUMP DRIVE)	
Resodyne and Exhaust Duct	69.3 lb
Gearbox	5.4
Hydraulic Pump	6.6
Turbine Containment	23.0
Support Structure	6.3
Controls and Battery	3.0
Air and Fuel Bottles	2.1
Basic Hydraulic System	31.0
Total	146.7 lb

TABLE XVII. RESODYNE HYDRAULIC ENGINE START (INLET-SIDE, RIGHT-ANGLE DRIVE)	
Resodyne	67.0 lb
Turbine Containment	23.0
Gearbox	6.1
Hydraulic Pump	6.6
Controls and Battery	3.0
Air and Fuel Bottles	2.1
Support Structure	7.1
Basic Hydraulic System	31.0
Total	145.9 lb

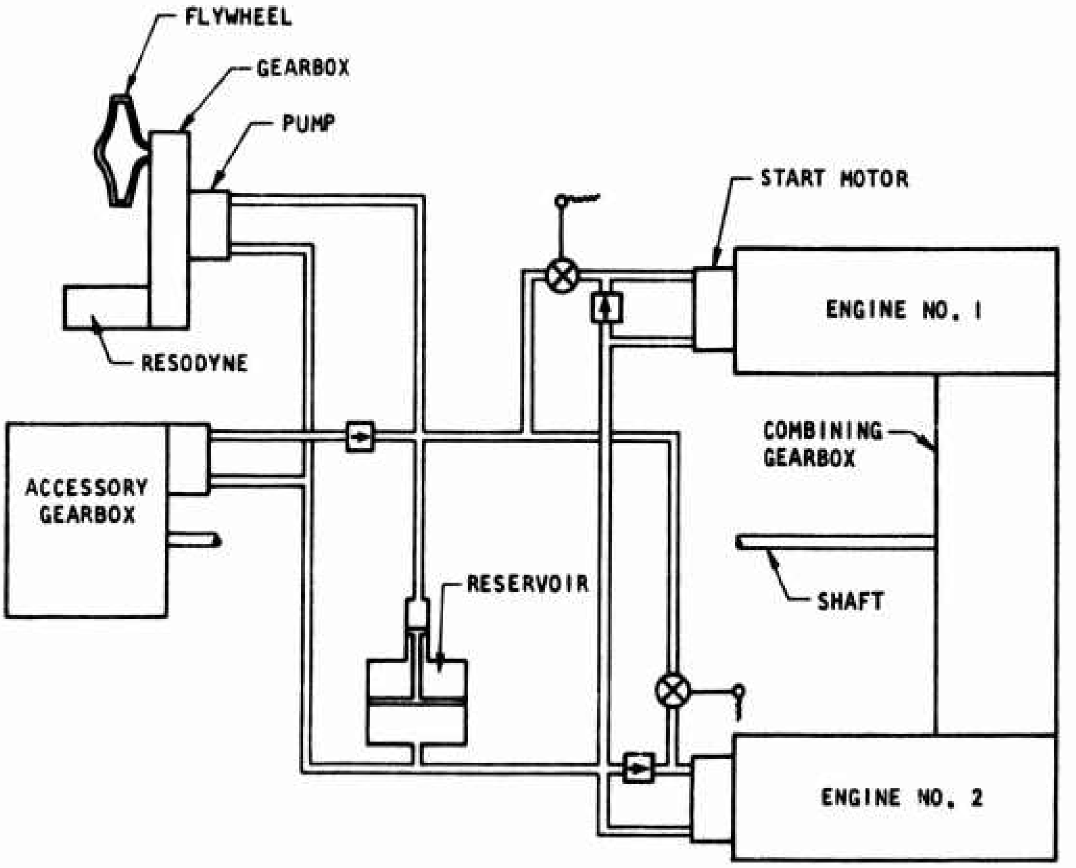


Figure 29. Resodyne Inertial Hydraulic System.

constant power at a fixed pump speed. The device really varies the pump displacement in such a manner as to hold the product of displacement and pressure constant. Thus, it is really a constant torque compensation when the case of variable input speed is considered.

The best inertial system appears to be that using the constant power pump compensation with that compensation beginning at a flow corresponding to the peak of the engine torque curve (in this case approximately 3000 rpm). This situation produces a minimum size system. To further reduce the size of the system, an electrical depressurizing feature was also added to the pump. This feature reduces the torque absorbed by the pump during the flywheel charging to roughly one-third of that which would be absorbed if the pump were allowed to operate at full pressure and zero output flow.

The weight of this system is shown in Table XVIII. Even with the depressurizing feature, the total system weight is quite heavy. Of the total energy produced by the Resodyne, approximately 27% is absorbed by the hydraulic pump during flywheel charging even with depressurizing features. Because this system is not power limited, it is possible to use a larger hydraulic pump and motor than for, say, the direct-start system. This allows a more rapid start to be made and reduces the amount of energy absorbed by the engine because of the reduced amount of energy used in overcoming friction. The other inefficiencies of the system, however, are such that the power required from the Resodyne to supply all the energy in the 2-minute charge period is essentially the same as that required to drive the hydraulic pump for a direct start of the engine. Thus, the direct-start system is lighter. This energy comparison is shown in Table XIX.

TABLE XVIII. RESODYNE INERTIAL-HYDRAULIC START OF ENGINE WEIGHT

Basic Resodyne	70.0 lb
Turbine Containment	24.5
Gearbox	11.5
Support Structure	7.4
Controls and Battery	3.0
Air and Fuel Bottles	3.5
Hydraulic Pump	11.5
Flywheel and Housing	61.0
Basic Hydraulic Start System	31.0
	223.4 lb

Hydraulic Accumulator Resodyne Recharge

This system (Fig. 30) is similar to the APU starting system with Resodyne recharge. Energy for the initial start of the engine is stored in a hydraulic accumulator. The utility system pump that provides starting power in the present hydraulic system is not operative during the start cycle with the accumulator energy source. The utility system pump can provide energy for starting the second engine once the first one is operating. In the event that the first engine does not start with the initial accumulator discharge, a Resodyne system provides power to drive a hydraulic pump to

TABLE XIX. ENERGY COMPARISON		
	Direct-Start, Hydraulic Transmission	Inertial-Energy, Hydraulic Transmission
Energy delivered to engine, hp-sec	249.7	214.4
Start time, sec	39.1	17.57
Peak starter output, hp	11.66	14.53
Energy delivered to hydraulic pump, hp-sec	456.0	392.0
Energy extracted from flywheel, hp-sec	-	401.0
Energy stored in flywheel, hp-sec	-	810.0
Energy absorbed by pumps during charging, hp-sec	-	309.0
Energy delivered by Resodyne, hp-sec	456.0	1160.0
Time, sec	39.1	126.0
Resodyne peak output (from gearbox), hp	11.66	11.3

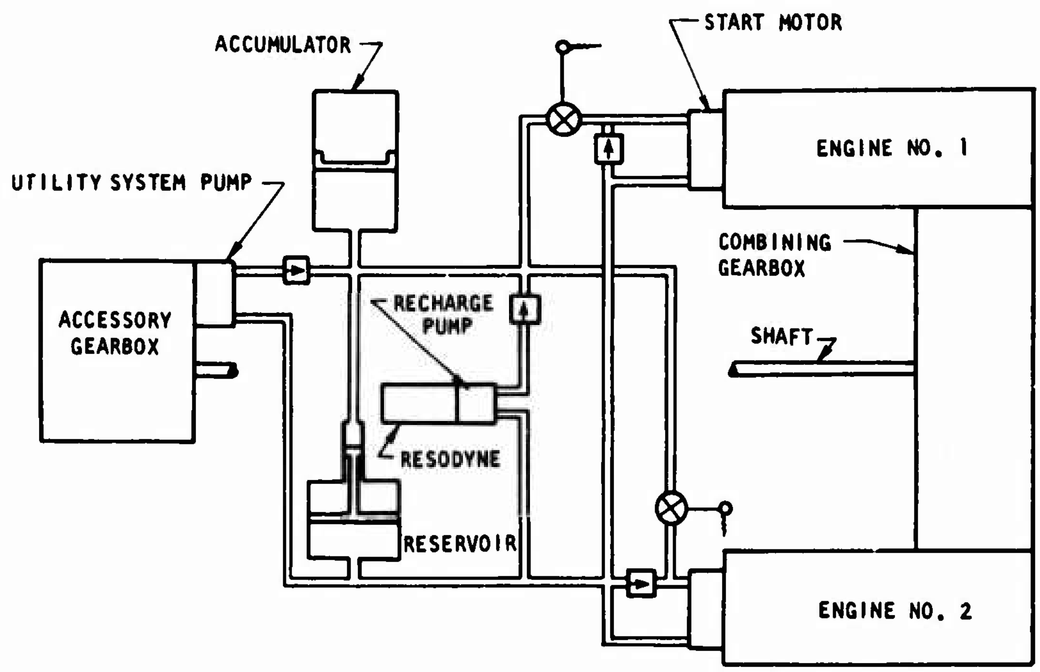


Figure 30. Hydraulic Accumulator Resodyne Recharge System.

recharge the accumulator so that an additional start attempt may be made. The Resodyne system is provided with sufficient energy storage to allow three recharges. Thus, with a partly or fully discharged accumulator, initially it is possible with this system to make three start attempts without external recharging. The remainder of the hydraulic system is identical with the present hydraulic system.

