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A SYSTEMS DESCRIPTION OF THE AEROPROPULSION SYSTEMS TEST FACILITY (ASTF)

Ronald L. Polce
AEDC/ASTF Project Office

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FOR THE COMMANDER

GUY P. YORK, Colonel, USAF
ASTF Program Manager

SUMMARY

A detailed description of the major process and support systems comprising the Aeropropulsion Systems Test Facility (ASTF) is presented. Also presented, are operational examples which illustrate the basic functions and interrelations of the major process systems as they work together to provide the concurrent values of mass flow, temperature, and pressure required for true flight simulation tests of airbreathing engine propulsion systems in a ground test facility.

The material presented includes a discussion of the facility operational and performance requirements for each of the major process and support systems, including both physical and performance specifications for each system.

This document was originally submitted as a thesis in partial fulfillment of requirements for the Master of Science degree in Mechanical Engineering at the University of Tennessee, Knoxville.

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NOMENCLATURE

A - Area

C_p - Constant Pressure Specific Heat

C_f - Flow Coefficient

D - Diameter

f - Friction Factor

h_{fg} - Heat of Vaporization for Water

K - Equivalant Pressure Loss Coefficient

L - Length

M - Mach Number

$\dot{m}$ - Mass Flow Rate

N - Compressor Speed

N_c - Corrected Speed

N_v - Number of Open Venturis

P - Pressure

PR - Pressure Ratio

Q - Volumetric Capacity

R - Specific Gas Constant

SH - Specific Humidity

T - Temperature

V - Velocity

γ - Ratio of Specific Heats

η - Efficiency

δ - Pressure to Reference Pressure Ratio

θ - Temperature to Reference Temperature Ratio

ρ - Density

SUBSCRIPTS:

A1, A2,..n	-	Air Supply Station Numbers
amb	-	Ambient
as	-	Afterspray
c	-	Compressor
ca	-	Cooling Air
corr	-	Corrected Airflow
D	-	Design Point
d	-	Discharge
da	-	Dry Air
E1, E2,..n	-	Exhaust System Station Numbers
e	-	Equivalant Diameter
eg	-	Engine Exhaust Gas
fs	-	Forespray
i	-	In; inlet
mix	-	Mixture
o	-	Outlet; out
R	-	Recovery
ref	-	Reference Condition
sp	-	Setpoint
t	-	Total
v	-	Venturi
ws	-	Water Supply
wv	-	Water Vapor
∞	-	Freestream Condition

1.0 INTRODUCTION

1.1 Background

The Aeropropulsion Systems Test Facility (ASTF) is under construction at the Arnold Engineering and Development Center (AEDC), Arnold Air Force Station, Tennessee, and is scheduled for operational status in 1984. The facility is designed for testing airbreathing engine propulsion systems over a wide range of altitudes and Mach numbers. Simulated flight tests conducted in the facility will determine the operational and performance characteristics of aeropropulsion systems; thus, the time required for flight tests is shortened, and the risks and expense of flight tests are minimized.

1.2 Purpose and Approach

The purpose of this report is to present a detailed systems description of the facility. The report is timely in that the system configuration is now established and essentially all components have been acquired. Therefore, the report can be used as a ready reference for personnel currently involved in the construction effort. In addition, this report should prove to be useful as a training aid for the new personnel currently being brought on-board to conduct final facility performance and acceptance testing, and for the personnel to be added later as the operating contingent.

An overview of the facility test capability and operational requirements is presented in Section 2.0. The test modes utilized and types of tests to be performed in the facility are briefly described. In addition, the requirements that establish the facility operational requirements are discussed.

A detailed description of the major process systems, support systems, and equipment comprising the facility is presented in Section 3.0. Additionally, a brief description of each facility building is provided.

Facility operational aspects are presented in Section 4.0. This includes a description of the Air Supply, Test, and Exhaust System operating configurations. Operational examples are also provided to illustrate how the major process systems are integrated into operating configurations to support example test scenarios.

2.0 FACILITY OVERVIEW

2.1 Test Capability

The ASTF provides the capability for true simulation of flight altitude and flight Mach number conditions to permit development, and surveillance tests of large air-breathing, jet propulsion engines throughout their operational envelopes. The facility is capable of performing direct-connect testing of turbojet and high-bypass (8:1) turbofan engines up to 75,000 pound-rated, sea level, static thrust throughout the appropriate engine operating envelopes [1][1]. The facility air supply and exhaust systems are sized to support freejet testing wherein the engine, complete with inlet and a portion of the airframe, is mounted in the test cell. Test cell inlet ducts, test cells, and exhaust ducts are also sized to accommodate the installation of freejet test hardware, including freejet nozzles and diffusers. Consideration has been given in the facility design to provide the capability for later expansion to accommodate testing of 100,000 pound thrust class engines. Basic facility structures such as the test cells, bulkheads, and some portions of the ducting, are now capable of handling these larger class engines. However, the air supply and exhaust systems will require the addition of compressors,

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[1]Numbers in brackets refer to similarly numbered references in Bibliography.

exhauster, air conditioning equipment, etc., to support the testing of these larger engines.

2.1.1 Test Modes. The ASTF has the capability, as discussed above, to accommodate testing in either the direct-connect or freejet mode. A brief description of these test modes follows [1], [3]:

a. Direct-Connect Testing. The least complex mode of testing has the engine directly connected to the facility air supply with a duct section using a bellmouth inlet. This direct-connect test arrangement is shown in Figure 1[2]. Direct-connect testing takes maximum advantage of the facility capability, since all the airflow generated by the plant passes through the engine. Such testing is ususally completely satisfactory for testing large subsonic engines for transport aircraft, such as high-bypass turbofans, and can also provide valuable baseline performance and operational data for all other turbine engines.

b. Freejet Testing. In this mode of testing, the airstream is accelerated up to flight Mach number by freejet nozzles, and the aircraft inlet is mounted so that the inlet plane is inside the test rhombus. Angle-of-attack testing is available by varying the attitude of the freejet nozzle. The freejet test arrangement, shown in Figure 2, provides a

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[2]All Figures appear in Appendix B.

realistic simulation of the flow from the aircraft inlet to the engine face, thus permitting both assessment of actual engine performance and examination of the interrelation between the engine, inlet, and airframe. While the ASTF air supply, exhaust, and test cell systems have been designed to accommodate freejet testing, the required test hardware, such as nozzles, is not provided with the basic facility systems described herein.

2.1.2 Types of Tests. The types of tests which will be performed in the facility are established by test article requirements. While steady-state testing is commonly conducted in ground test facilities, either of the test modes described above may also require transient testing, e.g., engine power transients, flight profile transients, or combinations of the two. Such transients require that the test facility be capable of varying pressure, temperature, and airflow rate to match changes in throttle setting, aircraft speed, and altitude at rates which duplicate engine and aircraft response. The ASTF has the capability to produce the transient rates-of-change necessary to follow both transient flight environment and transient engine power setting. The facility operating conditions and the corresponding engine operating conditions for the testing in ASTF can be categorized as follows:

a. Steady Environment--Steady Engine Power Setting. The facility will maintain the engine inlet pressure, engine inlet temperature, and test cell ambient pressure while the engine demand establishes the airflow.

b. Steady Environment--Transient Engine Power Setting. A typical engine power transient is a rapid change in power level position and a corresponding change in engine operating conditions. The facility control system will maintain the proper flight condition parameters during this engine transient.

c. Transient Environment--Steady Engine Power Setting. The facility will provide the time-dependent variations of inlet pressure, inlet temperature, and test cell ambient pressure required for flight conditions transient testing at steady engine power settings.

d. Transient Environment--Transient Engine Power Setting (Mission Profile Simulation). Mission profiles will be composed of periods of operation at a steady environment and steady engine power settings and change in engine power settings, flight speeds, and altitudes within the engine and aircraft operational flight maps.

2.2 Operational Requirements

The operational requirements for the ASTF are based on the requirements for the determination of the performance and operational characteristics of advanced, large, airbreathing turbine propulsion systems while operating at simulated flight conditions. These requirements can be expressed in terms of: (1) the environment required at the test cell inlet, (2) the test cells required to contain and restrain the test article and provide interface connections to the test article service and utility systems, (3) the instrumentation and data handling system required to quantify those physical phenomena which are necessary to determine the performance of the test article, and (4) the environment required at the inlet to the test cell exhaust duct. The facility described herein has been designed to meet these operational requirements. A site plan view and systems schematic of the facility are presented in Figures 3 and 4, respectively.

2.2.1 Test Cell Inlet Environment. The ASTF air supply system is capable of providing a wide range of coincident values of inlet total pressure, temperature, and airflow as required for tests of turbojet and turbofan engines. Air supply system pressure and temperature capability over the full range of airflow provided is shown in Figures 5 and 6, respectively [4].

2.2.2 Test Cells. Two test cells are included in the ASTF. One of the test cells is configured to provide the test capability for afterburning turbojet engines and the other cell is configured to provide the test capability for high-bypass ratio, turbofan engines. Although each test cell is specifically configured to provide maximum test capability for one type engine, both cells can provide limited test capability for engines of either type.

2.2.3 Instrumentation. Instrumentation and data handling equipment is provided to measure, transmit, acquire, display, and process those measurements which are required to determine the performance of the test article, [5]. The measurement capability for each test cell is identical and includes 970 pressure measurements, 820 temperature measurements, and 152 miscellaneous measurements, such as forces, flows, speeds, geometries, vibrations, accelerations, and strains. The data handling system is capable of supporting both steady-state and transient testing.

2.2.4 Test Cell Exhaust Duct Environment. The ASTF exhaust system is capable of providing a wide range of coincident values of exhaust duct pressure and exhaust gas flow, as required for tests of turbojet and turbofan engines. The exhaust system performance capability for turbojet and turbofan testing is shown in Figures 7 and 8, respectively. Exhaust system and air system capacities are matched to provide the requirements of engine and aircraft flight envelopes.

3.0 SYSTEMS DESCRIPTION

3.1 Air Supply System

The function of the air supply systems is to provide air to the test cells at the conditions necessary to simulate operating conditions at various altitudes and Mach numbers. The air supply system consists of all equipment upstream of the test cell inlet plenums, stations 1[1] and 2, respectively. Conditioned air is provided to the test cells via five major flow paths, designated as air supply leg 1, super cold; leg 2, cold; leg 3, hot; leg 4, super hot; and leg 5, atmospheric inlet. These flow paths are identified on Figure 4. The conditioned air provided through legs 1, 2, 3, and 5 is received and mixed in a common air header (station 3) prior to delivery to the test cells. Airflow through leg 4 is admitted directly to test cell C1 at station 4.

The air supply system is comprised of the following major systems, which are described below: air supply compressor system, process air cooling/drying system, and the process air heating system. The air supply system ducting, including expansion devices and configuration and control valves, completes the air supply system basic components. Supporting systems include instrumentation and control,

[1] All station references are shown on Figure 4, Appendix B.

electrical power, hydraulic, auxiliary air, fire protection, steam, and cooling water. These are discussed in paragraphs 3.4 and 3.5, respectively.

3.1.1 Air Supply Compressor System. The air supply compressor system consists of four first-stage and two second-stage axial flow compressor/drive motor units. Ducting and valving allow operation of these units in single-stage configuration for low pressure, high flow service; or two-stage configuration for high pressure, low flow service. A typical air supply compressor arrangement is shown in Figure 9.

Each of the four first-stage compressors (whose inlet is shown at station 5) has a volumetric capacity of 242,000 CFM at their design point and delivers 275 lbm/sec at a discharge pressure of 44 psia at rated operating conditions. Each of the second-stage compressors (whose inlet is shown at station 6) has a volumetric capacity of 150,000 CFM at their design point. When operating in the two-stage configuration (series operation with the first-stage compressors) each compressor delivers 550 lbm/sec at a nominal dicsharge pressure of 150 psia. The second-stage compressors can also be operated in parallel with the first-stage compressors and, as such, each compressor delivers 175 lbm/sec at a nominal discharge pressure of 44 psia. The air supply compressor/drive motor unit operating conditions are presented in Table 1[2].

Each of the six compressors is driven by a 3,600 rpm synchronous electric motor. Each first-stage compressor motor is rated at 27,500 horsepower, while each second-stage compressor motor is rated at 52,500 horsepower. The motors are two-pole, synchronous type requiring three-phase current of 60 Hertz and 13.8KV. A solid state static exciter is provided for each motor to supply excitation to the rotor during start-up and acceleration and to provide an adjustable power factor on the motor during operations. The motors are directly connected to each compressor through a flexible diaphragm type coupling.

The major compressor subsystems are the lube oil system and the Variable Frequency Starting System (VFSS). Three lube oil console systems serve the compressors and drive motors. Two lube oil consoles serve the four first-stage compressor/drive motor units and one lube console serves the second-stage compressor/drive motor units.

The motor starting system, VFSS, consists of a solid state variable frequency starter set rated at 40,000 horsepower, [6]. The VFSS is a combination converter and inverter, consisting of thyristor modules. The converter side is fed with constant frequency at constant AC voltage

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[2] All tables appear in Appendix A.

and converts this power to DC power. The DC power is then fed into the inverter side where it is inverted to variable frequency, variable voltage, AC power. The synchronous motor, separately excited, is supplied with this power from the inverter, beginning at very low frequency. By means of the synchronizing torque developed, the synchronous motor falls into step and runs synchronously with the frequency of its supply voltage. By increasing the VFSS output to maintain approximately 114% of full load current, the synchronous motor rapidly accelerates to full speed. This process is automatically controlled. When rated frequency is reached and voltage and phase matched, the motor is synchronized with, and transferred to, the system voltage. The starting unit is now ready to start another motor. A single VFSS unit is used for sequential starting of all air supply compressor drive motors. Redundancy is provided by an identical VFSS unit in the exhauster building which is inter-tied to the air supply compressor motor starting circuit.

3.1.2 Process Air Cooling/Drying System. The process air cooling and drying system required to provide the test cell inlet conditions of concurrent temperature and humidity consists of three air-to-fluid heat exchangers with mechanical refrigeration systems and five refrigeration turbines. These major equipment items are identified as coolers RC1, RC2, and RC3; and refrigeration turbines TC1, TC2, TC3, TC4, and TC5.

3.1.2.1 Cooler RC1. Cooler RC1, inlet at station 7, is an aftercooler and dehumidifier for the four first-stage compressors. The cooler conditions air from the first stage compressors for subsquent higher compression in the second-stage compressors or for additional conditioning by downstream equipment prior to use in the test cells. Cooler RC1 consists of a cylindrical shell 42 feet in diameter and 152 feet long and contains four cooling stages and one re-heat stage. The cooler RC1 schematic is shown in Figure 10.

The first-stage of the cooler, RC11, contains three cooling banks. The first two banks utilize a 50% glycol/water mixture as the heat transfer medium and the third bank uses water as the heat transfer medium. These coil banks cool 1100 lbm/sec of air, plus entrained moisture, from design point conditions of 322°F to 90°F and reduce the specific humidity from 114 grains per pound of air (gr/lb air) to 75.8 gr/lb air. The second-stage, RC12, contains two coil banks utilizing a 20% glycol/water mixture as the heat transfer medium. These coil banks cool 1100 lbm/sec of air, plus entrained moisture, from design point conditions of 90°F to 38°F and reduce the specific humidity from 75.8 gr/lb air to 12 gr/lb air. The third and fourth stages each contain four coil banks utilizing refrigerant R-30 (methylene chloride) as the heat rransfer medium. The third-stage, RC13, cools 1100 lbm/sec of air, plus entrained moisture, from design point conditions of 38°F to 0°F and reduces the specific humidity from 12 gr/lb air to 2 gr/lb air. The fourth and final stage of cooling, RC14, further reduces the air temperature from $0^{o}F$ to $-24^{o}F$ and reduces the specific humidity from 2 gr/lb air to 0.5 gr/lb air.

The fifth stage, RC15, is a reheat stage and it contains two coil banks utilizing a 50% mixture of glycol/water as the heat transfer medium. These coil banks are connected in series through a pressurized brine heat exchanger system with the first two coil banks of the first stage, RC11. The purpose of this arrangement is to recover part of the heat of compression from the first-stage compressors to reheat the air leaving the cooling stages. Dry air at temperatures ranging up to $200^{o}F$ is available for use in the test cells or for additional downstream heating when stages RC11 and RC15 are operated in the reheat mode.

Mechanical refrigeration equipment is utilized to cool the brine through the RC12, RC13, and RC14 coils in the RC1 cooler. Each grouping of coils has its own brine chiller system. The brine chiller units are identified by the BCRC1x.x designation on Figure 10.