Sizing of this system requires that first an estimate be made of the size of the accumulator required for an engine start. The equations describing the discharge of an accumulator through a hydraulic motor driving an engine result in a second-order nonlinear differential equation that was solved numerically assuming that the volumetric and torque efficiencies of the hydraulic motor were constant over the range of operation. A total accumulator volume of 1960 cu in. is required to start the engine at -65°F. This start requires 19 seconds and bleeds the accumulator from a pressure of 3000 psi initially to 854 psi at starter cutout. The Resodyne unit is then sized to recharge this accumulator in 2 minutes.

One of the major elements of weight in this hydraulic accumulator system is the accumulator itself. For that reason, accumulator sizing data are presented in the next section.

Accumulator Design. All accumulator sizing data used in this study are based on the assumption that the hydraulic system is a Type II system in accordance with MIL-H-5440. This means that the system operating pressure is 3000 psi and the maximum hydraulic oil temperature is 275°F.

One approach for estimation of accumulator weight is to scale the dry weight of currently available accumulators. Qualified Parts List QPL-5498-17 lists the vendors who will supply accumulators meeting MS28700. The maximum size available in these accumulators is 400 cu in. total volume. The lightest specific weight of these accumulators is 0.0625 lb/cu in. Scaling this to a 1960 cu in. case indicates a dry weight of 122.5 lb. Since these accumulators are a cylindrical, piston-separator type, it was believed desirable to estimate the weights of a spherical accumulator with a bladder-type separator.

To estimate the weight of the spherical accumulator, it was assumed that the design criteria of MIL-A-8897 could be applied to the spherical as well as the cylindrical configuration. The thickness of such pressure vessels is controlled by the requirement of MIL-A-8897 that the burst pressure of the accumulator be equal to or greater than 12,000 psi. Typically, this requirement gives a safety factor of approximately 2 on the yield strength at the proof pressure level of 6000 psi.

Allowable stresses for 18 nickel maraging (300) steel were taken from Ref. 11. A butt weld joint efficiency of 0.9 was assumed in accordance with Ref. 12. The stress at the burst pressure of 12,000 psi was compared to the ultimate strength of the material. The weights of the additional elements such as flanges, fittings, etc. (which amount to nearly 60% of the basic shell weight), were based on Ref. 13. The dry weight of this spherical-type accumulator is estimated at 0.035 lb/cu in., which results in a dry weight of 68.6 lb for a 1960-cu in. accumulator. While this weight is significantly lower than that for the piston type, it is still excessive. The weight of a titanium accumulator using 6Al-4V was slightly higher than for the steel because of the degradation in titanium strength at 275°F.[11]

A final alternative that was investigated was the use of fiber glass filament-wound pressure vessels. Data received from the manufacturer* indicate that a specific weight of 0.023 lb/cu in. can be obtained with the fiber glass bladder configuration. This results in an estimated dry weight of 45 lb for the 1960-cu in. volume case.

The accumulator weight data are summarized in Table XX. For an accumulator of this size, serious consideration must be given to the fiber glass configuration. The cost of the fiber glass device does not appear to be significantly higher than would be expected for metallic vessels.

TABLE XX. ACCUMULATOR WEIGHT COMPARISON FOR 1960-CU IN. TOTAL VOLUME

Accumulator Type and Shell Material	Dry Weight (lb)	Wet Weight (lb)
Piston Type, 4340 S[illegible]el	122.5	161.1
Spherical, 6Al-4V T[illegible]um	73.7	112.3
Spherical, 18 Nickel Maraging (300) Steel	68.6	107.2
Near Spherical, Fiber Glass	45.0	83.6

Weight Summaries. The weight of a one-start hydraulic accumulator engine start system is shown in Table XXI. The weight of a three-start accumulator system is shown in Table XXII. In both cases, weights are presented for the fiber glass and piston-type accumulators. Table XXIII presents the weight estimates for a complete Resodyne recharge unit combined with the single-start accumulator system, again for two accumulator types. This Resodyne system adds just over 50 lb to the weight of the single-start accumulator and thereby provides three-start capability. This compares with nearly 200 lb added to achieve the same capability using accumulator energy storage with the fiber glass vessel as shown in Table XX.

The possibility of reducing accumulator size by heating the engine oil for a -65°F start was also investigated. This was done in the same manner as previously described for APU starting. The reduction that would be achieved in accumulator size with oil heating was found to be less than 250 cu in. total volume. This would mean a reduction of less than 10 lb in accumulator weight. Because the heat exchanger and circulating pump that would have to be added to the system would weigh about the same amount, there appears to be no advantage to oil heating for starting of the ST9 engine.

*Personal communication from P. Duvall, Brunswick Corp., to R. L. Binsley, Rocketdyne, 28 July 1970.

TABLE XXI. HYDRAULIC ACCUMULATOR ENGINE START SYSTEM WEIGHT (ONE START)

	Fiber Glass Accumulator	Piston Accumulator
Basic Hydraulic System	31.0 lb	31.0
Accumulator	83.6	161.1
Additional Reservoir Capacity	10.0	10.0
Total	124.6 lb	202.1 lb

TABLE XXII. HYDRAULIC ACCUMULATOR ENGINE START SYSTEM WEIGHT (THREE STARTS)

	Fiber Glass Accumulator	Piston Accumulator
Basic One-Start System	124.6 lb	202.1 lb
Additional Accumulators	167.2	322.2
Additional Reservoir Capacity	23.2	23.2
Total	315.0 lb	547.5 lb

TABLE XXIII. RESODYNE RECHARGE HYDRAULIC ENGINE START (-65°F, THREE STARTS)

	Fiber Glass Accumulator	Piston Accumulator
Resodyne	29.0 lb	29.0 lb
Turbine Containment	8.3	8.3
Gearbox	5.5	5.5
Support Structure	2.6	2.6
Controls and Battery	3.0	3.0
Air and Fuel Bottles	1.5	1.5
Hydraulic Pump	2.3	2.3
One-Start Accumulator System	124.6	202.1
Total	176.8 lb	254.3 lb

Resodyne Inertial Pneumatic System

This system (Fig. 31) is identical to the present pneumatic starting system except that a Resodyne-driven flywheel provides the energy for a compressor which, in turn, provides energy in pneumatic form. The Resodyne inertial system is similar to that previously discussed except that it now drives a compressor rather than a hydraulic pump.

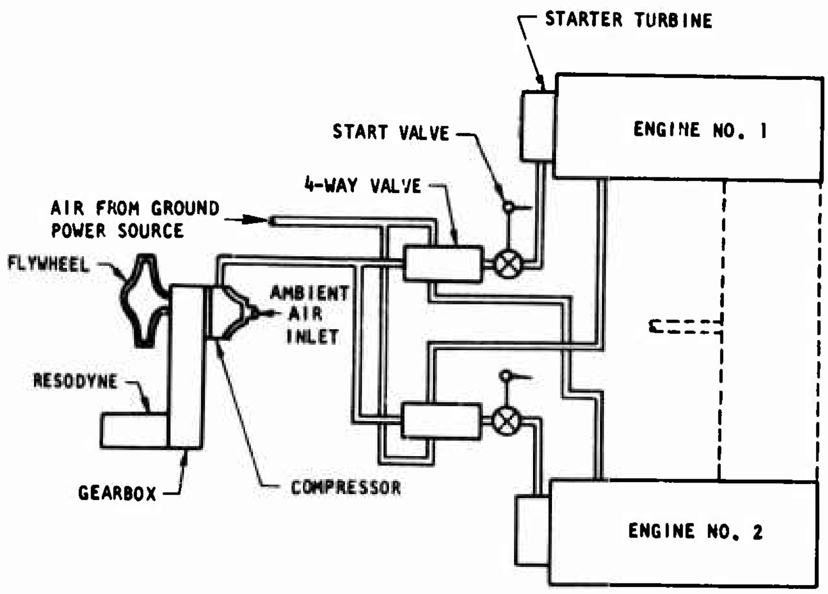


Figure 31. Resodyne Inertial Pneumatic System.

The weight of this system is summarized in Table XXIV. The weights of the Resodyne and energy storage flywheel are quite large. This is primarily caused by the inherent characteristic of the pneumatic system that consumes a large amount of energy while delivering very little energy to the engine at the low engine speeds.

TABLE XXIV. RESODYNE INERTIAL PNEUMATIC ENGINE START (-65°F, THREE STARTS)

Resodyne	72.0 lb
Turbine Containment	25.2
Gearbox	10.9
Flywheel	101.7
Compressor	3.1
Controls and Battery	3.0
Air and Fuel Bottles	3.8
Support Structure	7.2
Basic Pneumatic System	50.0
Total	276.9 lb

Direct Engine Start With Pneumatic Transmission

This system (Fig. 32) is inherently quite simple. A Resodyne drives a compressor that provides pneumatic power to the present pneumatic starting system. The Resodyne compressor combination substitutes for the presently used APU pneumatic power source.