Dehumidification of the process air occurs as it passes through cooler RC1 by condensation and collection of the entrained moisture on the third and fourth-stage coil banks. The coil bank faces are sprayed with an aqueous solution of ethylene glycol to wash the coil faces and thus prevent the formation of ice. The de-icing spray system consists of a pump and distribution system for each of the two cooling stages. A schematic of the de-icing spray system is shown in Figure 11. After washing, the diluted spray mixture drains to the bottom of the cooler and is returned to a concentrator system reboiler, where water from the dilute spray is removed. The glycol concentration unit, illustrated in Figure 12, raises the temperature of the mixture to a point at which the water is driven off as steam. The vapor rises up the distillation column, passes through the condenser and the condensed water is drained to a condensate pump out sump. The concentrated glycol then flows down the distillation column into the reservoir from which it is pumped back to the system.

The process air passing through cooler RC1 can be discharged from the cooler at two points. One location is downstream of the fourth cooling stage, station 8, and the other location is downstream of the fifth stage at station 9. The discharge path is dependent on the configuration of the air supply compressors or on downstream temperature requirements. For two-stage compressor operation, the air flow will discharge through the station 8 duct. In the single-stage operating mode, the air flow can be routed entirely through either the station 8 or station 9 ducts; or can be proportioned through both ducts. The routing, in this case, is dependent on the temperatures required at the test cells.

3.1.2.2 Cooler RC2. Cooler RC2, inlet at station 10, is a two-stage cooler acting as an aftercooler and dehumidifier for the two second-stage compressors. The first stage, RC21, of the cooler contains three coil banks and uses cooling water as the heat transfer medium. The second-stage, RC22, contains two coil banks and uses a 20% glycol/water mixture chilled by mechanical refrigeration as the heat transfer medium. RC2 is 32 feet in diameter and 79 feet long. A Schematic of cooler RC2 is shown in Figure 13.

There are two normal operating modes for cooler RC2--single-stage and two-stage compressor operation. During operation of the second-stage compressors in the single-stage configuration, the first-stage of cooler RC2 will cool the flow (350 lbm/sec) from the two compressors from a design point temperature of 325°F to 90°F. During this operation, the inlet design specific humidity of 114 gr/lb air is reduced to 76 gr/lb air. The second cooling stage further reduces the temperature to 38°F and the specific humidity to 12 gr/lb air. During operation of the second-stage compressors in the two-stage configuration, the first cooling stage will cool the flow (1100 lbm/sec) from the two compressors from a design point temperature of 264°F to 100°F. Normally, only the first cooling stage is used during two-stage operation since the required dehumidification of the airstream is accomplished in cooler RC1.

Cooling coil freeze protection is provided during subfreezing weather when the cooler is not operating. The first-stage coils are protected by flowing cooling water at reduced flow rates through the cooling coils. Brine circulated at reduced flow rates through a small steam-to-brine heat exchanger and the second-stage coils will maintain the brine above 20°F to prevent freezing in those coils.

3.1.2.3 Cooler RC3. Cooler RC3, inlet at station 11, is an atmospheric inlet cooler used to condition air induced directly into test cell C2. This cooler is utilized when the test conditions require a greater air weight flow than can be generated by the air supply compressors and when test engine inlet pressures are subatmospheric.

The cooler is a reinforced concrete structure, measuring approximately 47 feet wide by 51 feet long by 52 feet high and contains one cooling stage consisting of two coil banks. A 20% glycol/water mixture, chilled by mechanical refrigeration, is used as the heat transfer medium. The inlet design conditions for the cooler are a flow rate of 960 lbm/sec of air at a temperature of 85°F and a specific humidity of 114 gr/lb air. At these conditions, the cooler will condition the air to a temperature of 38°F and a specific humidity of 35 gr/lb air. The cooler is capable of operating at air flow rates up to 1440 lbm/sec with reduced drying and cooling capability. A schematic of cooler RC3 is shown in Figure 14.

3.1.2.4 Refrigeration Turbines. Testing of turbine engines at higher altitudes and lower Mach numbers requires inlet air temperatures significantly lower than attainable with coolers RC1, RC2, and RC3. To achieve these lower temperatures, the air temperature is first lowered by the coolers, as previously described, and then expanded through refrigeration turbines to obtain temperatures as low as -150°F (ducting temperature limit). Five refrigeration turbines with inlets at station 12 are provided to handle the capacity of the air supply compressor system.

The refrigeration turbines are radial flow; each having a rated airflow of 288 lbm/sec. At rated flow conditions, the turbines are designed to cool the air from -6°F to -108°F with an inlet pressure of 38 psia and a discharge pressure of 12.8 psia. A summary of refrigeration turbine operating conditions at both rated and off-design conditions is presented in Table 2.

Power absorption is accomplished with an integral, single-stage centrifugal compressor located on the opposite end of each turbine shaft that takes air from the atmosphere and discharges through an atmospheric discharge stack. Airflow through the turbines is controlled by continuosly variable inlet nozzles that surround the periphery of each turbine rotor. These nozzles are designated CV.TCx.1 (where x is the turbine number, 1 through 5) on Figure 4. Each turbine has its own lubricating system including oil reservoir, electric oil heater, motor drive, main and auxiliary oil pumps, water cooled air cooler, filters, and controls. A typical turbine arrangement is shown in Figure 15.

3.1.3 Process Air Heating System. The capability to heat the process air stream to test cell inlet temperature requirements is provided by a combination of air reheating in cooler RC1, indirect-fired air heaters, and a cooler RC2 bypass duct which allows direct use of the heat of compression from the second-stage air compressors.

3.1.3.1 Air Reheating. The air reheating system was previously described in paragraph 3.1.2.1. In summary, this system uses the heat of compression from the first-stage compressors to reheat the conditioned air leaving cooler RC1 to temperatures ranging up to 200°F.

3.1.3.2 Cooler RC2 Bypass. A bypass provision around cooler RC2 is provided to permit routing of air from the discharge of the second-stage air compressors during two-stage operation to the air heaters, or to provide conditioned air directly to the test cells. This bypass is located at station 13.

3.1.3.3 Air Heaters. Two radiant type, indirect-fired air heaters with inlets at stations 14 and 15 are provided to further heat the air to temperatures required at the test cells. Each heater consists of two box shaped cells which are approximately 90 feet long by 22 feet wide by 60 feet high. Each cell utilizes 12 burners which are divided into four banks of three for control purposes. The heaters are equipped to burn either natural gas or a wide range of hydrocarbon fuels.

Heater H1 can be used by itself, or as a first-stage heater for two-stage use with heater H2. H1 is capable of delivering 630^{o}F air to the test engine at an airflow rate of 1100 lbm/sec. Air temperatures required for extreme Mach number testing are provided by using heater H2 in series with H1. Heater H2 is a second-stage heater only, and is capable of delivering 1020^{o}F air to the test engine at 1100 lbm/sec. The air from heater H2 is routed through air supply leg 4 directly to the inlet bulkhead of test cell C1 at station 4. The operating conditions for heaters H1 and H2 are presented in Tables 3 and 4, respectively.

3.2 Test Area

The test area is the focal point for the testing activities. This area extends from the inlet ducting at stations 1 and 2 to, and including, the test cell isolation valves at stations 16 and 17. The major equipment and systems include the test cells and inlet plenums, and the airflow measurement system. The test area ducting, including configuration and control valves, completes the test area basic components. Supporting systems include instrumentation and control, electrical power, hydraulic, test fuel, cooling water, auxiliary air, gaseous nitrogen, and fire protection. These are discussed in paragraphs 3.4 and 3.5, respectively.

3.2.1 Test Area System Arrangement. Conditioned air, delivered from the air header, is directed by valve selection to the inlet ducting servicing each test cell. The test area system arrangement is shown in Figure 16. As shown in Figure 16, each inlet duct diverges into a larger diameter plenum which contains flow straightening grids and an array of venturi-type airflow measuring devices assembled in a bulkhead. Following the venturis, a second flow straightening grid precedes a portion of the plenum designated for installation of engine inlet equipment and freejet test hardware. This equipment is mounted in a bulkhead located in front of the test cell. At the aft end of the test cell is another bulkhead used to mount exhaust diffuser hardware. Each test cell has a large diameter exhaust duct to conduct engine exhaust gases to the exhaust gas cooling and exhaust gas compressor system. These duct sections are equipped with duct water sprays to provide initial cooling of the exhaust gas. Each exhaust duct also contains a test cell isolation valve used for isolation of the non-operating cell from the downstream exhaust system or to provide a disturbance-free opening into the exhaust ducting for the operating cell during test periods. These valves are described in paragraph 3.4.

3.2.2 Test Cells and Ducting. During facility design, a requirement was established that each test cell retain the maximum capability for testing engines of both types consistent with minimum cost penalty. Therefore, since the maximum size turbofan engine is projected to be somewhat larger than the maximum size turbojet engine, both cells are physically sized to accommodate the larger engines and consequently measure 50 feet long by 28 feet in diameter.

The basic test cells are uncooled and uninsulated. For purposes of structural temperature control, however, the test cell front bulkhead, rear bulkhead, and floor (ground plane) are water cooled. The uncooled cell wall structure is limited to 350°F maximum temperature to maintain thermal stresses at acceptable levels. Some turbojet tests will require the installation of test related shrouds or radiation shields to prevent cell wall overheating during long duration tests. The rear bulkheads in both cells can be translated approximately 35 feet downstream into the exhaust duct section. This allows test hardware to be extended into the exhaust ducting to permit testing of larger engines or testing with engine inlet simulation equipment, which occupies considerable space in the forward portion of the test cell. Each test cell is equipped with a large sliding hatch, which provides access for installation of the test article and all major pieces of test equipment which are located in the test cell or exhaust duct.

While both cells are identical in shape and size the operating principle for each cell is different. Test cell C1 is dedicated principally to testing augmented turbojet engines; therefore, the ducting arrangement, size, and pressure and temperature ratings are consistent with the maximum turbojet engine test requirements. The C1 inlet plenum is 22 feet in diameter, with rated pressures and temperatures from 0 to 150 psia and $-100^{o}F$ to $650^{o}F$, respectively. Provisions are included for the installation of an insulated duct within the C1 plenum for those tests requiring temperatures in excess of $650^{o}F$. Heater H2 is connected directly with this removable duct to provide engine inlet temperatures up to $1020^{o}F$ for testing up to Mach 3.8. The C1 exhaust ducting is designed for operating pressures and temperatures from 0 to 25 psia and $-15^{o}F$ to $2500^{o}F$, respectively. In addition to the duct water sprays which are contained in both the C1 and C2 exhaust ducting, cooling water jacketing of the C1 exhaust duct is also provided to accommodate the higher augmented turbojet exhaust gas temperatures.

Test cell C2 is dedicated principally to testing high-bypass turbofan engines; therefore, the ducting arrangement, size, and pressure and temperature ratings are consistent with maximum turbofan engine test requirements.

The C2 inlet plenum is 30 feet in diameter with rated pressures and temperatures from 0 to 50 psia and -100°F to 650°F, respectively. Atmospheric inlet air through cooler RC3 is ducted directly to the C2 inlet plenum, thus providing the high air mass flow requirements needed for certain turbofan engine tests. The centerline of the plenum is below the centerline of the test cell to allow maximum angle-of-attack positioning of a freejet nozzle during freejet testing. The C2 inlet bulkhead is also designed to accommodate freejet test hardware. The C2 exhaust ducting is designed for operating pressures from 0 to 25 psia and for operating temperatures from -15°F to 600°F.

3.2.3 Air Flow Measurement System. The accurate measurement of airflow during tests of turbojet and turbofan engines is essential to the determination of engine performance. The airflow measurement system used in ASTF is a critical-flow multiple venturi system. Remote closure of some of the venturis and manual closure of the remaining is provided so that the wide flow range requirements can be met while maintaining critical-flow at optimum pressure loss. All venturis are of identical design and size and are interchangeable between the test cells.

The venturi system for cell C1 consists of a bulkhead with provisions for accommodating 25 venturis of 1.39 square feet throat area each. Nine venturis are actually provided with the remaining 16 holes equipped with blank-off plates for future use. Four of the nine venturis are equipped with remotely operable closures. The C2 cell venturi bulkhead can accommodate 49 venturis. Thirty-six C2 venturis are provided with the remaining 13 holes equipped with blank-off plates. Ten venturis are equipped with remote closures.

3.3 Exhaust System

The function of the exhaust system is to establish and maintain simulated flight altitude conditions in the test cells and to cool the exhaust gases generated by the test article. The exhaust system consists of all equipment downstream of the test cell isolation valves, stations 16 and 17. The major systems and equipment, which are described below, include the exhaust gas compressor system, exhaust gas cooling system, and the exhaust gas compressor inter-coolers. The exhaust system ducting, including expansion devices and configuration and control valves, completes the exhaust system basic components. Supporting systems include instrumentation and control, electrical power, cooling water, hydraulic, fire protection, and the barometric well system. These are discussed in paragraphs 3.4 and 3.5, respectively.

3.3.1 Exhaust Gas Cooling. Cooling of the hot exhaust gases from the test cells can be accomplished by both direct water injection and by means of an indirect surface cooler. The cooling scheme employed is determined by the exhaust gas temperature. When required, water sprays located at stations 18 and 19 provide initial cooling of the exhaust gases prior to entry into the exhaust gas cooler, EC1, located at station 20. EC1 is a 65 foot diameter surface cooler, containing approximately 4,600 heat exchanger tubes. EC1 cooling is a "dry" process in which cooling water is circulated through the tubes while the exhaust gases pass over the exterior of the tubes. A cross sectional view of EC1 is shown in inset A of the exhaust system transition section illustration shown in Figure 17. Immediately downstream of EC1 at station 21 is an aftercooler spray system used to further reduce the exhaust gas temperature. This system sprays water onto a non-corrosive mist separator provided downstream of the sprays at station 22. Further cooling of the exhaust gas is provided by the evaporative cooling process which occurs at the separator. All excess spray water is drained to the bottom of the cooler, and then to a barometric well system.

The exhaust gas temperature from either test cell can range up to a maximum of 3500°F. Since the EC1 exhaust duct is water jacketed, temperatures ranging up to 2500°F can be accommodated within the duct. However, for exhaust gas temperatures above 2500°F, forespray cooling in the C1 exhaust duct is required to reduce the exhaust gas temperature to the 2500 ^{O}F limit. The C2 exhaust duct can accommodate temperatures only up to 600^{O}F, since it is not water jacketed; therefore, forespray cooling is required whenever the exhaust gas temperature in the C2 duct exceeds the 600^{O}F limit.

The maximum inlet gas temperature to EC1 will be 2500^{O}F as a result of the spray cooling in the exhaust ducts. EC1 is designed to cool a maximum of 1860 lbm/sec of exhaust gases at 2.92 psia from 2500^{O}F to 350^{O}F. The aftercooler sprays are capable of further reducing the exhaust gas temperature to approximately 100^{O}F.

3.3.2 Exhaust Gas Compressor System. The exhaust gas compressor system provides the capability for pumping out the exhaust gases from the test cells and for establishing and maintaining the required upstream pressures for altitude simulation. The exhaust gas compressors, typical inlet at station 23, are commonly referred to as exhausters and as a system discharge to the atmosphere at station 24. Twelve axial flow exhausters are used: (1) eight first-stage exhausters, E111 through E114 and E121 through E124; (2) three second-stage exhausters, E211, E212, and E213; and (3) one third-stage exhauster, E311. All twelve exhausters are identical and, based on dry air design conditions, are rated at],000,000 CFM each, with a pressure ratio of 3.5 when handling exhaust gas at 100^{O}F inlet temperature.

Each exhauster is driven by a synchronous motor through a reduction gear. The motors for the eight first-stage exhausters are each rated at 27,500 horsepower; the motors for the three second-stage exhausters and the third-stage exhauster are each rated at 44,000 horsepower. The motors are two pole, synchronous type requiring three-phase current of 60 Hertz and 13.8 KV. A solid stage static exciter is provided for each motor to supply excitation to the rotor during start-up and acceleration and to provide an adjustable power factor on the synchronous motor during operation. The speed reducing gear units, installed between the motors and the exhauster, contain a parallel shaft gear and pinion set of single helical design. The gear unit is connected to the motor with a flexible coupling. A hollow shaft having an integral solid coupling flange at each end connects the gear unit to the exhauster. The gear units reduce the drive speed from 3600 rpm to 2290 rpm. A typical exhauster arrangement is shown in Figure 18. Operating and extreme design conditions for the exhausters/drive motor units are presented in Table 5.

The two major exhauster subsystems are the lube oil system and the Variable Frequency Starting System, VFSS. Eight lube oil console systems serve the exhausters and drive motors. Four consoles serve the eight first-stage exhauster/motor units and the remaining four each serve a single second or third-stage unit. The motor starting system is identical to the one in the air supply system.

The twelve exhausters can operate in several combinations of stages, depending on the test cell flow and pressure requirements. The eight first-stage machines must have a discharge pressure below atmospheric pressure because of drive motor power limits, while the second and third-stage machines can discharge to atmospheric pressure. The maximum number of exhausters which can be operated in the possible stage configuration are:

a. Three stage -- Eight first-stage units, in series with three second-stage units, in series with one third-stage unit, discharging to atmosphere;

b. Two stage -- Eight first-stage units, in series with three second-stage units and one third-stage unit operating in parallel, and discharging to atmosphere;

c. Two stage -- Three second-stage units, in series with one third-stage unit, discharging to atmosphere; and

d. One stage -- Three second-stage units and one third-stage unit, operating in parallel and discharging to atmosphere.

3.3.3 Exhaust Gas Compressor Intercooling. The temperature of the exhaust gases at the inlet of the exhausters cannot be permitted to exceed 150°F, a limit set by material selection considerations. The exhaust gas temperature in the suction header, identified at station 25, which serves the exhausters will be less than 150°F as a result of cooling by the exhaust gas cooler and the after-spray system. However, since the discharge temperature from the exhausters can be as high as 500°F (heat of compression), it is necessary to provide intercooling before the exhaust gases are directed to the next exhauster stage of a multi-stage configuration. This inter-cooling is accomplished by the exhaust gas intercoolers WC11, WC12, and WC21.

Intercoolers WC11 and WC12 cool the exhaust gases from the eight first-stage exhausters. Intercooler WC11, inlet at station 26, handles the exhaust flow from exhausters E111, E112, E113, and E114. Intercooler WC12, inlet at station 27, handles the exhaust flow from exhausters E211, E212, E213, and E214. Both intercoolers are dimensionally identical and are approximately 62 feet long and 46 feet in diameter. Each intercooler contains one cooling stage of gas-to-water cooling coils. Intercooler WC21, inlet at station 28, cools the exhaust gases from the three second-stage exhausters, E211, E212, and E213. This cooler is used only when the second-stage exhausters are in series with the third-stage exhauster, E311. WC21 is approximately 51 feet long and 35 feet in diameter, and has one cooling stage of gas-to-water cooling coils. A schematic of these inter-coolers is presented in Figure 19. Specific design and operating conditions for the exhaust intercoolers are presented in Table 6.

Since dehumidification accompanies the cooling process under some conditions, mist separators are installed at the downstream end of each intercooler to remove the condensation that occurs. Collected water drains to a barometric well system.

3.4 Facility Process Air Ducting and Valves

The process air is routed to the various conditioning systems, test cells, and exhaust system and controlled by an elaborate ducting and valving system. The ducting system is equipped with expansion devices to compensate for thermal movements; valves to direct and control the airflow; turning vanes to reduce pressure loss and flow distortion; over-pressure devices to protect equipment and personnel; insulation to minimize thermal losses and provide sound attenuation; hatches to permit personnel access; and silencer stacks for air intake and discharge. Provisions have been made at key locations in the ducting system for future inter-connection with other AEDC facilities.

3.4.1 Air Supply Ducting. The air supply ducting ranges in size from 1.5 to 17 feet in diameter. Operating pressures range up to 150 psia and operating temperatures range from -150°F to 1200°F. The ducting and equipment in the air supply area incorporate features to insure a satisfactory cleanliness level of the air delivered to the test cells. The major considerations include filtering of all air intakes, the use of non-corrosive materials throughout the system, and the use of moisture eliminators downstream of the coolers.

3.4.2 Exhaust Ducting. The exhaust ducting ranges in size from 4 to 65 feet in diameter. Operating pressures range from 2 to 25 psia and operating temperatures range from $-15^{\circ}F$ to $600^{\circ}F$. The exhaust ducting is equipped with drains as required to allow all accumulated liquids to be drained to the barometric well system.

3.4.3 Process Air Valves. The facility process air valves function to provide the means of calibration and checkout of equipment; proper facility equipment configuration; compressor/exhauster surge control; equipment loading; test cell inlet pressure and temperature control; and altitude pressure control, as required by the test article. All valves, with the exception of the test cell isolation valves, AV.C1.2 and AV.C2.2; and the turbine control valves as previously described are of the butterfly type. The two test cell isolation valves are of the gate valve design. The process air valves are identified on Figure 4 and a tabulation with pertinent technical data is contained in Table 7.

3.4.3.1 Configuration Valves. The configuration valves, designated by the "AV" prefix, serve primarily as shutoff valves to isolate various items of equipment during operation and/or maintenance periods or as minimum flow restrictions to provide a particular airflow path. In order to achieve more efficient operation and better control, these valves are equipped with open-stop-closed control switches to permit fine tuning of the valve position.

Since the two test cell isolation valves AV.C1.2 and AV.C2.2 are of unique design and application, further description of their design and operating principle is in order. As discussed previously, the valves serve to isolate either of the test cells from the exhauster system while the other cell is provided with a disturbance-free opening into the exhaust ducting. Valve AV.C1.2, located at station 16, isolates test cell C1 and has an inside diameter of approximately 24 feet. Valve AV.C2.2, located at station 17, isolates test cell C2 and has an inside diameter of approximately 26 feet. An illustration of the valve structure is presented in Figure 20. This illustration is typical for both valves.

Closing of either valve is accomplished by lowering a circular closing insert into a gap in the valve shell. The insert is lowered by an electric hoist. After insertion, the valve is then sealed by an inflatable air seal located on the periphery of the insert. Opening of either valve is accomplished by raising the insert and closing the gap in the duct wall with a hatch cover. The hatch cover is moved from its stowed position, upstream of the valve by hydraulic cylinders. Once the hatch cover is positioned over the gap it is lowered by hydraulic cylinders and then sealed by an inflatable air seal. Both the insert seal and hatch cover seal are water cooled to prevent overheating.

3.4.3.2 Control Valves. The control valves, designated by the "CV" prefix, function as compressor/ exhauster surge control valves; system load valves; final controlling elements in the process which provides the required temperature and pressure at the test cell inlet; and provide altitude pressure control. These control functions are described below:

a. Surge Control. Since a pressure ratio across the compressors or exhausters in excess of design limits causes a reversal of flow through the machine, possible structural damage can occur. Therefore, surge control valves are provided in the air supply and exhaust ducting to prevent excessive pressures ratios from occurring. Individual surge control valves are provided for each air supply compressor. These valves allow the discharge flow to be vented to the atmosphere at station 29 (typical). Two methods of surge control are used for the exhausters: recirculation and atmospheric inbleed. The first-stage exhausters employ the recirculation method with a typical recirculation point shown at station 30. The second-stage exhausters have both recirculation and atmospheric inbleed systems, while the third-stage exhauster is equipped with an atmospheric inbleed system. The point of atmospheric inbleed is shown at station 31. The surge control valves work in conjunction with a pressure ratio control system which is subsequently described in paragraph 3.5.1.1.

b. System Load Control. The system load valves consist of clusters of three valves each and are located in air supply legs 2, 3, and 4 at stations 32, 33, and 34, respectively. These valves serve two controlling functions. First, the valves function to provide a means for loading the cooling/drying, and heating systems to permit the desired pressure and temperature conditions to be established in the air supply system without the necessity of flowing air through the test cells. This loading condition is especially important for calibration, checkout, and preconditioning of equipment. Second, during operation, the load valves permit the optimum pressure and temperature conditions to be established and maintained essentially constant upstream of the mixing header. These load valves allow all conditioned air provided by the air supply system and not required at the test cells to be vented to atmosphere at stations 35 and 36.

c. Test Cell Inlet Temperature and Pressure Control. The conditioned air, as previously discussed, is supplied through five main air flow paths (legs). Airflow through legs 1, 2, 3, and 5 is supplied to the air header where it is mixed to obtain the required temperature and pressure prior to delivery to the selected test cell. Airflow through leg 4 is admitted directly to test cell C1. Control valves located in these supply legs control and proportion the amount of air supplied. Valve clusters consisting of three valves each control the airflow through supply legs 2, 3, and 4. These clusters are located at stations 37, 38, and 39, respectively. Control of airflow through the refrigeration turbines and thus through supply leg 1 to the air header is provided by control valves (variable inlet nozzles) on the inlet side of the turbines at station 12. When the airflow required at test cell C2 exceeds the capacity of the air supply compressor system and the test cell inlet pressure is below atmospheric, air will be inbled through cooler RC3 at station 11 with valve CV.RC3.1 as the controlling element.

d. Altitude Pressure Control. Simulated altitude pressure over the entire range of facility flow conditions is maintained by control valve CV.C.10. This valve controls the pressure in the test cell exhaust duct, which establishes the test cell ambient or engine altitude pressure. In addition, control valves CV.EC1.1A and 1B, located at station 40, are butterfly valves used to control pressure when exhaust duct operating conditions are above atmospheric pressure. Valve CV.C.10 is a 45 foot diameter assembly interfaced into the exhaust duct system just downstream of EC1 at station 41, and is used to control pressure when operating conditions are below atmospheric pressure. It consists of one assembly having ten identical, separately controlled louver elements. The CV.C.10 arrangement is illustrated in inset B on Figure 17.

3.5 Support Systems

The treatment of the systems description thus far has been limited to the major process systems and major equipment items which make up the individual systems. The systems subsequently described are the systems which support, in most cases, all the previously described process systems. Together, these integrated systems provide the complete operational capability of the ASTF. The support systems include instrumentation and control, electrical power distribution, cooling water, hydraulic, test fuel, barometric well, auxiliary air, gaseous nitrogen, steam, and fire protection systems.

3.5.1 Instrumentation and Control System. The instrumentation and control system for ASTF includes those systems which perform the control, monitoring, recording, and data acquisition functions required for facility operation, test article operation, test article data processing, and safety. The three major systems that make up the ASTF instrumentation and control system are the Plant Instrumentation and Control System (PICS), Test Instrumentation System (TIS), and the Automatic Test Control System

(ATCS). An interface diagram for these systems showing high level control and data flow relating to the plant, test cell, and test article is shown in Figure 21.

3.5.1.1 Plant Instrumentation and Control System (PICS). The PICS consists of all devices and controls necessary to start, stop, configure, monitor, and operate safely and efficiently each item of equipment integrated into the total process system. A PICS interface diagram showing the major system elements is shown in Figure 22.

Control of plant equipment is provided from both local control stations located at or near the equipment item and from remote control stations located in the major area control rooms. Graphic and mimic panels are provided in the various control rooms to assist in the overall operation and surveillance of the process system.

Safety and hazard instrumentation and control systems are provided for all process elements and test cell systems. These systems include detection and alarms for fire, smoke, temperature, excessive hydrocarbon vapor level, excessive vibration, personnel safety, and overspeed of rotating machinery. With each of the systems, there are associated alarms with selected manual or automatic corrections. These corrective actions include modification of control, shutdown of a system, or initiation of alternate control systems such as fire suppression and test cell isolation.

Special communications system provide communications relevant to facility and test operations. These systems are separate and distinct from the utility telephone type communications and include a multi-channel, multi-party line, telephone type facility intercommunication system. A limited number of wireless (radio transmitter) type channels are included for remote location flexibility. Facility paging is also provided at selected locations utilizing telephone stations and by area coverage loud speakers.

Instrumentation is provided for continuous monitoring and display of parameters associated with the major equipment in the facility. Two basic systems are provided and are identified as the Facility Monitoring and Logging System (FML) and the Catastrophe Logging System (CLS).

a. FML System. The FML system consists of two separate independent systems -- one for the air supply system and one for the exhaust system. These systems are computer-based data loggers, and monitor plant functions that include the air supply compressors, exhausters, brine chillers and coolers, heaters, configuration and control valves, hydraulic consoles, exhaust duct sprays and coolers, barometric wells, and the test fuel system. All analog inputs, e.g., temperatures, pressures, are scanned and measured every 10 seconds. All status inputs, e.g., limit switches and breaker closures, are scanned and measured once each second. Input parameter storage tables are updated at each scan. At five minute intervals, the updated input parameters are written into magnetic tape records to provide a historical log of facility equipment operation. Updated parameters are also selectively displayed at the FML console station for monitoring by the control room operators.

b. CLS System. The CLS is a computer based system that measures and logs critical position, level, and status parameters. The parameters provide surge, inlet temperature and pressure, discharge temperature and pressure, and other information related to the operating status of the air supply compressors, exhausters, and refrigeration turbines. The CLS monitors the measured parameters and sets and displays alarms when out-of-limit or improper status conditions are detected. The position and level parameters are measured once every second, and the status parameters are measured twice a second. All measured parameters along with alarm information are written to disk every two seconds. Accumulated parameter information on disk is written to magnetic tape every five minutes to provide a historical log. The parameters measured and monitored by the CLS are also measured and monitored by the FML. However, the parameters are scanned much faster by the CLS, thus providing earlier detection of abnormal equipment operation. As in the FML, selected parameters are displayed at the CLS console station for monitoring by the control room operators.

Arrangement of the air supply and exhaust systems in the various operating configurations is provided by the Configuration and Control System (CCS). This system provides the capability to transition from one system configuration to another while at the same time maintaining airflow through the test article. The CCS consists of two separate, independent computer based systems. One system controls the air supply system configuration valves and the other controls the exhaust system configuration valves. Each system performs a monitoring as well as a control function. The control function is activated only when the configuration is to be changed, while the monitoring function is continuously active during testing. The monitored parameters provide information on compressors, exhausters, configuration valves, cooler, heaters, and other configuration related components. Measured parameters are stored on disks, updated, and selectively displayed at the CCS console terminals in the respective control rooms.

Compressor and exhauster surge protection is provided by the Pressure Ratio Control System (PRCS). The PRCS provides a means for automatically controlling the pressure ratio across the air supply compressors and exhausters. This is a computer based system using two individual pressure sensors and a deep surge temperature detector for each machine working in conjunction with surge control valves. The system operates by computing the pressure ratio across a compressor or exhauster from information furnished by absolute pressure sensors on the inlet and discharge and comparing this with a set point. When the pressure sensors begin to exceed the selected set point, a signal is applied to begin opening the corresponding surge control valve. The system also responds similarly to temperature detector indications of overheating in the machine.

The capability to record, display, and analyze vibration information is provided by the Rotating Machinery Analysis System (RMAS). This system is configured to analyze vibration signals from both the air supply system rotating equipment, and exhaust system rotating equipment.

3.5.1.2 Test Instrumentation System. The Test Instrumentation System acquires, conditions, processes, records, and displays engine and test cell data required to determine the performance of the test engine. The system includes both hardware and software, and is sufficiently flexible to support testing over the full range of facility capability.

The TIS is a partitioned system, implementing each major function with a unique set of hardware. A TIS block diagram showing the nine major hardware groupings is shown in Figure 23. The system is formed by integrating 17 minicomputers, one large scientific computer, and a large complement of peripherals and signal-conditioning equipment.

Communications between the five major computer-intensive, functional blocks is accommodated by a Hyperchannel.

As illustrated in Figure 23, data are acquired in the test cells and passed to the Data Conditioning System (DCS), where they are conditioned, digitized, and formatted. After being digitized, all data are recorded on the Wide Band Recording System (WBRS) as either a backup for the real-time data processing, or to be used for post-test analysis. Data flow from the DCS to the Data Acquisition and Processing System (DAPS) and to the Prime Engine Parameter System (PEPS). The DAPS is divided into two functional areas to support static and dynamic data, respectively. The PEPS is designed to acquire, condition, digitize, convert to engineering units, and display critical test cell data needed to safely operate the engine under test. The primary output of PEPS is a real-time graphic display at the engine operator's console. Both static and dynamic data are output from the DAPS to the Mass Data Storage Facility (MDSF), the Display System (DS), and the Executive Data Processing System (EDPS). The MDSF serves as a repository for acquired test data, as well as the center of system control. The DS formats data for display and serves as the man/machine interface between the operators and the TIS. The EDPS executes the engine performance programs, as well as other large computing tasks.

3.5.1.3 Automatic Test Control System. The function of the ATCS is to provide efficient, flexible, and safe control of the testing in ASTF. The following functions are performed by the ATCS:

a. Control of test conditions (simulated flight conditions to which the engine is subjected);

b. Control of engine operating conditions;

c. Selection of data taking modes by TIS, based on test and engine operating conditions;

d. Coordination of control of test and engine operating conditions with plant configuration changes;

e. Detection of abnormal plant and engine operating conditions and response thereto; and

f. Communication with facility operators.

Predetermined test plans provide the basis for conducting engine testing in the ASTF test cells. These test plans typically define a time-ordered sequence of Mach numbers and altitudes representing the test conditions to be established during the prescribed test period. The ATCS controls the parameters which establish a desired test condition by positioning of forty-six of the facility configuration and control valves. The ATCS control parameters, along with the control purpose, are presented in Table 8. The valves controlled by the ATCS are identified on Figure 4 and Table 7.