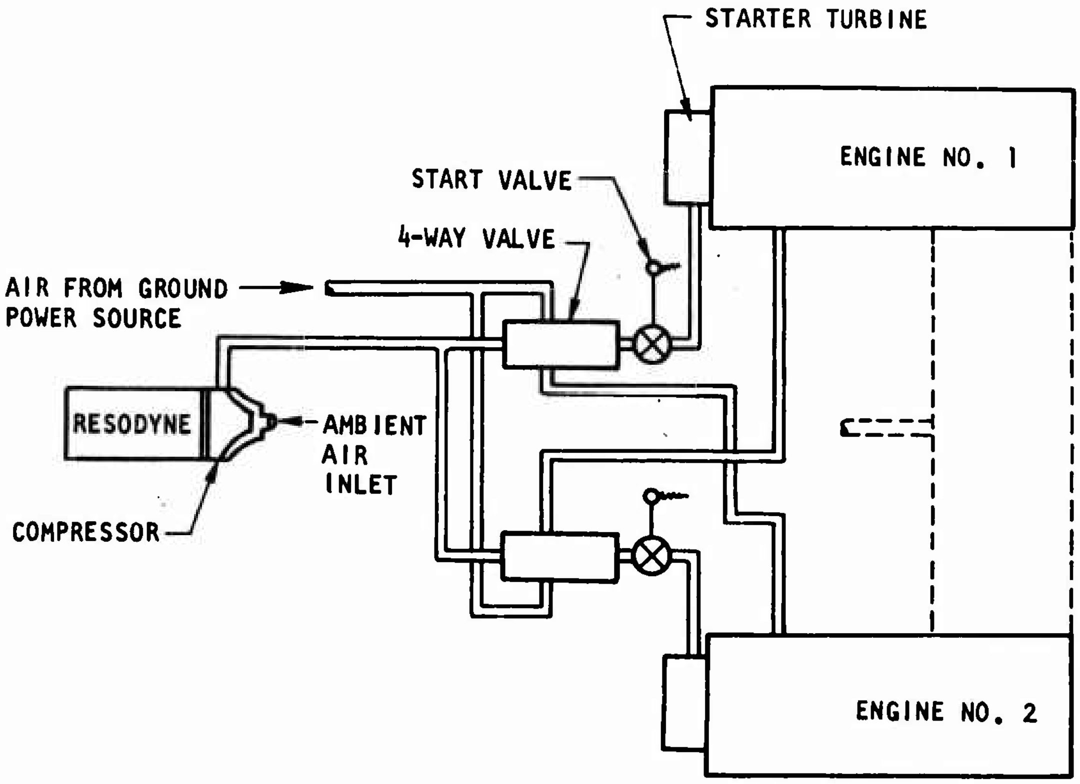


Figure 32. Resodyne Direct-Start Pneumatic System.

The weight of this direct start system pneumatic transmission is summarized in Table XXV. The Resodyne for this case is larger than that required for the direct start with hydraulic transmission because the limiting power condition is at high altitude on a hot day rather than at high altitude on a cold day. The compressor weight shown is based on a comparatively slow-speed efficient compressor. A weight saving of a few pounds is possible

TABLE XXV. RESODYNE PNEUMATIC ENGINE START DIRECT COMPRESSOR DRIVE, INLET SIDE (-65°F, THREE STARTS)

Resodyne	97.0 lb
Turbine Containment	36.8
Gearbox	7.1
Compressor	23.8
Controls and Battery	3.0
Air and Fuel Bottles	2.0
Support Structure	9.4
Basic Pneumatic System	50.0
Total	229.1 lb

if a higher speed compressor and additional gears are used. The Resodyne becomes larger in that case, since the compressor efficiency would be reduced.

System Comparison

The weights of the various engine starting systems considered in this study, together with their relative failure rates and relative costs, are shown in Table II. All the systems shown are capable of starting the engine at -65°F provided that the APU is capable of operating at -65°F.

The number of starts that can be made without recharging affects the comparison of starting systems for the engine. When an APU is used, the number of start attempts is essentially unlimited. The basic hydraulic or pneumatic engine starting system without the APU, on the other hand, is not capable of any starts, since the APU is the energy source. Thus, Resodyne systems that contain an energy source must be compared either with basic starting systems that do not have an energy source or with systems that include an APU.

The lightest weight Resodyne system is the direct start utilizing hydraulic transmission. The next lightest system is the hydraulic accumulator recharge, which has significantly lower relative failure rate and slight additional cost compared to the direct start. Again, as was the case with the APU, the recharge system has a comparatively lower failure rate because it is not called on as frequently. The majority of starts are made utilizing only the accumulator energy source without the necessity for recharging by the Resodyne. With a successful engine start, the accumulator is recharged by the utility system pump. Multiple-start capability is attained much more economically using the Resodyne combined with a one-start accumulator system than with a three-start accumulator system.

The full winterization system, which consists of a hydraulic accumulator recharge unit plus an engine oil heating capability, was not sized in detail. Such a unit would weigh approximately the same as the accumulator recharge unit. However, it would cost more and have a higher failure rate than the recharge unit. In addition, utilizing such a device with a two-engine system requires that the engine oil systems be intermingled in the engine oil heater or that two separate oil heating systems be utilized. Neither the weight and cost of two systems nor the mingling of oil in a single heating system is considered part of a satisfactory solution.

The hydraulic accumulator recharge system was selected for a more detailed study. It must be noted though, that should the direct-drive system with hydraulic transmission be felt to be applicable to future aircraft, the problems of integration with the vehicle will be nearly identical to those of the hydraulic accumulator recharge system. Thus, solutions to installation problems for the hydraulic accumulator recharge system are equally applicable to the physically larger Resodyne direct-starting system.

PRELIMINARY DESIGN STUDY

AUXILIARY POWER UNIT STARTING

The Resodyne system selected for further study for starting APU's is based on hydraulic starting of the APU. The system consists of a multiple-start/winterization kit that can be added to the basic hydraulic starting system. This kit circulates and heats the oil from the APU to reduce its drag at low ambient temperatures, and in addition, tops off the hydraulic start system accumulator. Following an unsuccessful start, the Resodyne winterization kit will completely recharge the start system accumulator. One of the major unknowns in this system is the heat exchanger. Efforts in this phase of the study were concentrated on design of the heat exchanger and the layout of the power-producing portion of this starting system.

Unit Sizing

The major sizing work accomplished was sizing of the heat exchanger. This unit was designed to heat 3 quarts of APU oil (MIL-L-007808C) from -65° to +135°F in 2 minutes. To prevent coking, it was conservatively assumed that no wall could exceed a temperature of 250°F. The available heat source is exhaust gases from the Resodyne at a temperature of about 1200°F.

The simplest way to heat the oil would be to heat it in the APU gearbox sump using an immersion heater or hot-gas impingement on the gearbox outer surfaces. This system would not require a circulating pump. Calculations showed that with such a natural convection heat transfer mechanism, approximately 5 sq ft of surface area would be needed. This compares with approximately 1 sq ft of wetted sump area available. The natural convection heat transfer is very low because of the high oil viscosity at -65°F and the low-temperature difference associated with a 250°F maximum wall temperature. Therefore, the approach is not practical.

A closed-loop circulation system was designed. This utilizes a heat exchanger of the shell and tube type with hot exhaust gases passing over the outside of the tubes and oil from the sump circulating inside them. Tube wall temperature was limited to 250°F. Initially, a constant tube wall temperature of 250°F and sump wall temperature of -65°F were assumed. Later, the validity of these assumptions was examined. Inside the tubes, a laminar flow with parabolic velocity profile was assumed. Gas-side heat transfer was based on an experimentally determined value of 40 Btu/hr-ft^2-°F. Again, natural convection was assumed to the sump walls.

Various tube diameters and lengths were examined. The best value appears to be a 32-ft length of 0.5- by 0.035-in. tube. This gives an initial pressure drop (based on full oil flow of 2.1 gpm) of 316 psi. This tube size was calculated to attain its steady-state temperature of 250°F in about 12 seconds from beginning of hot-gas flow, thus essentially validating the assumption of constant wall temperature. The rate of heat loss into the sump walls was also calculated to be small, as originally assumed.

The resulting estimates of heat exchanger performance are shown in Fig. 33. Sump oil temperature rises to 135°F in 2 minutes. The oil pressure drop initially is 316 psi. Within 20 seconds, this has dropped to less than 50 psi, and by 40 seconds is almost negligible. Thus, the power required for the circulating pump drops to a negligible (or nearly so) amount in 30 to 40 seconds. This allows the Resodyne power to be switched into the hydraulic pump for the remainder of the operating period. This switching is discussed further below.

System Description

The layout of the system (shown in Fig. 34) illustrates the basic combustor configuration together with the turbine, heat exchanger, gearbox, and pumps. The basic combustor configuration used is the four-tailpipe configuration with the tailpipes spiraled. Power generated in the turbine is extracted through a right-angle gearbox, which is brought out on the turbine inlet side by expanding the tailpipe spirals locally. To minimize package size, two pads were placed on the gearbox, one for the circulating pump and one for the hydraulic pump. The gearbox itself is a straightforward design with lubrication of the gears and bearings provided by slingers. The circulating pump is a straightforward gear pump supplying a comparatively low maximum pressure (316 psi). The hydraulic pump is a New York Air Brake model 65-WE002.