The ATCS is capable of controlling various engine controls such as power lever angle (PLA), fuel control, and customer bleed. The interface to the engine is effected at a panel in the test building control room.

The ATCS is interfaced with the TIS Display System (DS) to provide a communication path for coordinating ATCS test control activities with TIS data acquisition. Other communications include an exchange of information between ATCS and TIS, indicating that a particular engine condition has been reached and that the required data have been acquired. At this time, the ATCS advances to the next scheduled test point, either automatically or by manual direction. Measurements representing true test conditions are also transmitted to ATCS from TIS for use in removing bias errors that may exist in ATCS instrumentation.

Plant configuration changes are initiated and controlled through the Configuration and Control System (CCS). Upon initiation of a configuration change through the CCS, the ATCS is checked to ascertain if the existing test and engine operating conditions can be supported during the proposed change. If operating conditions cannot be supported, a message is sent to the operator and a signal is sent to the CCS inhibiting the change. Additionally, when the facility operator enters a command for test conditions or engine operating conditions, the command is checked to see if it can be executed in the existing facility configuration without danger to the facility or to the test article. If it cannot, a message describing the difficulty is dispatched to the operator, and execution of the command is inhibited.

The ATCS provides facility and engine status monitoring for the detection of unsafe operating conditions having a potential for causing damage to the engine and/or certain facility equipment. The facility and engine operating status information is obtained by the ATCS from various plant instrumentation and TIS systems. The TIS systems providing status information include the Prime Engine Parameter System (PEPS) and the Display System (DS). Plant instrumentation systems that provide status information include the Configuration Control System (CCS), Facility Monitoring and Logging System (FML), and the Catastrophe Logging System (CLS). Upon detection of emergency conditions, the ATCS analyzes the conditions to determine the appropriate recovery action and response, and then initiates execution of the selected recovery action. Messages indicating the emergency mode elected and the recovery action selected are displayed at the operator's station.

Control of the ATCS and communication between operating personnel and the ATCS is accomplished through four CRT terminals. The terminals provide the capability for interactive communication between operating personnel and the ATCS functions as required to control testing, initiate tasks, and display pertinent test information.

3.5.2 Electrical Power Distribution System. Electrical power for AEDC is supplied by the Tennessee Valley Authority (TVA) and delivered at 161KV on overhead transmission lines terminating at the AEDC main substation. Electrical power for the ASTF is provided through an expansion of the main substation and the addition of four 161KV underground feeders. Two feeders supply a 161KV substation adjacent to the air supply building to provide power for the air supply compressor drive motors and auxiliaries. Two feeders supply a 161KV substation adjacent to the exhauster building to provide power for the exhauster drive motors and auxiliaries. ASTF building service power at 13.8KV is supplied from two main substation central facility transformers through an underground duct system to four outdoor unit substations adjacent to the buildings they serve. The 161KV and 13.8KV electrical distribution systems are schematically shown in Figures 24 and 25, respectively.

Four bays have been added to the AEDC 161KV switching station to accommodate ASTF requirements. One feeder each to the air supply substation and to the exhauster substation originate in two bays at the west end of the station. The other two feeders (one to the air supply substation and one to the exhauster substation) originate in two bays at the east end of the station. Each bay contains a 161KV high pressure pipe-type feeder cable pothead, a 161KV feeder oil circuit breaker and three sets of disconnect switches. The four 161KV feeders are impregnated-paper-insulated, high pressure, pipe-type cables; each installed in a buried, pressurized, oil-filled steel pipe.

The air supply and exhauster substations each contain two 161KV potheads, a 161KV distribution bus, and line and transformer disconnect switches. Five oil-filled power transformers servicing the air supply compressors, variable frequency starting system and support systems, are included in the air supply substation. Seven oil-filled power transformers, servicing the exhausters, variable frequency starting system, cooling tower, and support systems, are included in the exhauster substation. A listing of these transformers with ratings and load data is presented in Table 9.

3.5.3 Cooling Water System. The ASTF cooling water system services all areas of the facility and provides the needed cooling water to remove the heat of compression generated by the air supply and exhaust gas compressors, reduce engine exhaust gas temperatures, protect ducting and equipment from excessive temperatures, prevent process systems from exceeding safe operating limits, and to supply building services. ASTF cooling water requirements range up to a maximum flow demand of about 387,000 gpm. These cooling water needs are supplied through interconnections with the AEDC cooling water system and by the ASTF cooling tower system.

Remotely operated butterfly valves are installed in the interconnecting pipelines to provide the capability for any of the following modes of operation:

a. The cooling tower system providing water for the exhaust gas cooler, EC1, and duct cooling with the balance of the ASTF systems supported by the AEDC system,

b. ASTF supported entirely by the cooling tower system and,

c. ASTF not in operation and the cooling tower system augmenting the AEDC cooling water system in support of other AEDC facilities.

3.5.3.1 Closed-Loop Cooling Tower System. The cooling tower system is comprised of a forced-draft, counter-flow, wood cooling tower consisting of eight cells arranged in two identical banks of four cells each, and two water basins including pumps and distribution piping. This system is a "closed-loop" system and is schematically shown in Figure 26. The cooling tower has a capacity to remove heat at the rate of 4.5×10^9 btu per hour. The tower design is based on a water flow rate of 200,000 gpm, with an inlet water temperature of $145^{\circ}F$, an outlet temperature of $100^{\circ}F$, and a wet bulb temperature of $77^{\circ}F$.

Cooling water supplied through the closed-loop cooling tower system is delivered to the site from the cooling tower basin. Seven horizontal, centrifugal, single-stage pumps at the basin provide the pumping capability. This system basically supplies up to 200,000 gpm of water at a nominal pressure of 108 psia to the exhaust gas cooler, exhaust ducting water jackets, and test cell isolation valves. Discharge water from the exhaust gas cooler flows directly back to the cooling tower while the other systems discharge to the return basin. Seven pumps, similar to the cooling tower basin pumps, return the hot water from the return basin to the cooling tower. At the cooling tower, the water may be diverted to the cooling tower basin, or partially diverted to control tower cell loading, or totally passed through the tower cells. Make-up water to account for evaporation and blowdown losses is supplied to the basins from the AEDC cooling water system. A tabulation of the return basin and cooling tower basin pumps including pumping capacities and motor ratings is presented in Table 10.

3.5.3.2 Open-Loop System. The open-loop cooling water system is a once-through system inter-tied with the AEDC cooling water system. This system basically supplies up to 175,000 gpm of cooling water at approximately 100 psig to the following equipment or subsystems: (1) Air supply and exhaust gas compressor motors, (2) lube oil systems, (3) hydraulic systems, (4) auxiliary air compressor and test fuel conditioning buildings, (5) test cells, (6) brine chillers, (7) cooling tower water make-up system, (8) building services, and (9) exhaust duct foresprays and after-sprays. All water from these systems, with the exception of the exhaust duct foresprays and aftersprays, discharge into return piping connected to the AEDC cooling water return system. The excess water from the foresprays and aftersprays discharge into the barometric well system.

3.5.4 Hydraulic System. A total of 18 independent hydraulic subsystems provide the motive power for the hydraulically actuated process configuration and control valves identified in Table 7. Each of the 18 hydraulic subsystems consist of either one or two hydraulic consoles; hydraulic supply, return, and drain piping; high and low pressure accumulators; and other controls and devices necessary to provide the flow, pressure, and temperature as required by the valves. Each console consists of a hydraulic reservoir, circulating pump and filter, high pressure pump assembly, pulsation damper, relief valves, oil cooler, and other devices as necessary to make a complete and functional unit. A tabulation of the individual hydraulic subsystems vs valves served, flow rate requirements, and associated hydraulic consoles is presented in Table 11.

3.5.5 Test Fuel System. A test fuel system is provided to supply hydrocarbon fuel at the proper pressure and temperature to the engines undergoing tests in test cells C1 and C2. The system contains two fuel supply systems, four fuel return systems, and a refrigerated fuel system.

Fuel supply system number 1 can supply a maximum of 275 gpm of fuel to either cell at any one time, at a selected engine face pressure between 15 and 55 psig over a selected temperature within the range of -65°F to 350°F. Fuel supply system number 2 can deliver up to 550 gpm to either test cell. However, provisions have been included for the addition of another pump to increase the flow rate capacity to 720 gpm. The design pressure for this system is 1,500 psig (ultimate) and the design temperature range is from -65°F to 350°F.

The fuel return systems include two normal return systems for fuel supply system number 1 and number 2, an atmospheric return system primarily used to return fuel to the AEDC fuel farm during system checkout, and a waste fuel return system to handle the drains from all fuel systems and installed equipment. The waste fuel return system discharges to a 2,000 gallon waste fuel tank from which a 300 gpm pump returns the waste fuel to the fuel farm.

The refrigerated fuel system is a batch type system designed for a flow capacity of 550 gpm and is capable of handling refrigerated and special fuels. Refrigerated fuel is stored in a 12,000 gallon insulated tank. Connections for a tank trailer are provided for introducing special types of hydrocarbon fuels into the system for tests of short duration. The design pressure for this system is 250 psig and the temperature range is from -70°F to 105°F.

3.5.6 Barometric Well System. Two barometric wells and associated drain systems are provided to drain all water and other liquids from the subatmospheric pressure exhaust ducting. Barometric well number 1 is located near the exhaust gas cooler, EC1, and handles the drains from EC1 as well as drains from the test cells and ducting upstream of EC1. Barometric well number 2 is located near the exhaust gas compressor intercoolers and handles drains from these intercoolers and from ducting downstream of EC1. The wells and drain systems are designed for a minimum duct pressure of 0.25 psia and for a maximum duct pressure of 25 psia with an average ambient barometric pressure of 14.2 psia.

The water discharged from the barometric wells is pumped into a separate cooling water return force-main. This force-main is connected to the AEDC cooling water return system. Barometric well system number 1 has two 6,000 gpm pumps and one 2500 gpm pump while barometric well system number 2 has two 1000 gpm pumps and one 500 gpm pump.

3.5.7 Auxiliary Air System. The auxiliary air system consists of a low pressure (nominally 100 psig) system and a high pressure (nominally 4000 psig) system. The low pressure system supplies low pressure air at each test cell to provide cooling for instrumentation equipment located within the test cell and to provide balance air for the test engine and inlet duct labyrinth seal. In addition, low pressure air is routed throughout the air supply, test, and exhaust areas to provide pneumatic services for operation of valves, tools, etc. The high pressure system supplies high pressure air at each test cell for use by the test article, for auxiliary test cell cooling, and for other special purpose uses.

The low pressure system is comprised of three package type centrifugal air compressor units, three air dryer units, five air receivers, interconnecting and distribution piping, and associated valving. The high pressure system is comprised of a four inch interconnecting line between the ASTF and the AEDC high pressure air system, two air receivers and filters, and pressure regulation stations at each test cell.

3.5.8 Gaseous Nitrogen System. Nitrogen gas is required for recharging hydraulic accumulators, venturi actuation, and other miscellaneous systems operations. The gas is supplied to the ASTF from the AEDC central supply through a two inch interconnecting supply line and is stored in a 50,000 SCF capacity nitrogen gas trailer located near the test building.

3.5.9 Steam System. Steam is required for heating the buildings, ethylene glycol recovery, fuel conditioning, and fire suppression in the test cells. Steam supply to the ASTF is provided through interconnection with the AEDC central steam system.

3.5.10 Fire Protection System. Six types of fire protection systems are used to protect the various operational areas and equipment within the ASTF. These systems are: (1) Fire hydrants, fire hoses and automatic sprinklers supplied from the potable water system, (2) fire monitors and deluge sprinklers supplied from the cooling water system, (3) carbon dioxide hose reels and nozzles supplied from high pressure storage containers, and carbon dioxide flooding and spurt systems supplied from low pressure storage containers, (4) halon systems supplied from high pressure storage containers, (5) foam systems supplied from foam storage containers and the potable water system, and (6) steam smothering systems supplied from the steam mains.

3.5.10.1 Fire Hydrants, Fire Hoses and Automatic Sprinklers. Fire hydrants are located along all ASTF perimeter roads. Each hydrant has two hose connections and one pumper connection. Fire hose cabinets are provided at numerous locations within the buildings. Automatic closed type sprinklers are also installed in selected areas of various buildings. These sprinklers activate via a fusible element that will melt at a predetermined temperature. All of the above systems are connected to the AEDC potable water system.

3.5.10.2 Fire Monitors and Deluge Sprinklers. Nine fire monitors are provided in the ASTF yard areas. Each monitor consists of an adjustable nozzle mounted on a y-shaped, swivel base. This arrangement permits rotation of the nozzle in both the vertical and horizontal plane. A deluge sprinkler system is provided beneath each test cell. The system is of the automatic, dry-pipe type designed for extra hazard protection. The fire monitors and the deluge sprinklers are connected to the AEDC cooling water system.

3.5.10.3 Carbon Dioxide Systems. A manual carbon dioxide fire suppression system is located near the hatch of each test cell. Both systems are comprised of three primary CO_2 supply cylinders, three reserve cylinders, two hose reels and all necessary controls.

An independent carbon dioxide fire suppression system is provided for each of the six air supply compressor motors and for each of the twelve exhauster motors. Each system has its own bank of high pressure storage cylinders capable of dispensing an initial, measured discharge and an additional, delayed discharge through a nozzle located inside the motor. Each system may be actuated either by a local, manual triggering device, or by a fire detector in the motor.

A centrally located, refrigerated storage tank supplies carbon dioxide to the test fuel conditioning building and to the test cells. This system provides total flooding of the test fuel conditioning building by activation of either an automatic or manual triggering device. Both flooding and spurt type discharges are available for the test cells. The flood system for the cells is actuated by manually tripping a triggering device. The spurt system releases CO_2 into the test cell only while a discharge switch is manually depressed.

3.5.10.4 Halon 1301 Systems. Each of the ASTF control rooms (data conditioning, analysis, processing and storage areas, instrument lab, and spectral analysis area) are protected by individual, high pressure halon 1301 fire suppression systems. Activation of a halon system is initiated by either automatic detection devices or by actuating a manual switch.

3.5.10.5 Foam System. A flood-type foam fire suppression system is provided for each of the three compressor system lube oil consoles and for each of the eight exhauster system lube oil consoles. Deluge-type foam-water sprinkler heads are arranged above each lube oil console to provide uniform coverage of the entire console area. Foam-water discharge for any individual console can be either automatically or manually triggered.

3.5.10.6 Steam Smothering System. Connections to the AEDC steam mains are provided at the test cells for future use by steam smothering systems that will be designed for particular test installations.

3.6 Facility Buildings

Three major buildings and five support buildings are included in the ASTF. The three major buildings include the air supply building, test building, and the exhauster building. The support buildings include the heater control building, refrigeration control building, test fuel conditioning building, auxiliary air compressor building, and the cooling tower control building. The location of these buildings is shown in the site plan view, Figure 3.

3.6.1 Air Supply Building. The air supply building is comprised of a high-bay, basement, and attached two-story annex. Major equipment items and systems housed in the air supply building include the air supply compressors and drive motors, the variable frequency starting system, cooler RC1 and RC2 refrigeration equipment, a compressor air inlet plenum including ducts and filters, and supporting electrical and mechanical building systems. Control of the air supply system is accomplished within a control room in the adjacent annex.

The high-bay of the air supply building is 96 feet wide and 340 feet long with approximately 49 feet of clear height. The air supply compressors, drive motors, and refrigeration equipment are located in this area. An overhead traveling crane, with 100 ton capacity on the primary hoist and 15 ton capacity on the auxiliary hoist, is provided in the high-bay for servicing of all the equipment. A full basement with 17 feet of clear head room is under the high-bay area. Equipment contained in the basement includes the compressor lube oil systems, cooling water and brine pumps for the refrigeration equipment, and miscellaneous support equipment. The annex alongside the building is 44 feet wide and 230 feet long. The variable frequency starting system and other building service equipment is located in the basement beneath the annex. The total approximate air supply building area is 113,210 square feet.

3.6.2 Test Building. The test building is comprised of a high-bay area and an attached three-story annex. This building houses the two engine test cells, test instrumentation system, automatic test control system, and supporting mechanical and electrical building systems.

The high-bay is 96 feet wide and 240 feet long, overall, with 61 feet of clear height. The two test cells are located in this area. Work space is provided outboard of both test cells and in an area between them for the preparation and installation of test engines, test instrumentation and test hardware. The main floor is on grade, however, the floor beneath each test cell is depressed to form a utility trench which also serves to drain accidental spills of fuel. An overhead traveling crane, with a capacity of 50 tons on the primary hoist and 10 tons on the auxiliary hoist, is provided for handling of equipment and test engine and related hardware installation.

The annex is 62 feet wide by 110 feet long with an extension of approximately 40 feet into the high-bay area. Control of the testing operation is accomplished within a control room on the second floor of the annex. Test instrumentation system and automatic test control system equipment is also located in the annex. Other areas for special tasks or usages include mechanical and electrical work rooms, an instrument laboratory, and rooms for data analysis. The total approximate test building area, including the high-bay and annex, is 51,730 square feet.

3.6.3 Exhauster Building. The exhauster building is also comprised of a high-bay, basement, and attached two-story annex. This building houses the exhausters, drive motors, lube oil consoles, variable frequency starting system, and building mechanical and electrical systems.

The high-bay is 106 feet wide and 383 feet long overall, with approximately 52 feet of clear height. The exhausters and drive motors are located in this area. As in the air supply building, an overhead traveling crane with 100 ton and 15 ton hoist capacity is provided for equipment handling. The basement beneath the high-bay is the full width and length of the high-bay area, with approximately 25 feet of clear head room. This area provides access for exhaust duct and utility runs, and for auxiliary equipment including the lube oil consoles.

The adjacent annex is 44 feet wide and 242 feet long overall. Control of the exhaust system is accomplished within a control room on the second floor. The variable frequency starting system and other miscellaneous equipment is located in the basement beneath the annex. The total approximate exhauster building area is 110,451 square feet.

3.6.4 Support Buildings. Five support buildings are included in the ASTF. The heater control and refrigeration control buildings are located in the air supply area. The heater control building houses the controls for the process air heaters H1 and H2. The controls for the refrigeration turbines and cooler RC3, along with the refrigeration equipment supporting RC3, is housed in the refrigeration control building.

The support buildings located in the test area are the test fuel conditioning building, and the auxiliary air compressor building. The test fuel conditioning building houses the equipment used for pumping, drying, filtering, and temperature conditioning of hydrocarbon fuel supplied to the engine undergoing testing in one of the two test cells. The auxiliary air compressor building houses the compressors for the low pressure air system and the refrigeration unit used in conjunction with the fuel conditioning equipment in the test fuel conditioning building.

The cooling tower control building is located adjacent to the cooling towers. This building provides an office, control room, and a switchgear room for the pumping operation, and a storeroom for water treatment chemicals.

4.0 OPERATIONAL ASPECTS

4.1 Air Supply Configuration

An air supply system configuration is defined as the equipment, ducting path, and valves necessary to produce a range of pressure, temperature, humidity, and airflow conditions to the test cell inlet. As discussed in earlier sections, both compressed air and atmospheric air may be provided as dictated by the test requirements. This air is provided through five main flow path legs. During operation, two flow paths at different operating temperatures are used simultaneously to control the test cell inlet air temperature. Desired cell inlet temperatures and pressures are established by the appropriate mixing and throttling of the two air streams.

The air supply system is arranged such that the equipment can be utilized in parallel, series, or series-parallel configurations. Operational configurations are formed by the selective combination of the various flow paths and include any combination or all of the air supply compressors and atmospheric intake in the following configurations:

a. Single-stage compressor configuration,

b. Single-stage compressor configuration plus the atmospheric intake,

c. Two-stage compressor configuration and,

d. Atmospheric intake only.

4.1.1 Air Supply Compressor and Atmospheric Inlet Configuration. The single-stage compressor configuration includes the operation of any combination or all of the six air supply compressors in parallel. The routing of the air for single-stage compressor operation is shown in Figure 27. While the routing of air is shown through all six compressors, lesser numbers of compressors may actually be used as dictated by test requirements. Referring to Figure 27, air is induced through the air supply intake filter plenum into the compressors. Subsequent to compression, air is then admitted to Coolers RC1 and RC2 for the required cooling and drying. Valves AV.A.2 and AV.A.5 are closed in this configuration. The positions of valves AV.A.7, AV.A.6, and AV.A.3 are optional depending on the temperature distribution desired in the downstream supply legs. The single-stage compressor configuration can also operate in parallel with the atmospheric intake (flow through cooler RC3). Air supply in this configuration is available only to test cell C2 and only when operating at subatmospheric pressures in the C2 venturi inlet plenum. The routing of the air for the single-stage compressor configuration with atmospheric intake is shown in Figure 28.

Air routing for two-stage (series) compressor operation is shown in Figure 29. Again, lesser numbers of compressors than shown may be used in the two-stage configuration provided the operating characteristics of the first-stage and second-stage compressors are properly matched. In this configuration, cooler RC1 is used as an intercooler and cooler RC2 as an aftercooler. Valves AV.A.1, AV.A.7, and AV.A.3 are closed while valve AV.A.2 is open to connect the flow path from the first-stage compressor discharge (through RC1) to the second-stage compressor inlet. The positions of valves AV.A.4 and AV.A.5 are optional depending on downstream temperature requirements.

The routing of the air for the atmospheric intake (only) configuration is shown in Figure 30. This configuration utilizes none of the air supply compressors and induces atmospheric air directly into the air supply system through cooler RC3 and through a bleed stack. This configuration can be used only when operating at subatmospheric pressures in the venturi plenum.

4.1.2 Air Supply Leg Configurations. Air supply and operating temperatures for the five flow path legs identified in Figure 4 are as follows:

a. Leg 1 -- Air is supplied to this leg from the air supply compressor system through the refrigeration turbines. The minimum normal operating temperature provided by this leg as a result of turbine cooling is $-108^{\circ}F$.

b. Leg 2 -- This leg receives air from the air supply compressors through cooler RC1 or cooler RC2 and routes it directly to the mixing header with no further cooling or heating. The operating temperature range provided by this leg is -24°F to 200°F. This temperature range is consistent with cooler output temperature.

c. Leg 3 -- Air is supplied to this leg from the air supply compressors through heater H1. Heater H1 may be fired or unfired depending on the air temperature desired. The operating temperature range provided by leg 3 is 200°F to 630°F.

d. Leg 4 -- Air is supplied to this leg from leg 3. Heater H1 serves as a first-stage heater and heater H2 serves as a second-stage heater. The operating temperature range provided by this leg is 630°F to 1020°F. Airflow through leg 4 is available to test cell C1 only.

e. Leg 5 -- Air is supplied to this leg directly from the atmosphere through cooler RC3. The operating temperature is consistent with the cooler RC3 output temperature of 38°F. The leg 5 airflow path is available to test cell C2 only.

These flow path legs can be structured into various configurations as required to support test operations by the opening and closing of the appropriate configuration valves. While there are several possible air supply operating configurations encompassing both single-stage and two-stage compressor operation with flow through the various flow path legs, seven standard operating configurations can be defined that represent the full range of required test temperatures. These configurations are presented in Table 12.

4.2 Test Cell Configurations

Test cell configurations are defined as: (1) Air-off, (2) cell ready, and (3) air-on. The function of these configurations is identical for both test cells.

4.2.1 Air-off Configuration.

The test cell air-off configuration provides for the complete and total isolation of the test cell from the air supply and exhauster systems; and for the venting of the test cell internal pressure to atmosphere. The air-off configuration for test cell C1 is established when the test cell exhaust isolation valve AV.C1.2 and the inlet isolation valve AV.C1.1 (Figure 4) are closed and sealed, and the test cell atmospheric in-bleed cooling air valve CV.C1.1 is fully opened. Isolation of test cell C2 is established when the test cell exhaust isolation valve AV.C2.2 and inlet isolation valves AV.C2.1 and AV.RC3.1 are closed and sealed, and the test cell atmospheric in-bleed cooling air valve CV.C2.1 is fully opened.

4.2.2 Cell-ready Configuration.

The cell-ready configuration maintains the test cell air-off configuration (paragraph 4.2.1) and provides all conditions necessary for final test cell readiness in the respective test cells. The cell-ready configuration is established when:

a. All test cell manway hatches are closed and locked;

b. The venturi inlet plenum and test cell inlet plenum equipment hatches are closed and locked;

c. The test cell equipment hatch is closed and locked, the operating controls deactivated, and the seal pressurized;

d. The test cell atmospheric in-bleed cooling air valve is opened; and

e. The man-in-cell alarm system is activated.

A configuration change from the Air-off configuration to the cell-ready configuration is normally made shortly before the beginning of test operation.

4.2.3 Air-on Configuration. The air-on configuration provides all conditions necessary for the safe and reliable test operation in the respective test cell. The cell-ready conditions a. through e. above are maintained at all times when a cell is in the air-on configuration. The air-on configuration is established when the test cell exhaust and inlet isolation valves are opened, and when the test cell atmospheric in-bleed valve is switched to control status which allows it to be positioned as required. In addition to the normal air-on configuration described above, an air-on vacuum check configuration is possible which permits the inlet isolation valve to remain closed when the normal air-on configuration is established and allows the inlet isolation valve to be opened later to fulfill the complete air-on configuration. A configuration change from the cell-ready configuration to the air-on configuration is made at the beginning of a test operation. A configuration change from the air-on configuration to the air-off configuration is made at the end of a test operation.

4.3 Exhaust System Configuration

An exhaust configuration is defined as the equipment, ducting path, and valves necessary to produce a range of pressure and exhaust gas flow conditions in the test cell exhaust ducting. The exhaust system is arranged such that the equipment can be utilized in parallel, series, or series-parallel configurations. The following exhaust system configurations are employed:

a. Single-stage exhauster configuration,

b. Two-stage exhauster configuration,

c. Three-stage exhauster configuration,

d. Atmospheric exhaust.

4.3.1 Exhauster Single-Stage Configuration. The single-stage exhauster configuration includes the operation of any combination or all of the three second-stage exhausters and third-stage exhauster in parallel. The routing of the exhaust gas for single-stage exhauster configuration is shown in Figure 31. This figure shows exhaust gas flow through all four exhausters, however, lesser numbers of exhausters may be used as dictated by test requirements. Also shown in Figure 31 is the route for atmospheric in-bleed air used for exhauster surge control.

4.3.2 Exhauster Two-Stage Configuration. There are two major divisions of two-stage exhauster configuration. First, the two-stage configuration includes the operation of any or all of the second-stage exhausters in series with the third-stage exhauster. The routing of the exhaust gas for this two-stage configuration is shown in Figure 32. Secondly, the two-stage configuration includes the operation of any or all of the first-stage exhausters in series with any or all of the second-stage and third-stage exhausters. The routing of the exhaust gas for this configuration is shown in Figure 33. Also shown in Figures 32 and 33 is the route for in-bleed air or exhaust gas used for exhauster surge control. Both Figures 32 and 33 show the exhaust gas being routed through the maximum number of exhausters possible for the configuration, however, lesser numbers of machines may actually be utilized as dictated by test requirements.

4.3.3 Exhauster Three-Stage Configuration. The three-stage exhauster configuration includes the operation of any combination or all of the first-stage, second-stage, and third-stage exhausters successively in series. The exhaust gas route for this configuration is shown in Figure 34.

Again, maximum numbers of exhausters possible for the configuration are shown, but lesser numbers may actually be used.

4.3.4 Atmospheric Discharge Configuration. The final configuration for the exhaust system utilizes no exhausters; instead exhaust gases from either test cell are released directly into the test cell atmospheric discharge stack. The routing of the exhaust gas for the atmospheric discharge configuration is shown in Figure 35. This configuration is utilized when test operations yield above atmospheric pressures in the test cell exhaust ducting.

4.4 Operational Examples

The objective of this section is to illustrate how the major process systems are integrated into operating configurations to support steady-state testing of modern-day aircraft turbine engines at select operating points. While the examples presented do not require full utilization of all facility equipment items, they do illustrate the basic functions and interrelations of the major process systems as they work together to provide the concurrent values of mass flow, temperature, and pressure required for true flight simulation.

4.4.1 Scope and General Assumptions. The examples presented include a description of the test scenario, a schematic presentation of the required facility operating configuration with key parameter data at select station locations, a discussion of the basic considerations surrounding the selected operating configuration and equipment operating conditions, and a summary analysis of the process. In the analysis, detailed calculations are presented only when needed for clarity.

Evaluation of the facility operating conditions is based on the following general assumptions. More specific assumptions are presented where they apply in the analysis.

a. The working medium behaves as an ideal gas. Gas properties at major facility stations are dependent on the specific humidity level at the particular station.

b. Flow is assumed to be adiabatic (except for heaters and coolers) and one-dimensional.

c. Because airflow Mach numbers at major facility stations are low (by facility design), total and static pressures and temperatures are assumed to be equal. Exceptions include control valves, venturis, and diffusers.

d. The temperature and pressure is uniform throughout any section of the ducting.

e. Coolers and heaters control to a setpoint; therefore, setpoints for these elements define the process air or gas temperature.

f. Airflow leakage across closed valves is negligible. The inlet air supply to the air supply compressors could be treated as dry air with only slight effect on the process. However, the dry air assumption is not used so that the dehumidification process can be illustrated.

4.4.2 Test Scenario No. 1. This test scenario considers steady-state testing of a typical low by-pass ratio, mixed-flow, augmented turbofan engine operating at maximum power level, at Mach 2.3, and at an altitude of 50,000 feet. The engine is configured in test cell C1 in the direct-connect arrangement as illustrated in Figure 1. The ambient pressure and temperature are assumed to be 14.2 psia and 80°F, respectively; and the specific humidity of the ambient air is 0.015 pounds of water vapor per pound of dry air (lbm/lbm air). Ambient air properties for these conditions are defined by [7]:

$$R_{mix} = \frac{SH\ R_{wv} + R_{da}}{1 + SH} , \qquad (1)$$

$$C_{p_{mix}} = \frac{SH\ C_{p_{wv}} + C_{p_{da}}}{1 + SH} , \qquad (2)$$

and

$$\gamma_{mix} = 1/(1 - R_{mix}/C_{p_{mix}}) . \qquad (3)$$

Therefore, for $SH_{amb} = 0.015$ lbm/lbm air where $R_{wv} = 85.76 \frac{ft\text{-}lbf}{lbm\ ^{o}R}$, $R_{da} = 53.35 \frac{ft\text{-}lbf}{lbm\ ^{o}R}$, $C_{p_{wv}} = 0.49 \frac{BTU}{lbm\ ^{o}R}$, and $C_{p_{da}} = 0.24 \frac{BTU}{lbm\ ^{o}R}$

$$R_{amb} = 53.83 \frac{ft\text{-}lbf}{lbm\ ^{o}R} ,$$

$$C_{p_{amb}} = 0.244 \ \frac{Btu}{lbm\ {}^{o}R},$$

and

$$\gamma_{amb} = 1.396.$$

In order to illustrate the air supply dehumidification process, a requirement is established that the specific humidity of the air at the engine inlet not exceed 7.0×10^{-4} lbm/lbm air.

Conditioned air is supplied to the engine inlet at the total pressure and temperature required to simulate the desired flight conditions. Test cell pressure is set at the level corresponding to the desired altitude based on the geopotential measure (h) of the U.S. Standard Atmosphere [8]. One-dimensional, isentropic, compressible flow functions are used to determine the freestream total temperature and total pressure for the desired Mach number. The flow functions[9] used are

$$T_{t_\infty} = T_\infty \left[1 + \frac{\gamma - 1}{2} M^2\right] \quad (4)$$

and

$$P_{t_\infty} = P_\infty \left[1 + \frac{\gamma - 1}{2} M^2\right]^{\frac{\gamma}{\gamma - 1}}, \quad (5)$$

respectively.

Since the engine is mounted in the test cell in the direct-connect arrangement, an inlet bellmouth is used instead of the engine's actual air inlet duct to duct the airflow from the test cell inlet plenum to the engine face. However, the pressure recovery effects of the actual air inlet duct must be considered in determining the pressure to be established at the engine face for true flight simulation. Considering the pressure recovery realized as the airflow diffuses through the air inlet duct to the engine face, the total pressure at the engine compressor inlet is given by

$$P_t = \eta_R \, P_{t_\infty} \tag{6}$$

where η_R is the inlet ram recovery[10] for the air inlet duct defined by

$$\eta_R = 1.0 - 0.075(M_\infty - 1)^{1.35} \tag{7}$$

for $1 \leq M \leq 5$ and

$$\eta_R = 1.0, \text{ for } 0 \leq M \leq 1. \tag{8}$$

Further, since the air inlet duct smoothly ducts the airflow to the engine face at very low Mach numbers,

$$T_t \simeq T_{t_\infty}. \tag{9}$$

The freestream static conditions at an altitude of 50,000 feet are

$$P_\infty = 1.68 \text{ psia}$$

and

$$T_\infty = 390.3\ ^{\circ}R;$$

therefore, from Eqs. 4 and 5, the freestream total temperature and total pressure for Mach 2.3 are

$$T_{t_\infty} = 799.1 \, ^oR$$

and

$$P_{t_\infty} = 21.0 \text{ psia},$$

respectively. At Mach 2.3, the inlet ram recovery found from Eq. 7 is

$$\eta_R = 0.89;$$

therefore, the total pressure at the engine compressor inlet as determined from Eq. 6 is

$$P_t = 18.7 \text{ psia}.$$

Accordingly, the total temperature at the engine compressor inlet given by Eq. 9 is

$$T_t = 799.1 \, ^oR.$$

For this example, it is determined that pre-test predictions from an engine math model gives the following typical data:

$$\dot{m}_{inlet} = 147.8 \text{ lbm/sec},$$

$$\dot{m}_{eg} = 156.2 \text{ lbm/sec},$$

$$T_{eg} = 3610.5 \, ^oR,$$

and

$$P_{eg} = 20.9 \text{ psia (at nozzle exit)}.$$

The following typical exhaust gas properties are also assumed:

$$R_{eg} = 53.6 \, \frac{\text{ft-lbf}}{\text{lbm} \, ^oR} \, ,$$

$$C_{p_{eg}} = 0.34 \frac{Btu}{lbm\ ^{\circ}R},$$

$$SH_{eg} = 0.087\ lbm/lbm\ gas,$$

and

$$\gamma_{eg} = 1.256.$$

4.4.2.1 Operational Analysis. The facility air supply and exhaust system configurations required to support this test scenario are presented in Figures 36 and 37, respectively. Key parameter data reflecting process conditions at select station locations are also included on the figures. Reference to these figures is implied when stations locations are referred to in subsquent paragraphs of this section.