The heat exchanger design is as previously described. A single tube is spiraled in a basic counterflow configuration. Hot gases are admitted to the heat exchanger through a ring valve. The ring valve is controlled by a thermostatic actuator sensing temperature of the tube wall near the oil outlet. Thus, the tube walls will always be maintained at or below 250°F. Most of the exhaust gas will travel out the exhaust duct bypassing the heat exchanger. With the ring valve closed, all exhaust gases pass out the duct. An alternate heat exchanger control scheme will be discussed later. Provisions for mounting the unit to the vehicle are also shown. Main support of the power-producing section is at the turbine area. Some support is also required at the air inlet end of the combustor. A flexible mounting at this position gives support to the combustor but allows axial or longitudinal expansion. The exhaust duct from the turbine is attached to a stiffener on the aircraft skin through a simple asbestos gasket or seal.

Figure 34 represents only the power-producing elements of the Resodyne multiple-start/winterization kit. The control elements are not shown. These are all straightforward items that can be designed into an integrated package. This single module can then be mounted at any convenient location in the vicinity of the power-producing section. Size of the control element package may be inferred from sizes of the fuel accumulator (49 cu in., 4-3/4-in. OD) and air bottle (9 cu in., 2-3/4-in. OD). Batteries are 1.4-in. diameter by 4.5-in. long.

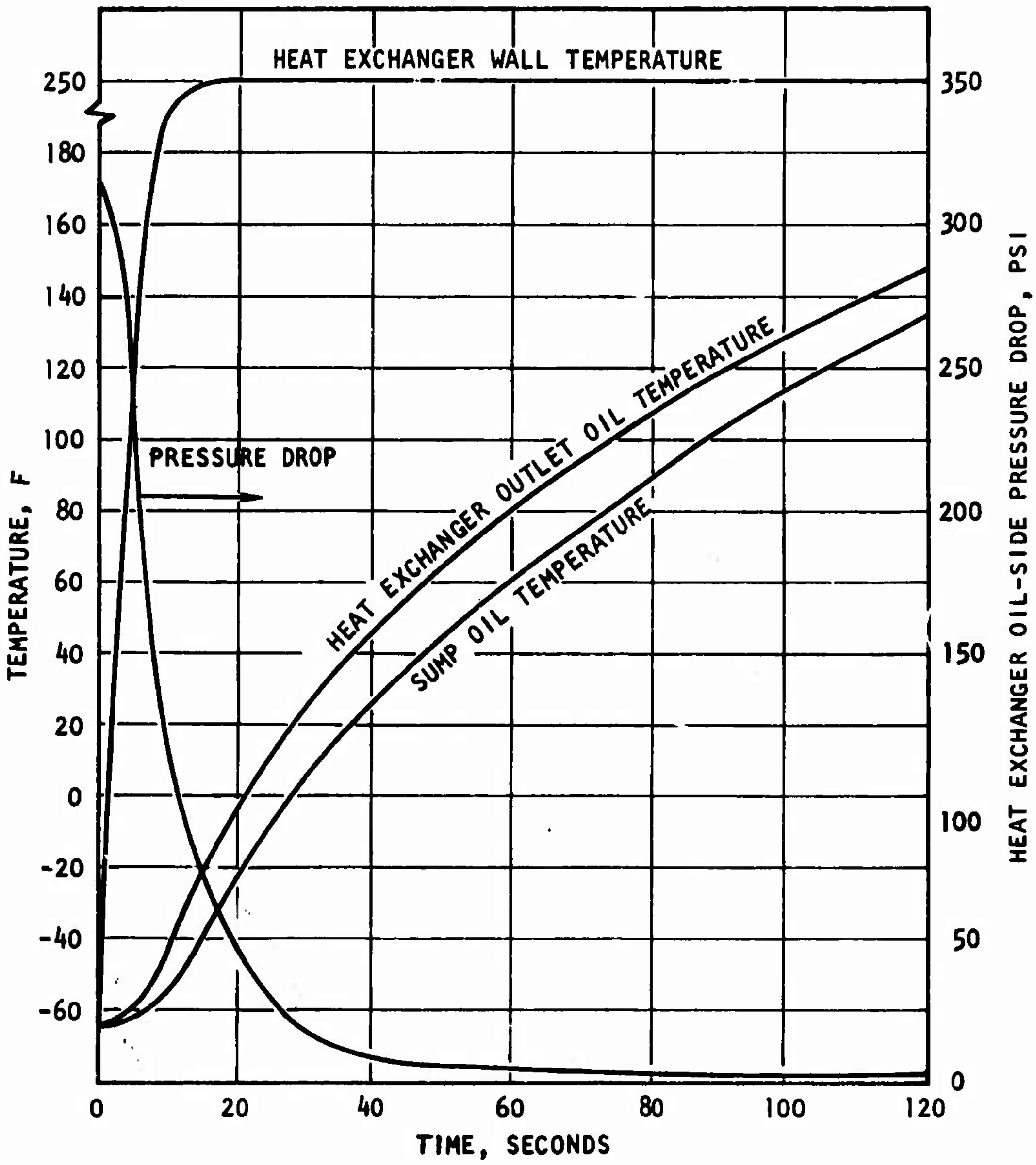


Figure 33. Resodyne Oil Heating Performance With Solar T-62T-2A Engine.

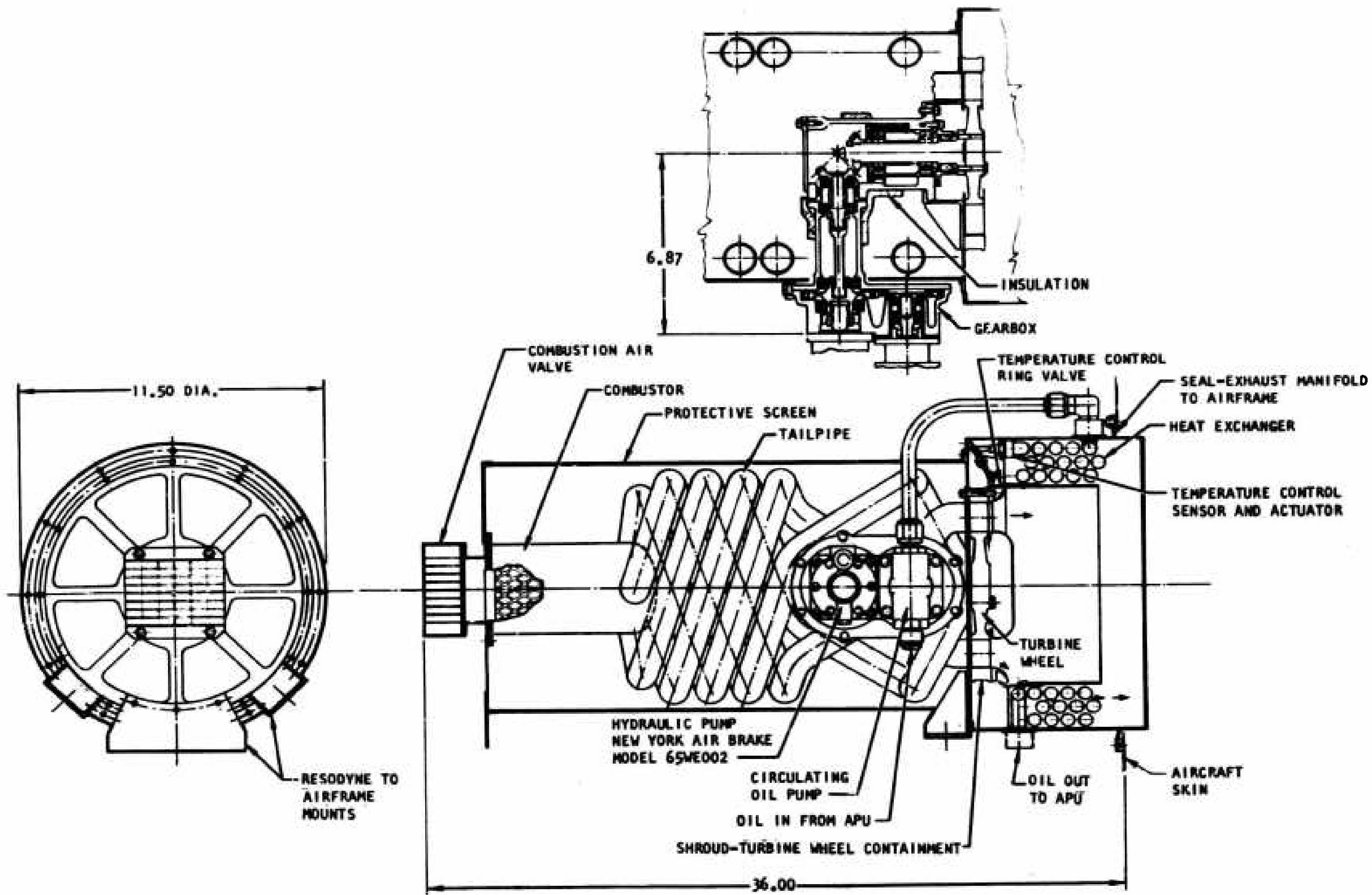


Figure 34. APU Starter Layout.

The design study revealed several variations and improvements that might be made on the configuration just described. For example, the circulating pump might be better integrated into the unit by either integrating it into the gearbox or by placing it on the turbine shaft. In either case, adequate design effort should produce a simplified mechanical configuration.