4.4.2.2 Air Supply Configuration. Engine inlet pressure, temperature, and mass flow requirements form the primary basis for selection of the air supply system configuration. If test cell cooling air is provided from the main air supply system (by-pass around engine inlet from upstream of venturis), it is also considered in establishing total airflow requirements. However, since the required test cell pressure for this test scenario is below atmospheric pressure, test cell cooling air is induced directly into the test cell from atmosphere. Test cell cooling air, therefore, is considered in the exhaust system analysis.

The values of the required engine inlet pressure, temperature, and mass flow were given in paragraph 4.4.2 and are identified at station 2 on Figure 36. The inlet bellmouth used to duct the airflow from the test cell inlet plenum to the engine face is a bell-shaped funnel having a rounded inlet contour which offers practically no air resistance; therefore bellmouth pressure loss is negligible. Now considering the general assumptions made in paragraph 4.4.1.b and c, station 2 conditions exist at station A15. Therefore,

$$P_{A15} = 18.7 \text{ psia},$$

$$T_{A15} = 799.1\ °R,$$

and

$$\dot{m}_{A15} = 147.8 \text{ lbm/sec}.$$

During steady-state testing, engine inlet airflow is metered by operation of the venturis at critical-flow conditions. A discussion on the use of critical-flow venturis for the accurate measurement of airflow during tests of airbreathing propulsion systems is found in reference 11. From this reference data, critical-flow conditions exist when the venturi pressure is within the range

$$0 \leq P_{v_d}/P_{v_i} \leq 0.88. \quad (10)$$

The venturi mass flow rate for critical-flow is defined by

$$\dot{m}_v = 0.5317 \frac{P_{v_i} A C_f}{\sqrt{T_{v_i}}} \quad (11)$$

where A is the total throat area of all open venturis,

$$A = N_v A_v ; \tag{12}$$

therefore, the venturi inlet pressure and thus the pressure which must be established by throttling the mixing control valves is defined by

$$P_{v_i} = \dot{m}_v \frac{\sqrt{T_{v_i}}}{0.5317 N_v A_v C_f} . \tag{13}$$

Now for $N_v = 1$, $A_v = 200.16$ square inches, and assuming $C_f = 1.0$ for this example, Eq. 13 yields

$$P_{v_i} = P_{A14} = 39.3 \text{ psia.}$$

A check of the venturi pressure ratio shows that

$$P_{A15}/P_{A14} \leq 0.88;$$

therefore, critical-flow venturi conditions exist with one open venturi. Two open venturis reduce the venturi inlet pressure such that critical-flow flow conditions do not exist; therefore, one open venturi is the selected venturi configuration. In summary, the venturi inlet conditions are

$$T_{A14} = 799.1 \text{ °R},$$

$$P_{A14} = 39.3 \text{ psia},$$

and

$$\dot{m}_{A14} = 147.8 \text{ lbm/sec.}$$

From these conditions, the following conclusions can be drawn on the required air supply system configuration:

a. One first-stage compressor can provide the required mass flow.

b. The required engine inlet temperature is beyond the capability of cooler RC1 reheating, but is within heater H1 capability. Reheating can be used, however, to pre-heat the airflow to H1 and thus reduce heater fuel costs.

c. The required temperature is within the range provided by the leg 2 and 3 flow path configuration as shown in Table 12 for single-stage compressor configuration.

It is likely that a single-stage compressor configuration can provide the required pressure. Therefore, the analysis of the air supply process will be based on single-stage compressor operation. Should the pressure loss considerations reveal that a single-stage configuration is not adequate, then a two-stage configuration must be utilized.

Considering the general assumption of adiabatic flow, the temperature at station A13 is the same as the temperature at the venturi inlet, station A14. Additionally, since test cell cooling air is induced directly into the test cell from atmosphere, $\dot{m}_{A13} = \dot{m}_{A14}$. Therefore,

$$T_{A13} = 799.1\ °R$$

and

$$\dot{m}_{A14} = 147.8\ \text{lbm/sec.}$$

The pressure at station A13 is given by

$$P_{A13} = P_{A14} - \Delta P_{A13\text{--}A14} \tag{14}$$

A determination of the pressure loss, $\Delta P_{A13\text{--}A14}$, is based on the following general pressure loss definition which applies for all system pressure losses between the major facility stations identified on Figures 36 and 37.

For near steady-state conditions, the forces in the ducting are very nearly in balance. The pressure loss is therefore approximately equal to that caused by duct wall friction. Over a duct length, L, the pressure loss is typically expressed as[12]

$$P = \left(\frac{fL}{D}\right)\left(\frac{V^2}{2\ g_c}\right) \tag{15}$$

Now for

$$\dot{m} = \rho A\ V, \tag{16}$$

$$A = \frac{\pi D^2}{4}, \tag{17}$$

and

$$P = \rho R\ T, \tag{18}$$

Eq. 15 can be expressed as

$$\Delta P = \left(\frac{fL}{D}\right)\frac{8\ R\ T\ \dot{m}^2}{\pi^2\ g_c\ D^4\ P}. \tag{19}$$

In case the control volume considered has varying diameter or internal components (such as the control volumes between the major facility stations identified in this example), Eq. 19 can be made more general by defining an equivalant pressure loss coefficient, K, to account for the combined losses. Thus, the pressure loss between the major facility stations identified is defined by

$$\Delta P = \frac{8 \; R \; K \; T_i \; \dot{m}^2}{\pi^2 \; g_c \; D_e^4 \; P_i} \tag{20}$$

where T_i and P_i are the inlet temperature and pressure to the control volume (upstream station), respectively; and D_e is the equivalant diameter of the control volume. The equivalant pressure loss coefficient (K) values and the corresponding equivalant diameters (D_e) which apply to the ducting and equipment between the major facility stations identified for the air supply and exhaust system configurations supporting test scenario No.1 are presented in Table 13[13]. An iterative solution of Eq. 20 using the K and D_e values presented in Table 13 results in an extremely low $\Delta P_{A13\text{--}A14}$ which, for this example, can be considered negligible. Therefore, from Eq. 14

$$P_{A13} = P_{A14} = 39.3 \text{ psia.}$$

The required temperature, T_{A13}, is obtained by mixing the airflow from the supply legs in the mixing header.

Assuming that the mixing is carried out adiabatically, application of the steady-state, steady-flow energy equation to the process yields

$$\sum(\dot{m}\ C_p\ T)_i = \sum \dot{m}_i\ C_{p_o}\ T_o, \tag{21}$$

or

$$T_o = \frac{\sum(\dot{m}\ C_p\ T)_i}{\sum \dot{m}_i\ C_{p_o}}; \tag{22}$$

where

$$C_{p_o} = \frac{\sum(\dot{m}\ C_p)_i}{\sum \dot{m}_i}\ . \tag{23}$$

Since the airflow to the mixing header is through legs 2 and 3 and C_p = const., Eq. 21 yields

$$\dot{m}_{11}\ T_{A11} + \dot{m}_{A12}\ T_{A12} = \dot{m}_{A13}\ T_{A13}.$$

Therefore,

$$\frac{\dot{m}_{A11}}{\dot{m}_{A12}} = \frac{T_{A13} - T_{A12}}{T_{A11} - T_{A13}}\ .$$

Temperatures T_{A11} and T_{A12} (assuming adiabatic flow) correspond to the cooler RC1 and heater discharge temperatures, respectively. Since reheating of the process air can be accomplished in RC1 to pre-heat the airflow to H1, the reheat stage of cooler RC1 is utilized. Therefore, the RC1 discharge temperature is equal to the reheat setpoint temperature. Now assuming RC1 reheat at maximum capability results in

$$T_{sp(reheat)} = T_{A5} = T_{A9} = T_{A10} = T_{A11}$$

$$= 660\ °R.$$

For the conditions considered in this example, a setpoint temperature for H1 at approximately five percent greater than the required engine inlet temperature is selected to account for instabilities in burner operation.(Such instabilities can occur at low mass flow rates since the heaters are designed to deliver a high heat load at high mass flow rates). Therefore,

$$T_{sp(H1)} = T_{A7} = T_{A8} = T_{A12} = 840\ °R.$$

Now that the temperatures of the flow streams involved in the mixing process are established, the ratio of leg 2 to leg 3 flow delivered to the mixing header can be determined. Thus,

$$\frac{\dot{m}_{A11}}{\dot{m}_{A12}} = 0.29.$$

From which,

$$\dot{m}_{A11} = \dot{m}_{A10} = 33.2 \text{ lbm/sec}$$

and

$$\dot{m}_{A12} = \dot{m}_{A8} = 114.6 \text{ lbm/sec.}$$

In summary, the conditions of the leg 2 and 3 flow streams passing through the mixing control valves and into the mixing header are

$$T_{A11} = T_{A10} = 660\ ^{\circ}R,$$

$$\dot{m}_{A11} = \dot{m}_{A10} = 33.2 \text{ lbm/sec;}$$

and

$$T_{A12} = T_{A8} = 840\ ^{\circ}R,$$

$$\dot{m}_{A12} = \dot{m}_{A8} = 114.6 \text{ lbm/sec,}$$

respectively. In addition, for the above conditions the pressure loss from the downstream side of the leg 2 and 3 mixing control valves (stations A11 and A12, respectively) to station A13 as determined by an iterative solution of Eq. 20 using Table 13 K and D_e values is negligible. Therefore,

$$P_{A11} = P_{A12} = P_{A13} = 39.3 \text{ psia.}$$

Airflow provided by the air supply system that is now required for mixing is dumped to atmosphere through the leg 2 and 3 load control valves located at stations A5' and A7', respectively. The amount of airflow dumped is determined from a mass balance on the flow legs. The amount of airflow into the flow legs, however, is dependent on the upstream process. Therefore, attention is now directed to evaluation of that process.

One first-stage air supply compressor provides sufficient mass flow for the desired flight condition. Its performance is defined by

$$\frac{\dot{m}\sqrt{\theta}}{\delta} = f(P_d/P_i,\ N_c)$$

where $$\theta = T_i/T_{ref}, \tag{21}$$

$$\delta = P_i/P_{ref}, \tag{22}$$

and $$N_c = N/N_D\sqrt{\theta}\ . \tag{23}$$

The first-stage compressor performance map is presented in Figure 38. At rated pressure ratio, PR = 3.19, the corrected mass flow rate and efficiency from Figure 38 are

$$\frac{\dot{m}\sqrt{\theta}}{\delta} = 279 \text{ lbm/sec}$$

and

$$\eta_c = 0.84,$$

respectively. The actual mass flow rate through the air supply inlet filter plenum and, in turn, through the compressor is therefore given by

$$\dot{m}_{A1} = \dot{m}_{A2} = \dot{m}_{A3} = 279 \frac{\delta}{\sqrt{\theta}}$$

or

$$\dot{m}_{A1} = \dot{m}_{A2} = \dot{m}_{A3} = 279 \frac{P_{A2}}{\sqrt{T_{A2}/T_{ref}}\ P_{ref}} \tag{24}$$

where $$T_{ref} = 540\ °R$$

and

$$P_{ref} = 13.8 \text{ psia.}$$

Again considering the general assumption of adiabatic flow,

$$T_{A2} = T_{A1} = T_{amb} = 540\ °R.$$

The pressure at station A2 is given by

$$P_{A2} = P_{A1} - \Delta P_{A1--A2} \ . \tag{25}$$

An iterative solution is again used to determine the pressure at station A2 and, in turn, the actual mass flow rate through the compressor as follows:

a. Select a value for P_{A2}.

b. Determine $\dot{m}$ from Eq. 24.

c. Determine ΔP from Eq. 20 using calculated value of $\dot{m}$.

d. Determine P_{A2} from Eq. 25 and compare with selected value. (Note, $P_{A1} = P_{amb}$).

Based on the above solution,

$$P_{A2} = 13.9 \text{ psia}$$

and

$$\dot{m}_{A1} = \dot{m}_{A2} = \dot{m}_{A3} = 281 \text{ lbm/sec.}$$

The pressure at station A3 is given by

$$P_{A3} = P_{A2} \, PR$$

where, for rated pressure ratio,

$$P_{A3} = 44.3 \text{ psia.}$$

As the air is compressed by the compressor, its temperature increases and is given by

$$T_d = T_i \left[1 + \frac{1}{\eta_c} \left(PR^{\frac{\gamma-1}{\gamma}} - 1 \right) \right] ; \tag{26}$$

therefore, $T_{A3} = 790.5\ °R.$

Continuing with the pressure loss analysis using Eq. 20 (values of K and D_e from Table 13) and the station A3 pressure and mass flow rate, $\Delta P_{A3--A3'}$, is found to be negligible. Therefore,

$$P_{A3'} = P_{A3} = 44.3 \text{ psia.}$$

Additionally, for adiabatic flow

$$T_{A3'} = 790.5\ °R.$$

The mode of cooler RCl operation is determined by the desired downstream conditions. Since a specific humidity level requirement for the engine inlet airflow less than the ambient level has been established, operation of the cooling stages is required for dehumidification of the process air. In addition, operation of the reheat stage is required for pre-heating the process air after dehumidification. The number of cooling stages required is determined by the desired specific humidity of the process air which is defined by[7]

$$SH = 0.622 \frac{P_{wv}}{P - P_{wv}} \qquad (27)$$

where P_{wv} is the partial pressure of water vapor and P is the system pressure. Based on station A3' conditions, the partial pressure of the water vapor entering the cooling stages (determined from Eq. 27 using SH_{amb}) is

$$P_{wv_{A3'}} = 1.02 \text{ psia.}$$

Assuming operation of the first three cooling stages in RC1 at design set point, e.g. outlet temperature of 0°F, the discharge temperature of the process air leaving the third cooling stage is assumed to be

$$T_{A4} = 460 \text{ °R.}$$

At 460 °R, the saturation pressure of water is 0.0185 psia[14], which is less than the initial partial pressure of water vapor ($P_{wv_{A3'}}$) in the entering airstream. Consequently, the air is saturated at 460 °R. Therefore,

$$P_{wv_{A4}} = 0.0185 \text{ psia.}$$

Considering the pressure loss through the first three cooling stages as determined from Eq. 20

$$P_{A4} = 43.2 \text{ psia.}$$

Therefore, the specific humidity of the process air leaving the third cooling stage as determined from Eq. 27 is

$$SH_{A4} = 2.7 \times 10^{-4} \text{ lbm/lbm air}$$

which meets the established requirement. Operation of the first three cooling stages and reheat stage is therefore the established RC1 operating mode.