Another major configuration variation (which only became apparent following the engine starting system study to be described next) is that of placing the pumps inside the combustor tailpipe spiral. With this configuration, if the turbine and pump speeds are well matched, it is possible to eliminate the gearbox entirely. The main price paid for this gearbox elimination is slightly larger external dimensions of the combustor and the addition of thermal insulation to the pumps to prevent overheating during combustor operation. To apply this configuration to the multiple-start/winterization system would require that the combustor be elongated several inches.

Additional Controls

To mechanize the Resodyne multiple-start/winterization start system, it is necessary to add some controls beyond those needed to start, operate, and shut down the Resodyne itself. These elements are shown schematically in Fig. 35.

Control of the heat exchanger to prevent tube wall temperature from exceeding 250°F requires that the flow of hot Resodyne exhaust gases be controlled. One way to do this is the ring valve approach shown in Fig. 34. Its operation is shown schematically in Fig. 36a. The thermostatic actuator is attached to the heat exchanger tube and thus senses tube wall temperature. When 250°F is approached, the actuator extends, thus moving the ring valve to cover the bypass port and reduce exhaust gas flow through the heat exchanger. A ring valve of this size offers some challenges from the point of view of maintaining low friction, noncocking operation. An alternate, more conventional scheme is shown in Fig. 36b. In this system, louvers block off the normal exhaust and force gases through the heat exchanger. As the oil heats, the louvers are opened and bypass flow is reduced.

The choice of heat exchanger control schemes depends on the actual gas flow and the detailed mechanical design possibilities. The gas flow through the heat exchanger may not be large enough when maximum heating is required even with the ring valve full open. On the other hand, it may not be small enough when no heating is needed, even with the louver valves full open. Only experiments can establish which of these situations prevails. Detailed mechanical design must await these data.

The hydraulic pump flow control is needed because the Resodyne was not sized large enough to provide maximum circulating pump power and hydraulic pump power simultaneously. The flow sensitive bypass valve bypasses flow back to the pump suction and, by preventing pump pressure buildup, minimizes pump power absorption. When the circulating pump power has decreased and Resodyne

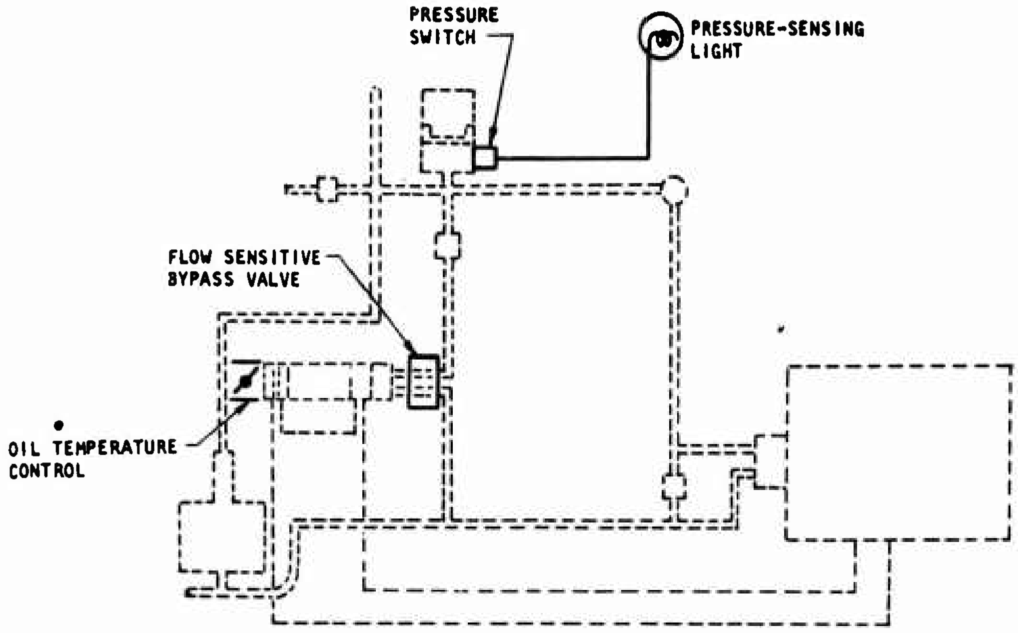


Figure 35. Additional Control Elements Required for Multiple-Start/Winterization System.

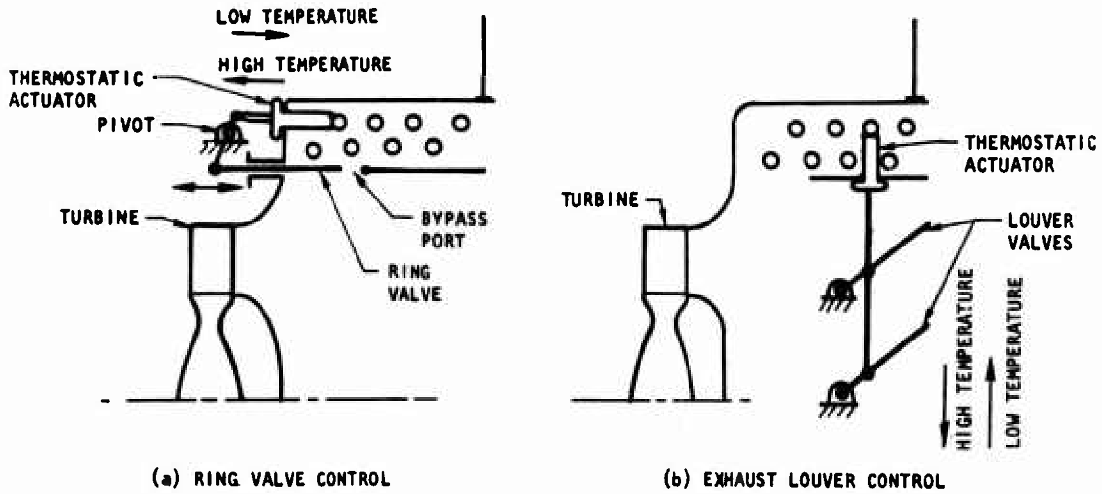


Figure 36. Heat Exchanger Control Schemes.

speed increased, the valve senses increased flow and closes. This allows the hydraulic pump to operate normally and refill the accumulator in the pressurized system. Finally, when the accumulator is being recharged, and the process is complete, a pressure switch and cockpit light will signal the completion.

Operating Sequences

The multiple-start/winterization system has several modes of operation: recharge/topping, oil heating, and combined heating and recharge. The controls are such, however, that no decisions are required from the pilot regarding the operating modes. This will become apparent as the operating sequence is described. The pilot first starts the Resodyne using the single lever control as described earlier. At this time, the hydraulic pump is in the bypass mode, thus absorbing only a small amount of torque. A circulating pump begins to circulate the low-temperature APU oil through the heat exchanger that is now heating up. As the power absorbed by the circulating pump reduces, the Resodyne speed increases. As Resodyne speed increases, the hydraulic pump bypass flow increases. When the predetermined value has been reached, the flow sensitive bypass valve actuates, allowing the hydraulic pump to be repressurized.

The Resodyne drives the hydraulic pump in this recharge mode until the accumulator pressure reaches its full value. At that time, the pressure switch closes, lighting the indicator light in the cockpit. This light informs the pilot that the accumulator is now fully charged. The pilot immediately shuts off the Resodyne and is now prepared to proceed with the normal start sequence for the APU. In the event that the APU does not start, the same procedure may be used for initiating and operating the Resodyne. Since the APU oil will already be warm, hydraulic pump operation will start almost immediately. Otherwise, operation is identical.

Vehicle Integration

The exact location of the multiple-start/winterization starting system in the vehicle depends on the location selected for the APU. Figure 37 shows two possibilities. These represent the most likely configurations but do not exhaust the possibilities. If the APU is located next to the main vehicle gearbox above the payload compartment, the most convenient location for the starter system would be in the same compartment area. The most likely possibility is shown in Fig. 37. The major difficulty with that approach shown is the exhaust situation. There is not sufficient room to orient the starter so that the exhaust is normal to and flush with the vehicle skin. This exhaust inset configuration will probably not have any significant effect on the vehicle other than to raise the production cost slightly. Its effect on the Resodyne may, however, be significant.