The mass of water removed by condensation is given by

$$\dot{m}_w = \frac{\dot{m}_{A3'}(SH_{A3'} - SH_{A4})}{1 + SH_{A3'}} .$$

From which,

$$\dot{m}_w = 4.1 \text{ lbm/sec.}$$

Therefore, the mass flow rate of process air delivered to the flow legs is

$$\dot{m}_{A3'} - \dot{m}_w = 276.9 \text{ lbm/sec.}$$

Since the specific humidity of the process air changes, the air properties also change as defined by Eqs. 1, 2, and 3. Therefore, the properties of the process air at station A4 and subsquent downstream air supply stations are:

$$R_{A4--2} = 53.36 \ \frac{\text{ft-lbf}}{\text{lbm °R}} ,$$

$$C_{p_{A4--2}} = 0.24 \ \frac{\text{Btu}}{\text{lbm °R}} ,$$

and

$$\gamma_{A4--2} \approx 1.4 .$$

The pressure loss through the reheat stage is again determined from Eq. 20 and is found to be negligible. Therefore,

$$P_{A5} = P_{A4} = 43.2 \text{ psia.}$$

The reheat stage was previously assumed to be operating at maximum capability resulting in a cooler discharge temperature of

$$T_{A5} = 660\ °R.$$

The airflow leaving RC1 is split at station A9 into legs 2 and 3. The split is determined by the load control valves. The mass flow rate to heater H1 and thus to leg 3 is set at the minimum rate consistent with heater performance specifications (Table 3). Therefore,

$$\dot{m}_{A6} = 200 \text{ lbm/sec.}$$

Hence, the leg 2 flow rate is

$$\dot{m}_{A9} = \dot{m}_{A5} - \dot{m}_{A6} = 76.9 \text{ lbm/sec.}$$

The excess airflow dumped to atmosphere through the load valves can now be determined as follows:

$$\dot{m}_{A5'} = \dot{m}_{A9} - \dot{m}_{A10} = 43.7 \text{ lbm/sec}$$

and

$$\dot{m}_{A7'} = \dot{m}_{A7} - \dot{m}_{A8} = 85.4 \text{ lbm/sec.}$$

Continuing with the pressure loss analysis from the cooler RC1 discharge (station A5) to the upstream side of the leg 2 and 3 mixing control valves (stations A10 and A8, respectively) results in the following station pressures:

$$P_{A9} = 43.2 \text{ psia (negligible loss),}$$

$$P_{A6} = 43.2 \text{ (negligible loss)},$$

$$P_{A7} = 43.1 \text{ psia},$$

$$P_{A8} = 43.1 \text{ psia (negligible loss)},$$

and

$$P_{A10} = 43.2 \text{ psia (negligible loss)}.$$

From the above pressure loss analysis, it is concluded that single-stage compressor operation is an adequate configuration for providing the required pressure at the engine inlet. This completes the basic air supply system configuration analysis. Attention is now directed to a similar analysis of the supporting exhaust system configuration.

4.4.2.3 Exhaust System Configuration. Test cell pressure, exhaust gas temperature, and exhaust gas flow (including test cell cooling air and water vapor resulting from the evaporative cooling process) form the primary basis for selection of the exhaust system configuration. The required test cell pressure to be established and maintained for altitude simulation at 50,000 feet is

$$P_{cell} = P_{\infty} = 1.68 \text{ psia}.$$

As shown in Figure 1, an exhaust gas diffuser is installed in the exhaust duct downstream of the test article. The purpose of the diffuser is to convert a portion of the exhaust stream's kinetic energy into a pressure increase and thus decrease the pumping required by the exhaust gas compressors.

The amount of pressure recovery realized is a function of the Mach number of the flow entering the diffuser, engine power level, and the diffuser design point. Representative exhaust diffuser recovery ratio for turbojet and mixed-flow turbofan engines is presented in Figure 39[15]. The Mach number of the flow entering the diffuser assuming an isentropic expansion as determined from Eq. 5 (based on the expansion ratio of P_{eg}/P_{cell}) is

$$M_{eg} = 2.3.$$

Therefore, the ratio of exhaust duct pressure to test cell pressure at maximum power level (from Figure 39) is about

$$\frac{P_{exh\ duct}}{P_{test\ cell}} = \frac{P_{E1}}{P_{cell}} = 3.8.$$

Based on this pressure ratio, the exhaust duct pressure that must be established and maintained by the exhaust system is

$$P_{E1} = 6.4 \text{ psia}.$$

The total exhaust gas flow at station E1 is equal to the engine exhaust gas flow plus test cell cooling airflow. Test cell cooling airflow at rates up to approximately ten percent of the engine flow rate is usually adequate for cell cooling; therefore, set

$$\dot{m}_{ca} = 16 \text{ lbm/sec}.$$

Hence, $$\dot{m}_{E1} = \dot{m}_{ca} + \dot{m}_{eg} = 172.2 \text{ lbm/sec.}$$

The temperature of the exhaust gas stream at station E1 is given by Eq. 21

$$T_{E1} = \frac{\dot{m}_{ca}\, C_{p_{ca}}\, T_{ca} + \dot{m}_{eg}\, C_{p_{eg}}\, T_{eg}}{\dot{m}_{E1}\, C_{p_{E1}}}$$

where from Eq. 23,

$$C_{p_{E1}} = 0.33 \frac{\text{Btu}}{\text{lbm °R}} .$$

Therefore,

$$T_{E1} = 3411.4 \text{ °R.}$$

Additionally,

$$SH_{E1} = \frac{\dot{m}_{ca}\, SH_{ca} + \dot{m}_{eg}\, SH_{eg}}{\dot{m}_{ca} + \dot{m}_{eg}} = 0.08 \text{ lbm/lbm gas,}$$

$$R_{E1} = \frac{\dot{m}_{ca}\, R_{ca} + \dot{m}_{eg}\, R_{eg}}{\dot{m}_{ca} + \dot{m}_{eg}} = 58.62 \frac{\text{ft-lbf}}{\text{lbm °R}},$$

and from Eq. 3,

$$\gamma_{E1} = 1.264.$$

In summary, the conditions at station E1 are:

$$T_{E1} = 3411.4 \text{ °R,}$$

$$P_{E1} = 6.4 \text{ psia,}$$

and

$$\dot{m}_{E1} = 172.2 \text{ lbm/sec.}$$

The temperature of the exhaust gas stream entering the exhaust gas compressors must be limited to a maximum of 180 °F. Cooling of the exhaust gas stream is accomplished by a combination of direct water sprays (evaporative cooling) and indirect cooling in the exhaust gas cooler EC1. Since the temperature of the exhaust gas stream entering the exhaust duct exceeds 2500 °F, foresprays (located at station E1') are used to cool the exhaust gas stream to 2500 °F or less before the flow passes through EC1. For this spray cooling process, assuming that the heat added to the water is extracted from the exhaust gas in the evaporation process,

$$\dot{m}_{E1}\, C_{p_{E1}} (T_{E1} - T_{E2}) = \dot{m}_{fs} C_{p_{ws}} (T_{E2} - T_{ws}) + \dot{m}_{fs} h_{fg}$$

where $\dot{m}_{fs}$ is the mass flow rate of forespray water evaporated into the exhaust gas stream. From this,

$$\dot{m}_{fs} = \frac{\dot{m}_{E1}\, C_{p_{E1}} (T_{E1} - T_{E2})}{C_{p_{ws}} (T_{E2} - T_{ws}) + h_{fg}} .$$

Therefore, to cool the exhaust gas stream to 2500 °F (at station E2) with an 80 °F water supply requires

$$\dot{m}_{fs} = 12.1 \text{ lbm/sec.}$$

Since water vapor is added to the exhaust gas stream, the specific humidity changes, Hence,

$$SH_{E2} = \frac{\dot{m}_{ca}\ SH_{ca} + \dot{m}_{eg}\ SH_{eg} + \dot{m}_{fs}}{\dot{m}_{ca} + \dot{m}_{eg}}$$

$$= 0.156 \text{ lbm/lbm gas.}$$

In addition, the exhaust gas properties change accordingly;

$$R_{E2} = \frac{\dot{m}_{E1}\ R_{E1} + \dot{m}_{fs}\ R_{ws}}{\dot{m}_{E1} + \dot{m}_{fs}} = 60.37\ \frac{\text{ft-lbf}}{\text{lbm °R}},$$

$$C_{p_{E2}} = \frac{\dot{m}_{E1}\ C_{p_{E1}} + \dot{m}_{fs}\ C_{p_{ws}}}{\dot{m}_{E1} + \dot{m}_{fs}} = 0.34\ \frac{\text{Btu}}{\text{lbm °R}},$$

and

$$\gamma_{E2} = 1/(1 - R_{E2}/C_{p_{E2}}) = 1.296.$$

The pressure loss, ΔP_{E1--E2}, as determined from Eq. 20 using K and D_e values from Table 13 is found to be negligible. Therefore,

$$P_{E2} = P_{E1} = 6.4 \text{ psia.}$$

In summary, the conditions at station E2 are:

$$T_{E2} = 2960 \text{ °R},$$

$$P_{E2} = 6.4 \text{ psia},$$

and

$$\dot{m}_{E2} = \dot{m}_{E1} + \dot{m}_{fs} = 184.3 \text{ lbm/sec.}$$

The exhaust gas stream enters the tube-and-shell heat exchange, cooler EC1, at station E3. Considering the general assumption of adiabatic flow, the temperature of the gas stream at station E3 is the same as the temperature at station E2. Again the pressure loss, ΔP_{E2--E3}, is found to be negligible; therefore,

$$P_{E3} = P_{E2}.$$

In addition, the gas properties at station E3 are the same as those at station E2. Now assuming EC1 cooling of the gas stream to minimum design point temperature,

$$T_{E4} = 840\ °R.$$

Since no water is added to the exhaust gas stream between stations E3 and E4,

$$\dot{m}_{E4} = \dot{m}_{E3} = 184.3 \text{ lbm/sec.}$$

Additionally, ΔP_{E3--E4} is found to be negligible; therefore,

$$P_{E4} = P_{E3} = 6.4 \text{ psia.}$$

All other gas properties at station E4 are the same as those at station E3.

Direct spray cooling with the aftersprays at station E4' provides further cooling of the exhaust gas stream. The final outlet temperature at station E5 is determined from saturation conditions at the exhaust duct pressure and is given by

$$T_{E5} = \frac{C_{PE4}T_{E4}(1+SH_{E4})-(SH_{E5}-SH_{E4})(h_{fg}-C_{p_{ws}}T_{ws})}{C_{p_{E4}}(1+SH_{E4})+(SH_{E5}-SH_{E4})C_{p_{ws}}}.$$

The specific humidity of the gas stream after spraying is given by Eq. 27,

$$SH_{E5} = \frac{0.622\ P_{wv}}{P_{E5} - P_{wv}}$$

where the partial pressure of the water vapor is a function of the outlet temperature,

$$P_{wv} = f(T_{E5});$$

and

$$P_{E5} = P_{E4} - \Delta P_{E4\text{--}E5}.$$

An iterative solution is used to determine the final temperature, T_{E5}, of the exhaust gas stream as follows:

a. Select T_{E5} (100 °F is a good starting point).

b. Determine P_{wv} (from steam tables at T_{E5}).

c. Determine P_{E5} (using Eq. 20 to determine pressure loss).

d. Determine SH_{E5}.

e. Determine T_{E5} (using SH_{E5}) and compare with selected value.

Assuming an 80 °F water supply to the aftersprays results in

$$T_{E5} \cong 583\ °R$$

with a corresponding specific humidity of

$$SH_{E5} = 0.251 \text{ lbm/lbm gas.}$$

The mass flow rate of water being evaporated into the exhaust stream is

$$\dot{m}_{as} = \frac{\dot{m}_{E4}\ (SH_{E5} - SH_{E4})}{1 + SH_{E4}} = 15.1 \text{ lbm/sec.}$$

Therefore,

$$\dot{m}_{E5} = \dot{m}_{E4} + \dot{m}_{as} = 199.4 \text{ lbm/sec.}$$

The gas properties again change as a result of water vapor addition to the gas stream. Hence,

$$R_{E5} = \frac{\dot{m}_{E4}\ R_{E4} + \dot{m}_{as}\ R_{ws}}{\dot{m}_{E4} + \dot{m}_{as}} = 62.30\ \frac{\text{ft-lbf}}{\text{lbm °R}},$$

$$C_{p_{E5}} = \frac{\dot{m}_{E4}\ C_{p_{E4}} + \dot{m}_{as}\ C_{p_{ws}}}{\dot{m}_{E4} + \dot{m}_{as}} = 0.35\ \frac{\text{Btu}}{\text{lbm °R}},$$

and

$$\gamma_{E5} = 1/(1 - R_{E5}/C_{p_{E5}}) = 1.297.$$

In summary, station E5 conditions are:

$$T_{E5} = 583 \text{ °R},$$

$$P_{E5} = 6.4 \text{ psia},$$

and

$$\dot{m}_{E5} = 199.4 \text{ lbm/sec.}$$

Pressure in the exhaust duct is controlled by throttling the exhaust gas flow through valve CV.C.10. The throttling requirements are established by the conditions on the upstream side of the valve and on the operating conditions of the exhaust gas compressors. Considering the general assumption of adiabatic flow and negligible pressure loss as determined from Eq. 20, the conditions on the upstream side of CV.C.10 (station E6) are the same as those at station E5. The temperature, mass flow rate, and gas properties at station E7 are the same as those at station E6.

The performance of the exhaust gas compressors is determined in the same fashion as the air supply compressor performance previously defined in paragraph 4.4.2.2. The exhaust gas compressor performance map is presented in Figure 40. Assuming operation of the third-stage exhaust gas compressor at rated pressure ratio (PR = 3.5), the corrected mass flow rate through the compressor is

$$\frac{\dot{m}\sqrt{\Theta}}{\delta} = 95.7 \text{ lbm/sec.}$$

From this corrected mass flow rate,

$$\dot{m}_{E8} = \dot{m}_{E9} = \frac{95.7 \, P_{E8}}{\sqrt{T_{E8}/T_{ref}} \; P_{ref}}$$

where $T_{E8} = T_{E7} = 583\ °R$ (assuming adiabatic flow),

$$T_{ref} = 560\ °R \text{ (from Figure 40)},$$

and

$$P_{ref} = 1.2 \text{ psia (from Figure 40)}.$$

Therefore,

$$\dot{m}_{E8} = \dot{m}_{E9} = 78.16\ P_{E8}\ .$$

Now, based on the compressor ratio,

$$P_{E8} = \frac{P_{E9}}{PR}\ .$$

Hence,

$$\dot{m}_{E8} = \dot{m}_{E9} = \frac{78.16\ P_{E9}}{PR} = 22.33\ P_{E9}.$$

Additionally, the exhaust gas compressor discharge temperature as determined from Eq. 26 is

$$T_{E9} = 804.4\ °R.$$

Since the pressure at station E10 is also known (ambient pressure), P_{E9} can now be determined from Eq. 20 using the above expression for $\dot{m}_{E9}$, the calculated value of T_{E9}, and K and D_e values from Table 13. From this, it is found that

$$P_{E9} = 14.21 \text{ psia}.$$

Based on this discharge pressure,

$$\dot{m}_{E8} = \dot{m}_{E9} = 317.3 \text{ lbm/sec}$$

and $$P_{E8} = 4.06 \text{ psia}$$

which concludes that operation of the third-stage exhaust gas compressor is an acceptable configuration. The balance of airflow needed at the exhaust gas compressor inlet is inbled (at station E7') from atmosphere through the surge control valve.

The pressure loss between stations E7 and E8 as determined by an iterative evaluation similar to that made in the air supply system analysis is found to be negligible; therefore,

$$P_{E7} = P_{E8} = 4.06 \text{ psia.}$$

Therefore, CV.C.10 must throttle the pressure from 6.4 psia to 4.06 psia. This concludes the analysis of the required exhaust gas system configuration.

4.4.2.4 Configuration Summary. The air supply system configuration utilizes a single first-stage air supply compressor and operation of the first three cooling stages and the reheat stage of cooler RC1. Operation of heater H1 is also required to further heat the air to meet test cell inlet temperature requirements. Airflow is delivered to the mixing header through flow path legs 2 and 3. After mixing, airflow is metered to the engine by one open venturi.

The exhaust system configuration utilizes one exhaust gas compressor. Test cell cooling air is induced directly into the test cell from atmosphere. Exhaust gas cooling is accomplished by forespray cooling, EC1 cooling, and after-spray cooling.

4.4.3 Test Scenario No. 2. This test scenario considers steady-state testing of a typical high by-pass ratio turbofan engine operating at maximum power level, at Mach 0.6, and at an altitude of 35,000 feet. The engine is configured in test cell C2 in the direct-connect arrangement. Ambient conditions and air properties are assumed to be the same as those used in test scenario No. 1 and are summarized as follows:

$$P_{amb} = 14.2 \text{ psia},$$

$$T_{amb} = 540 \ ^{o}R,$$

$$SH_{amb} = 0.015 \text{ lbm/lbm air},$$

$$R_{amb} = 53.83 \ \frac{\text{ft-lbf}}{\text{lbm} \ ^{o}R},$$

$$C_{p_{amb}} = 0.244 \ \frac{\text{Btu}}{\text{lbm} \ ^{o}R},$$

and

$$\gamma_{amb} = 1.396.$$

For this test condition, a requirement is established that the specific humidity of the airflow to the engine inlet be as low as possible.