If the alternate APU location shown in Fig. 37 is utilized, a much better location for the starter is possible. The starter may be mounted next to the APU in the compartment just behind the payload. Its best position is

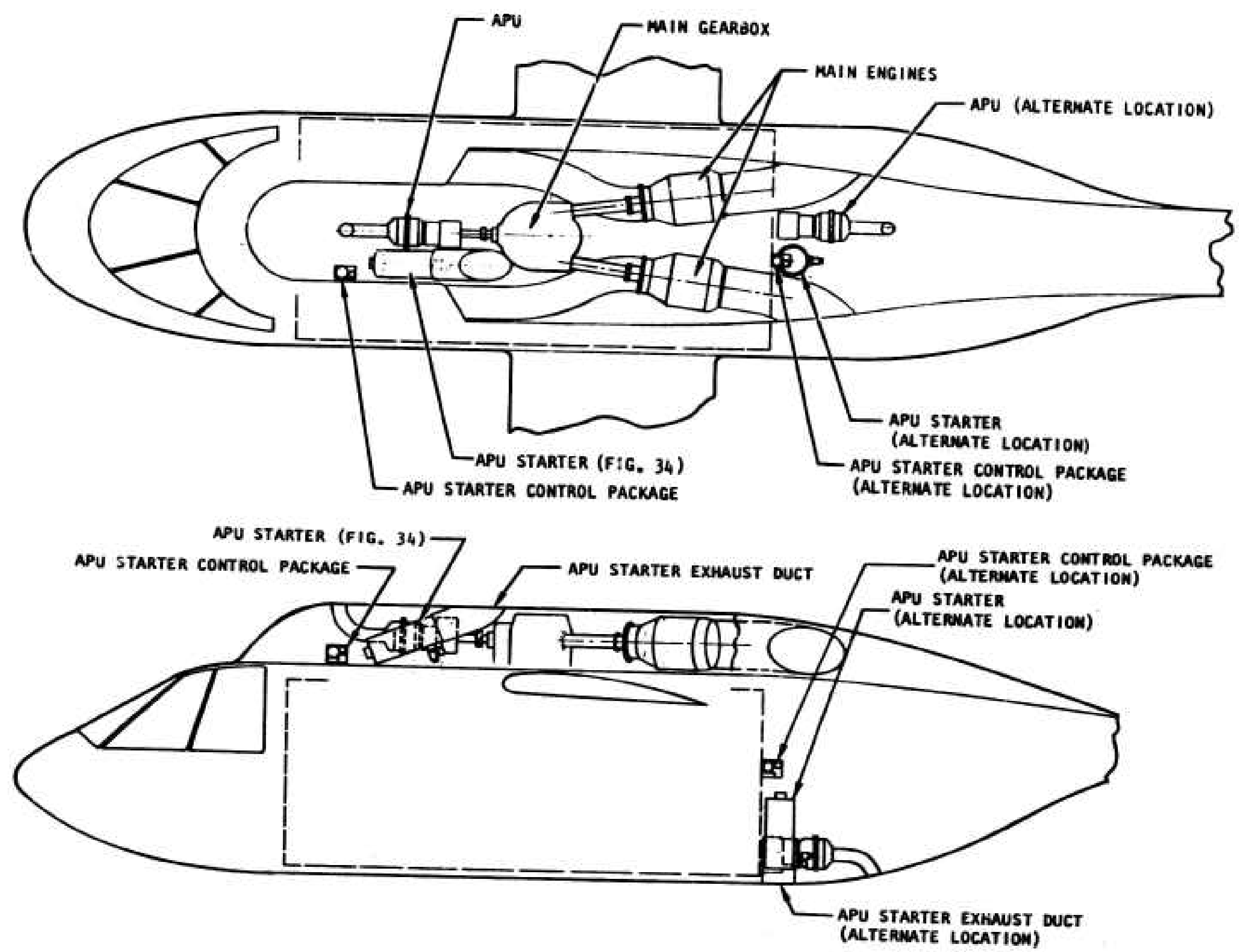


Figure 37. APU Starter Installation.

vertical with the exhaust downward. In this position, there is minimum chance of personnel injury due to the exhaust. There is also minimum opportunity for rain, sand and dust, etc., to enter the duct and interfere with operation. Dirt, in fact, will tend to fall out. In the event of a misfire in the Resodyne, the fuel would tend to drain out, thus minimizing possible hazard. It is also conceivable that the alternate location shown for the starter can be used with the APU in the location above the payload. This degree of physical separation of the starter and APU would add some line pressure drop, and hence, would possibly increase slightly the size of the Resodyne required to do the job.

Comparison With Initial Estimates

With a layout drawing available, it is now possible to prepare more refined estimates of system weight. Table XXVI shows such estimates compared with those prepared earlier during the system comparison phase of the program. It will be seen that the gearbox is somewhat heavier.

TABLE XXVI. RESODYNE MULTIPLE-START/WINTERIZATION SYSTEM WEIGHT COMPARISON

	Initial Estimate	Refined Estimate
Resodyne	15.5 lb	15.3 lb
Gearbox	3.8	5.7
Turbine Containment	3.9	3.2
Support Structure	1.4	5.8
Controls and Battery	3.0	3.0
Air and Fuel Bottles	1.1	1.1
Hydraulic Pump	2.3	2.3
Circulating Pump	1.5	0.9
Heat Exchanger and Fluid	3.6	7.6
Basic Hydraulic Start System (less hand pump)	22.1	22.1
Total	58.2 lb	67.0 lb

This is caused by use of two output pads rather than the one originally assumed. Heat exchanger and fluid is approximately 4 lb heavier than originally estimated. As noted earlier, the preliminary sizing of heat exchangers was based on the assumption that gas-side heat transfer controlled. The more-detailed calculations showed that the oil side was also significant. The heat exchanger could have been made smaller, but only at the expense of pump power. The other major weight difference is in the structure, which is approximately 4.5 lb heavier. The original estimate primarily included the protective screen that covers the combustor. The current estimate includes that screen (weighing slightly more than originally estimated), as well as the mounting feet and flanges for attaching the whole Resodyne unit to the vehicle.

This discrepancy in structural weight would be common to all Resodyne systems as compared in Table I, and in addition would apply to some extent to the present starting systems where no allowance was made for structural weight. Thus, the comparisons of weights in Table I are still essentially valid, although the magnitude of all may be slightly optimistic.

It becomes apparent by studying Table XXVI that removing the gearbox and placing the pumps inside the combustor tailpipes may allow a significant reduction in weight. The weight, in fact, may be reduced close to that originally called out in Table I.

The reliability and cost of the system will be essentially as originally estimated. Use of the two output pads will slightly increase the cost and reduce the reliability. Removing the gearbox and placing the pumps inside the combustor would reduce the cost measurably and increase the reliability somewhat. These factors, together with the weights, make compelling arguments for using the no-gearbox, pump-inside configuration.

<u>Unknowns</u>

Several factors associated with the multiple-start/winterization system could be considered unknowns. Some of these might prevent successful application of the resonant combustor if they cannot be solved.

The largest number of unknowns are associated with the operation of and control of the heat exchanger in conjunction with the Resodyne. The basic heat exchanger sizing may be overly conservative. Operation of a Resodyne with such an exhaust device has not been demonstrated. Operation with such a device exhausting either normal to or at an angle to a vehicle skin has not been demonstrated. Control of the exhaust gas flow through the heat exchanger has not been demonstrated. Ability of the circulating pump to circulate oil through the system at -65°F without cavitating requires demonstration. Successful operation using the flow sensitive bypass valve to control where the Resodyne power goes is also a matter of some concern. A program for further investigation of these factors is suggested in the Conclusions and Recommendations section.

<u>ENGINE STARTING SYSTEMS</u>

For starting an engine without use of an APU, the hydraulic accumulator energy storage system with a Resodyne recharge was chosen. This system will normally recharge by drawing energy from the vehicle utility pumping system following start of the engine. In the event of an unsuccessful engine start, the Resodyne recharge unit will recharge the accumulator to allow another start. The Resodyne recharge unit can also be used to top off the accumulator charge when it has bled down during a period of aircraft inactivity.

This system provides multiple starts at -65°F with only enough energy stored in the hydraulic system for a single start. Should engines other than the ST9 be considered, and should oil heating produce a significant reduction in engine drag, the Resodyne recharge unit can be adapted as a full winterization kit similar to that used for the APU starting case.

Unit Sizing

The accumulator for this system was previously calculated to have a total volume of 1960 cu in. That volume is still satisfactory. More refined calculations have been made to determine the size of the Resodyne and hydraulic pump necessary to recharge this accumulator at 10,000 ft, -65°F. The refinements in calculations are basically improved estimates of losses and efficiencies. One important parameter varied during the preliminary design study was recharge time. If a longer recharge time is used, a lower pump input power is required; hence a smaller Resodyne can be used to drive the pump. The effect of this recharge time variation is shown in Fig. 38.

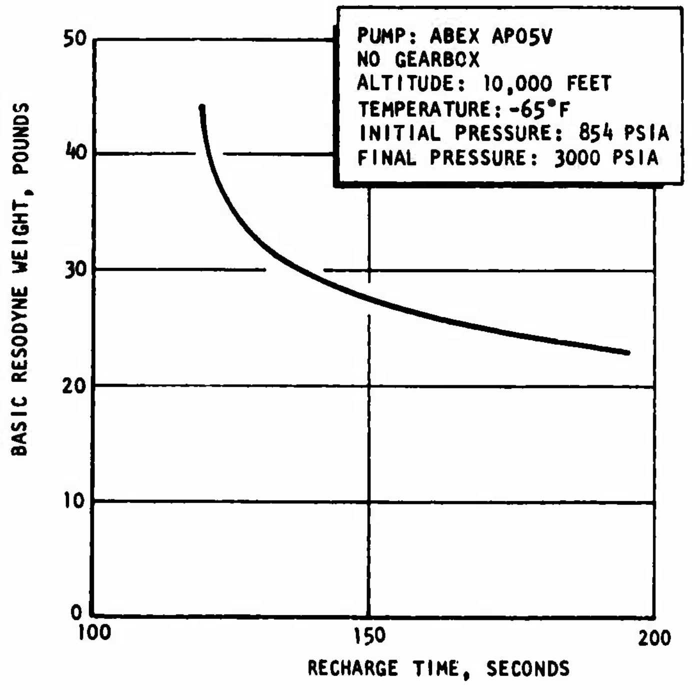


Figure 38. Effect of Recharge Time.

A system that will recharge the accumulator in 2 minutes is significantly heavier than one that will do the same job in 3 minutes. Because of this considerable weight difference, it was decided to design the engine start system for a 3-minute recharge time. The main penalty incurred by so doing is the increased time to recharge following an unsuccessful engine start. The main benefit is significantly reduced system weight.

System Description

The layout of power components is shown in Fig. 39. This system is similar to that for the APU starting. It has been possible, however, by slightly enlarging the combustor, to place the hydraulic pump inside the combustor and thereby eliminate the gearbox. This represents a significant simplification. This system also differs from the APU starting system in that no heat exchanger is involved. Should heating of engine oil prove desirable, it would not be difficult to add the heat exchanger to the turbine exhaust, as was done for the APU starting system. An engine oil circulating pump can also be added in line with the hydraulic pump. The hydraulic pump selected for this specific machine is the Abex Model AP05V. The pump will require a constant power pressure compensator to limit the maximum power absorbed by the pump to approximately half that required with full power and full pressure.

Mounting for this power-producing portion of the starting system is arranged to support the main load at the turbine. Mounting brackets at the turbine will connect directly to the airframe structure. Flexible mounting at the combustor inlet to the airframe allows longitudinal movement of the combustor. Exhaust will again be through the vehicle skin with an asbestos seal as described for the APU starting system.

Controls components required with the Resodyne have not been shown. However, they will be comparatively small. For example, the air bottle for start air required with the Resodyne has a volume of 17 cu in., thus producing an OD of about 3-1/4 in. The fuel bottle has a total volume of 131 cu in., thus producing an OD of about 6-1/2 in. There will be no difficulty in mounting these bottles together with the batteries, ignition exciter, and valves as a single controls package in the vicinity of the power producing-package.

Operating Sequence

This engine recharge unit has only one mode of operation (recharging of the engine start accumulator). If the accumulator has lost some of its pressurization while sitting, the Resodyne recharge unit may be used to top off the accumulator charge. If an unsuccessful start has been made and the accumulator is completely discharged, the Resodyne recharge unit may be used to fully recharge the accumulator. The main difference in these two situations is that the complete recharge takes a longer period of time. In both cases, need for operation of the Resodyne recharge unit is determined by observation of the hydraulic accumulator charge pressure. If this pressure is below 3000 psi, the recharge unit may be activated.

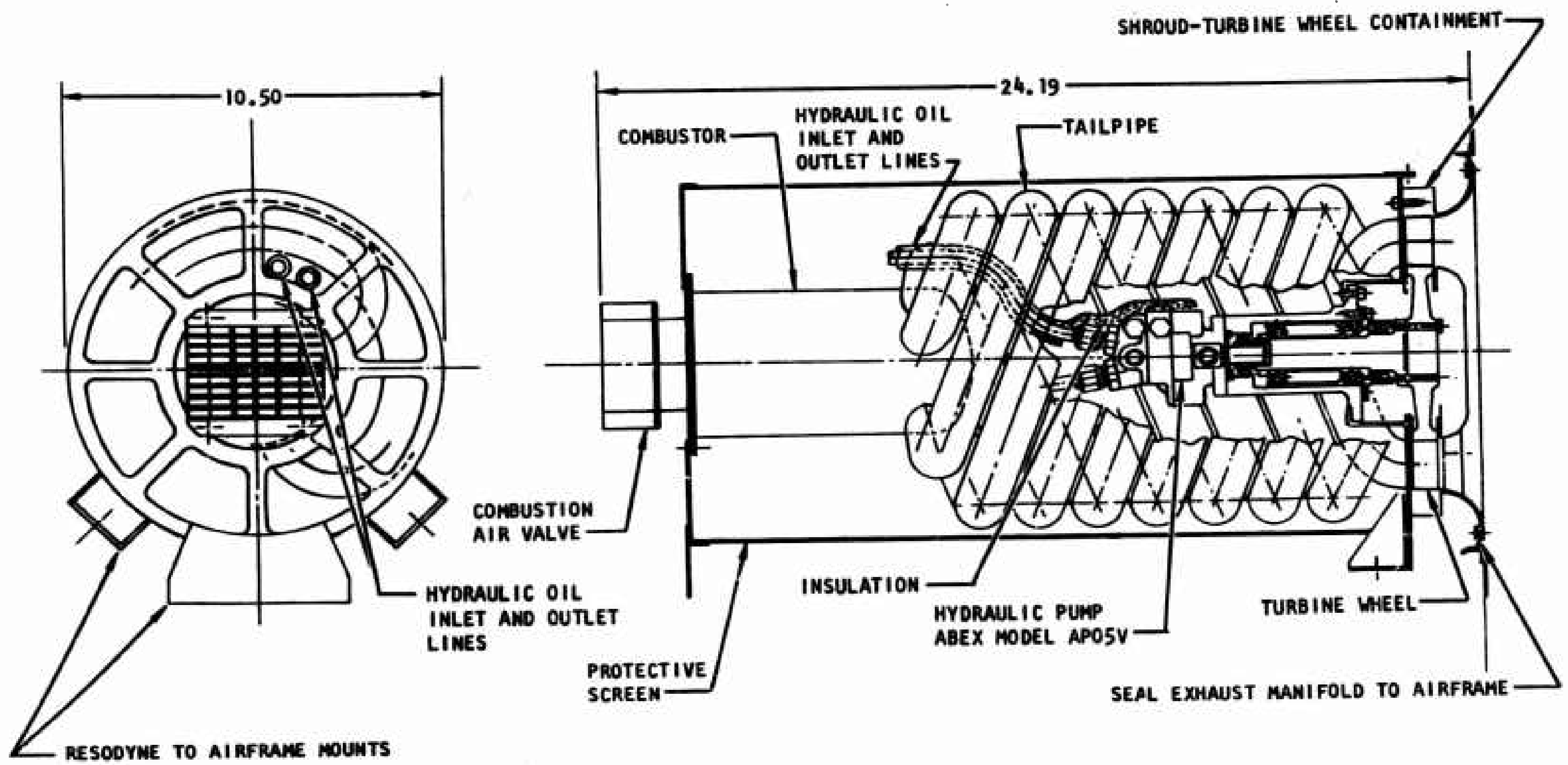


Figure 39. Resodyne Engine Starter.

Initiation of operation of the Resodyne itself is accomplished as described previously under the section entitled Study Criteria. With the Resodyne operating, no control is required other than the "constant power" pressure compensation built into the hydraulic pump. When the recharge has been completed (i.e., when the accumulator pressure has reached 3000 psi), it is necessary to shut off the Resodyne. This may be accomplished either manually under the control of the pilot or, if desired, may be made automatic by means of a pressure sensitive switch.

Vehicle Integration

Since the power-producing package is approximately 2 ft long and nearly 1 ft in diameter, and since the Resodyne must exhaust overboard with a minimum of ducting interference, the possible locations of the Resodyne are limited. Two possible locations for the Resodyne recharge unit are shown in Fig. 40. The first alternate location places the Resodyne recharge unit in the engine compartment above the main body of the aircraft. Placing the Resodyne on the centerline of the vehicle and slightly tilted does not allow the exhaust to be normal to the skin. Interference with normal Resodyne operation is possible with this configuration. The hydraulic accumulator, since it represents the largest single weight in the starting system, is placed on the vehicle centerline as close to the rotor as possible to minimize balance problems.

The alternate location for the Resodyne unit is in the section behind the main compartment. The best location in this compartment is on vehicle centerline and with a vertical orientation exhausting downward. This places the exhaust flush with and normal to the vehicle skin. The vertical mounting has some additional benefits for the Resodyne. In the event of a misfire or any other fuel system difficulty in the Resodyne, excess fuel would drain out the bottom of the unit. Further, in a sand and dust environment, contaminants are least likely to penetrate far into the unit through an opening on the bottom of the vehicle. In other words, dirt will also tend to fall out of the unit.

Weight of the hydraulic and control lines for the two alternate locations of the Resodyne which are shown are nearly the same. A final decision on Resodyne recharge unit location is, therefore, a function of details of the particular vehicle in which it will be used. The Resodyne can probably be operated satisfactorily in either location. Other locations that also satisfy the exhaust requirements and therefore will be satisfactory will probably exist in any aircraft.

Comparison With Initial Estimates

Because a recharge time of 3 minutes has now been selected for this system, the system weight has been reduced compared to that previously estimated. This is shown in Table XXVII. The Resodyne itself and the weight of the turbine containment material have both been reduced because of the reduced Resodyne power requirement compared to the original value. The weight of

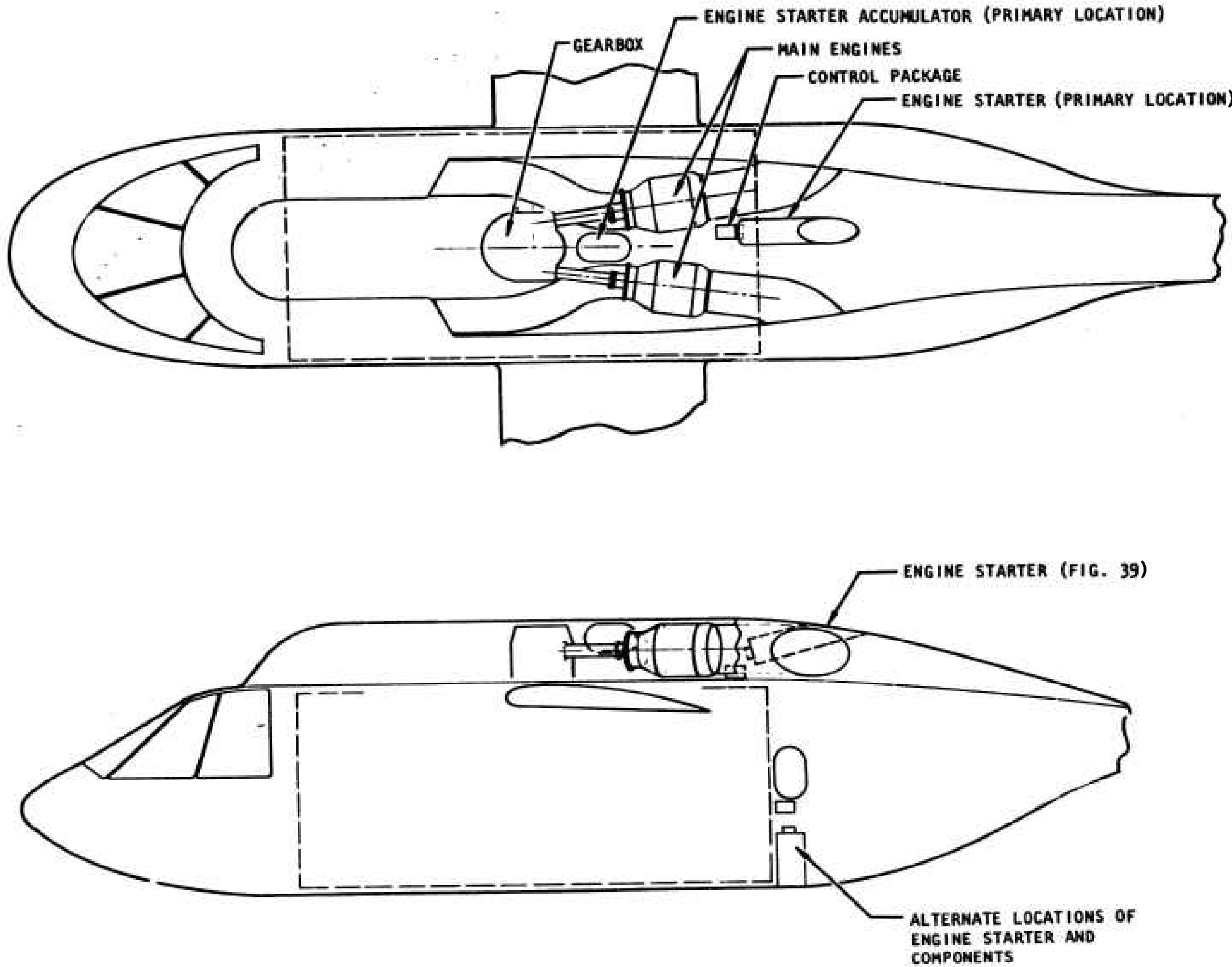


Figure 40. Engine Starter Installation.

TABLE XXVII. RESODYNE RECHARGE SYSTEM WEIGHT COMPARISON		
	Original 2-Minute Recharge	Final 3-Minute Recharge
Resodyne	29.0 lb	24.5 lb
Containment	8.3	6.2
Gearbox	5.5	0.0
Controls and Battery	3.0	3.0
Air and Fuel Bottles	1.5	2.1
Hydraulic Pump	2.3	2.1
Structure	2.6	6.2
One-Start Accumulator System	124.6	124.6
Total	176.8 lb	168.7 lb

the gearbox has been entirely eliminated by driving the pump at turbine speed and mounting the pump inside the combustor. The weight of the air and fuel bottles has, however, gone up slightly because the fuel bottles must now be sized for 9 minutes of operation rather than the previous 6. The only weight which increased was that of the structure. As with the APU starting system, the original structure weight estimates were optimistic, in this case by about 3.6 lb. The net result of these weight variations is that the total Resodyne weight is 8 lb less than originally estimated. The total system weight is also 8 lb less.

The reliability of the revised unit will be almost the same. Removal of the gearbox tends to improve the reliability, but the increase in operating time tends to decrease it. No significant change in the net failure rate is expected. Elimination of the gearbox and reduction in size of the Resodyne unit will tend to reduce the cost of the system slightly over that originally estimated. The relative cost is now estimated to be 2.11 compared to the original value of 2.29 in Table II.

It may be concluded that the hydraulic accumulator engine start system with Resodyne recharge is at least as competitive as it was originally judged to be on the basis of the results shown in Table II. The results of this study, however, have disclosed some characteristics which require better definition before the system is applied to a vehicle.

Unknowns

As with the APU starting system, the question of Resodyne exhaust flush or not flush with a skin is unresolved. Experimental verification is required. A new concept to this system is operation of a hydraulic pump inside the combustor tailpipes. With adequate insulation, it is expected that this operation would be satisfactory. Experimental verification, however, is desirable. The present Resodyne recharge system design calls for a maximum period of operation of 3 minutes. During Resodyne development testing, very little operation for this duration has been attempted.

As has been previously discussed, a minimum weight application of the hydraulic accumulator Resodyne recharge system requires that a fiber glass accumulator with bladder-type separator be utilized. While this is believed to be well within the present state of the art for fiber glass pressure vessels, it has not been demonstrated. Experimental verification is desirable.

CONCLUSIONS AND RECOMMENDATIONS

The resonant combustion device appears to offer a feasible solution to the problems of starting APU's and engines at temperatures down to -65°F and with multiple-start attempts. For the particular APU studied (Solar T62T-2A) and, possibly, for other engines and APU's, the multiple-start/winterization kit approach is practical. This system gives up to three start attempts by recharging of a hydraulic accumulator at temperatures down to -65°F. As an add-on unit to an existing accumulator hydraulic start system, it can also reduce the APU or engine drag, thereby allowing starting with a smaller accumulator than would normally be required at -65°F. For the particular engine studied (Pratt & Whitney ST9), the same general type of system with recharging of the hydraulic accumulator appears practical. In both the APU and engine cases, the resonant combustion unit may be thought of as an add-on device to go with a hydraulic accumulator energy storage starting system.

Mounting of Resodyne resonant combustion units has proved to be comparatively easy. Use of the hydraulic energy transmission means that the resonant combustion unit itself is not severely restricted as to where it may be placed relative to the APU or engine to be started. It is only required that it be in the vicinity of the engine or APU and that it be able to exhaust through the vehicle skin with no exit ducting required. In the vehicle studied, this appeared to be feasible in more than one location. Some otherwise desirable locations do, however, appear to involve partial exhaust ducts because of inability to orient the exhaust normal to the vehicle skin.

The major advantage to the resonant combustion unit as applied to Army aircraft engine starting is that it allows multiple-start attempts at -65°F without external equipment. This increased capability is attained at the expense of increased costs and slightly increased failure rates. The multiple-start/winterization kit approach offers an additional, less obvious advantage. Heating of the oil in the APU will reduce the wear on the rotating parts of the APU, thus increasing APU reliability and decreasing maintenance requirements. For some engines, heating of the oil may pay off in reduced system weight if the accumulator required is quite heavy. Again, the heating of engine oil will improve the wear characteristics of the engine, and hence, increase the reliability and decrease the maintenance required on the engine.

All Resodyne sizing results presented in this study have been based on performance levels actually achieved on Rocketdyne- and U.S. Army-funded programs.[4,5] No allowance has been made for possible performance improvements and their corresponding weight reductions. Reducing the stringency of the design conditions could reduce Resodyne weights. For example, if the maximum design altitude were 8000 ft rather than 10,000 ft, Resodynes could be about 8% lower in weight.

Several potential problem areas have been uncovered as a result of this study. One of the unknowns is the ability to operate and control the heat exchanger in the multiple-start/winterization kit. A related question is the effect of the heat exchanger and its controls on the performance of the resonant combustion unit. Operation of the various system controls in the major control modes is also a matter of concern. The ability of a circulating pump to circulate APU oil through the heat exchanger at -65°F is a further consideration. Operation with exhaust flush with vehicle skin and with a partial exhaust duct are related areas of concern.

For the Resodyne recharge system for engine starting without an APU, Resodyne operation is required for a 3-minute operating period. For a minimum weight recharge system, the hydraulic pump must be mounted inside the tailpipes of the resonant combustor and thus be exposed to significant heat and vibration. Verification of the existence of solutions to these problems depends on further experimental work. It is therefore recommended that an experimental program be undertaken to design and build a demonstration system suitable for starting a typical APU such as the T-62T-2A. Such a system will allow demonstration of multiple-start attempts at -65°F. It will also either demonstrate solutions or produce design data required for solution of those problems.

A demonstrator unit should be sized to be capable of starting an APU. By removing the heat exchanger and circulating pump, the same unit could then be used with one of the advanced demonstrator engines to show operation of the accumulator start system with Resodyne recharge. Because the power would be somewhat lower than the optimum value, a longer time (about 5 minutes total) would be required for recharge of the accumulators. This longer operating time, however, will allow development of design data verifying ability of the Resodyne to operate for longer periods of time.

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