The analysis of the facility configuration required to support this test scenario closely follows that used for test scenario No. 1; therefore, frequent reference is made to the scenario No. 1 analysis. Some exceptions have been made, however, and are noted where they apply. The freestream static conditions at an altitude of 35,000 feet are

$$P_\infty = 3.5 \text{ psia}$$

and

$$T_\infty = 394\ ^oR;$$

therefore, from Eqs. 4 and 5, the freestream total temperature and total pressure for Mach 0.6 are

$$T_{t_\infty} = 422.1\ ^oR$$

and

$$P_{t_\infty} = 4.5 \text{ psia},$$

respectively. At Mach 0.6, the inlet ram recovery found from Eq. 8 is

$$\eta_R = 1.0;$$

therefore, the total pressure at the engine inlet as determined from Eq. 6 is

$$P_t = 4.5 \text{ psia}.$$

Accordingly, the total temperature at the engine inlet given by Eq. 9 is

$$T_t = 422.1\ °R.$$

For this example, the following typical engine parameters are assumed:

$$\dot{m}_{inlet} = 925\ lbm/sec,$$

$$\dot{m}_{eg} = 926.7\ lbm/sec\ \text{(core and by-pass flow)},$$

and

$$T_{eg} = 755\ °R\ \text{(mixed core and by-pass flow)}.$$

The following typical exhaust gas properties are also assumed:

$$R_{eg} = 53.81\ \frac{ft\text{-}lbf}{lbm\ °R},$$

$$C_{p_{eg}} = 0.245\ \frac{Btu}{lbm\ °R},$$

$$SH_{eg} = 0.016\ lbm/lbm\ gas,$$

and

$$\gamma_{eg} = 1.393.$$

4.4.3.1 Operational Analysis. The facility air supply and exhaust system configurations required to support this test scenario are presented in Figures 41 and 42, respectively. Key parameter data reflecting process conditions at select station locations are also included on the figures. Reference to these figures is implied when station locations are referred to in subsquent paragraphs of this section.

4.4.3.2 Air Supply Configuration. The basis for selection of the air supply configuration was previously discussed in paragraph 4.4.2.2. The values of the required engine inlet pressure, temperature, and mass flow were given in paragraph 4.4.3 and are identified at station 2 on Figure 41. As discussed in paragraph 4.4.2.2, these conditions also exist at station A14. Therefore,

$$P_{A14} = 4.5 \text{ psia},$$

$$T_{A14} = 422.1 \text{ °R},$$

and

$$\dot{m}_{A14} = 925 \text{ lbm/sec}.$$

Metering of the engine inlet airflow is again accomplished by operation of the venturis at critical-flow conditions. Since the number of open venturis establishes the venturi inlet pressure which, in turn, affects the upstream operating configuration and conditions, an assessment of the upstream configuration is in order at this time. This assessment is made with consideration given to the required engine inlet parameters and the established dryness requirement for the inlet airflow to the engine.

The required engine inlet temperature, as shown in Table 12, can be obtained by delivering airflow to the mixing header through either a leg 1 and 2 flow path configuration; or a leg 1, 2, and 5 flow path configuration. However, since maximum dryness of the process air is obtained by dehumidification in cooler RC1 and since the four first-stage air supply compressors can provide adequate airflow to meet engine inlet requirements, the leg 1 and 2 flow path configuration is utilized. It is noted that the turbine discharge pressure corresponds directly with the venturi inlet pressure (less any ducting pressure loss) since valve AV.TC.2 serves only as a configuration valve. Therefore, the operating conditions of the turbines are the primary factors considered in selecting the number of open venturis.

Air supply compressor performance and operating conditions are the same as determined in test scenario No.1 except that all four first-stage compressors are required to support this test scenario. Station A2 and A3 conditions from the scenario No.1 analysis are summarized for each compressor as follows:

$$P_{A2} = 13.9 \text{ psia},$$

$$T_{A2} = 540 \text{ °R},$$

$$P_{A3} = 44.3 \text{ psia},$$

$$T_{A3} = 790.5 \text{ °R},$$

and

$$\dot{m}_{A2} = \dot{m}_{A3} = 281 \text{ lbm/sec}.$$

Now considering operation of all four compressors and the general assumption of adiabatic flow

$$\dot{m}_{A4} = 1124 \text{ lbm/sec}$$

and

$$T_{A4} = 790.5 \text{ °R.}$$

The pressure at station A4 is given by

$$P_{A4} = P_{A3} - \Delta P_{A3\text{--}A4}$$

where the value of $\Delta P_{A3\text{--}A4}$ along with all other pressure loss values associated with this test scenario are found in the test scenario No.2 pressure loss summary presented in Table 14. Table 14 pressure losses are nominal values for similar flow conditions found in reference 16. Based on the $\Delta P_{A3\text{--}A4}$ from Table 14,

$$P_{A4} = 42.4 \text{ psia.}$$

Operation of all four cooling stages in cooler RC1 is required to obtain maximum dehumidification of the process air. Now assuming operation of all four cooling stages at design set point, e.g. outlet temperature of -24 °F, the discharge temperature of the process air leaving the fourth cooling stage is assumed to be

$$T_{A5} = 436 \text{ °R;}$$

and considering the pressure loss through the cooling stages

$$P_{A5} = P_{A4} - \Delta P_{A4--A5} = 40.1 \text{ psia.}$$

An analysis of the dehumidification process like that made for scenario No.1 yields a specific humidity level of the process air leaving the fourth cooling stage equal to

$$SH_{A5} = 7.6 \times 10^{-5} \text{ lbm/lbm air.}$$

The mass of water removed is also found to be

$$\dot{m}_w = 16.5 \text{ lbm/sec;}$$

therefore, the mass flow rate of process air delivered to the flow legs is

$$\dot{m}_{A5} = \dot{m}_{A4} - \dot{m}_w = 1107.5 \text{ lbm/sec.}$$

Since the specific humidity of the process air changes, the air properties also change as defined by Eqs. 1, 2 and 3. Therefore, the properties of the process air at station A5 and subsquent downstream air supply stations are:

$$R_{A5} = 53.35 \frac{\text{ft-lbf}}{\text{lbm °R}},$$

$$C_{p_{A5}} = 0.24 \frac{\text{Btu}}{\text{lbm °R}},$$

and

$$\gamma_{A5} \simeq 1.4.$$

The airflow leaving RC1 is delivered to leg 2 where it is partially diverted at station A6 through the refrigeration turbines and into leg 1; thus establishing the leg 1 and 2 flow path configuration. The conditions at station A6 are as follows:

$$T_{A6} = T_{A5} = 436 \text{ °R (adiabatic flow)},$$

$$P_{A6} = P_{A5} - \Delta P_{A5\text{--}A6} = 39.3 \text{ psia},$$

and

$$\dot{m}_{A6} = \dot{m}_{A5} = 1107.5 \text{ lbm/sec}.$$

Consideration of the flow mixing process and of the turbine operating conditions is now given in determining the air flow rate delivered to the turbines, the turbine discharge temperature, and the number of open venturis required for this operating configuration.

The flow mixing process is again defined by Eq. 21. From Eq. 21

$$\dot{m}_{A11} T_{A11} + \dot{m}_{A8} T_{A8} = \dot{m}_{A12} T_{A12}.$$

Therefore,

$$\frac{\dot{m}_{A11}}{\dot{m}_{A8}} = \frac{T_{A12} - T_{A8}}{T_{A11} - T_{A12}}$$

where considering the general assumption of adiabatic flow,

$$T_{A12} = T_{A13} = 422.1 \text{ °R}$$

and

$$T_{A8} = T_{A7} = T_{A6} = T_{A5} = 436 \text{ °R}.$$

Since T_{A11} corresponds with the turbine discharge temperature, T_{A10}, which is dependent on the turbine performance characteristics as shown in the turbine performance map presented in Figure 43, a trial and error matching solution is used to determine turbine flow and discharge temperature. This solution also establishes the number of open venturis required for this configuration.

Table 2 shows turbine operating conditions for three flow conditions. Now using the rated flow conditions as a starting point, set

$$T_{A10} = 352 \text{ °R}$$

and

$$\dot{m}_{A9} = \dot{m}_{A10} = 288 \text{ lbm/sec.}$$

The corrected mass flow is defined by

$$\frac{\dot{m}_{A9}\sqrt{\theta}}{\delta}$$

where

$$\theta = T_{A9}/T_{ref} = 436/454 = 0.96$$

and

$$\delta = \frac{P_{A9}}{P_{ref}} = \frac{P_{A6} - \Delta P_{A6\text{--}A9}}{P_{ref}} = \frac{38.9}{38} = 1.02;$$

therefore,

$$\dot{m}_{corr} = 276.6 \text{ lbm/sec.}$$

In addition, the turbine temperature ratio is

$$T_{A10}/T_{A9} = 352/436 = 0.81.$$

Entering Figure 43 with $\dot{m}_{corr}$ and the above temperature ratio yields

$$P_{A10}/P_{A9} = 0.4.$$

From which,

$$P_{A10} = 15.6 \text{ psia}.$$

The venturi inlet pressure (P_{A13}), therefore, must correspond with P_{A10} (less any ducting losses). Assuming ducting pressure losses from station <u>A10</u> to <u>A13</u> equal to those presented in Table 14,

$$P_{A11} = 15.5 \text{ psia},$$

$$P_{A12} = 15.5 \text{ psia},$$

and

$$P_{A13} = 15.4 \text{ psia}.$$

Therefore, the number of open venturis corresponding to P_{A13} as determined from Eq. 13 is

$$N_v = 11.6.$$

However, the venturis are fixed area (non-variable); therefore set

$$N_v = 11$$

and determine the corresponding venturi inlet pressure from Eq. 13. The corresponding pressure is

$$P_{A13} = 16.2 \text{ psia.}$$

Again considering the pressure loss in the ducting

$$P_{A10} = P_{A13} + \Delta P_{A10--A13} = 16.4 \text{ psia.}$$

The turbine pressure ratio is now equal to

$$P_{A10}/P_{A9} = 0.42.$$

Now that the turbine pressure ratio is established for the selected venturi configuration, an iterative solution is used to determine the mass flow rate through the turbines and the turbine discharge temperature. The solution used is summarized as follows:

a. Select $\dot{m}_{A9}$.

b. Calculate $\dot{m}_{corr}$.

c. Determine T_{A10}/T_{A9} from Figure 43 (enter with P_{A10}/P_{A9} and $\dot{m}_{corr}$).

d. Calculate T_{A10} ($T_{A11} = T_{A10}$ assuming adiabatic flow).

e. Calculate $\dot{m}_{A11}/\dot{m}_{A8}$ (use T_{A11} and previously determined values of T_{A12} and T_{A8}).

f. Calculate $\dot{m}_{A11}$ and compare with value selected in a. above ($\dot{m}_{A11} + \dot{m}_{A8} = \dot{m}_{A12}$).

Based on the above solution,

$$T_{A10} = T_{A11} = 361.9\ °R,$$

$$\dot{m}_{A8} = \dot{m}_{A7} = 751.4\ \text{lbm/sec},$$

and, in turn,

$$\dot{m}_{A9} = \dot{m}_{A11} = \dot{m}_{A10} = 173.6\ \text{lbm/sec}.$$

It is noted that for this test scenario one operating turbine provides sufficient cooling capacity.

The leg 2 flow rate is

$$\dot{m}_{A6} - \dot{m}_{A9} = 933.9\ \text{lbm/sec}.$$

Since this exceeds the amount required for mixing, the balance is dumped to atmosphere through the load control valves located at station A6'. The amount dumped is

$$\dot{m}_{A6'} = \dot{m}_{A6} - \dot{m}_{A8} = 182.5\ \text{lbm/sec}.$$

Considering the duct pressure losses as presented in Table 14,

$$P_{A7} = P_{A6} - \Delta P_{A6\text{--}A7} = 38.8\ \text{psia}$$

and

$$P_{A8} = P_{A12} + \Delta P_{A8\text{--}A12} = 15.6\ \text{psia}.$$

This completes the basic air supply system configuration analysis. Attention is now directed to a similar analysis of the supporting exhaust system configuration.

4.4.3.3 Exhaust System Configuration. The basis for selection of the exhaust system configuration was previously discussed in paragraph 4.4.2.3. The required test cell pressure to be established and maintained for altitude simulation at 35,000 feet is

$$P_{cell} = P_{\infty} = 3.5 \text{ psia.}$$

Since high by-pass ratio turbofan engines have relatively low energy level exhaust gases, no pressure recovery by the diffuser is assumed for this example. Therefore, the exhaust duct pressure that must be established and maintained by the exhaust system is

$$P_{E1} = P_{cell} = 3.5 \text{ psia.}$$

The total exhaust gas flow at station E1 is equal to the engine exhaust gas flow plus test cell cooling airflow. For this example approximately ten percent cooling air is again assumed; therefore, set

$$\dot{m}_{ca} = 93 \text{ lbm/sec.}$$

Hence,

$$\dot{m}_{E1} = \dot{m}_{ca} + \dot{m}_{eg} = 1019.7 \text{ lbm/sec.}$$

The temperature and gas properties at station E1 are determined similarly as those in scenario No. 1 and are found to be

$$T_{E1} = 753.4\ ^{o}R,$$

$$C_{p_{E1}} \simeq 0.245 \frac{\text{Btu}}{\text{lbm}\ ^{o}\text{R}},$$

$$R_{E1} \simeq 53.81 \frac{\text{ft-lbf}}{\text{lbm °R}} ,$$

and

$$\gamma_{E1} \simeq 1.393.$$

Since the temperature of the exhaust gas stream is extremely low, all required exhaust gas cooling can be accomplished within cooler EC1; therefore, foresprays and aftersprays are not required for this configuration. The conditions at the inlet to EC1, station E3, are

$$\dot{m}_{E2} = \dot{m}_{E1} = 1019.7 \text{ lbm/sec},$$

$$T_{E2} = T_{E1} = 753.4 \text{ °R},$$

and

$$P_{E2} = P_{E1} - \Delta P_{E1--E2} = 3.4 \text{ psia}.$$

Since the foresprays are not utilized, no water is added to the exhaust gas stream; therefore, the gas properties at station E2 are the same as those at station E1.

Assuming cooling of the exhaust gas stream in EC1 to rated exhaust gas compressor inlet temperature, set

$$T_{E3} = 560 \text{ °R}.$$

In addition, since the pressure loss through EC1 is negligible (see Table 14)

$$P_{E3} = P_{E2} = 3.4 \text{ psia}.$$

All other gas properties at station E3 are the same as those at station E2. Now considering the general assumption of adiabatic flow, negligible pressure loss, and no water addition by the aftersprays, the conditions and gas properties at the inlet to the exhaust gas pressure control valve (station E4) are the same as those at station E3.

Typical exhaust gas compressor system performance limits for turbofan engine testing are presented in Figure 44. As shown in Figure 44 for an inlet pressure at the exhaust gas compressors on the order of 3.0 psia and for an exhaust gas flow on the order of 1000 lbm/sec, a two-stage exhaust compressor configuration utilizing four first-stage and two second-stage compressors is required. Therefore, for this example, compressors E121 through E124 (first-stage) and E211 and E212 (second-stage) are selected as the operating configuration. Other combinations of first, second, and third stage compressors could also be utilized. This configuration requires the use of intercooler WC12 to remove the heat of compression added by the first-stage compressors to the exhaust gas stream prior to its entry into the second-stage compressors.

Considering the pressure loss from the second-stage compressor discharge, station E11, to the atmospheric discharge stack, station E12,

$$P_{E11} = P_{E12} + \Delta P_{E11\text{--}E12} = 14.3 \text{ psia.}$$

The compressor inlet pressure is defined by

$$P_i = \frac{\dot{m}_i \; R \; T_i}{Q} \tag{28}$$

where $\dot{m}_i$ is equal to the total exhaust gas flow, T_i is equal to the compressor inlet temperature, and Q is the volumetric capacity of the compressor. Now assuming that intercooler WC12 cools the exhaust gas to

$$T_{sp(WC12)} = T_{E9} = T_{E10} = 560\ °R;$$

and for

$$\dot{m}_i = \dot{m}_{E10} = 1019.7\ \text{lbm/sec}$$

and

$$Q = 2{,}056{,}000\ \text{ft}^3/\text{min (capacity of}$$

two compressors)

Eq. 28 yields

$$P_i = P_{E10} = 6.2\ \text{psia.}$$

Therefore, the compressor pressure ratio is

$$PR = P_{E11}/P_{E10} = 2.3.$$

Entering Figure 40 with this pressure ratio and Q = 1,028,000 ft^3/min shows that the compressor efficiency for this operating condition is approximately

$$\eta_c = 0.71.$$

Now that both pressure ratio and efficiency have been determined, the compressor discharge temperature can be calculated from Eq. 26. Hence,

$$T_{E11} = T_{E12} = 768.9\ °R.$$

Continuing with the pressure loss analysis,

$$P_{E9} = P_{E10} + \Delta P_{E9--E10} = 6.3 \text{ psia},$$

$$P_{E8} = P_{E9} + \Delta P_{E8--E9} = 6.7 \text{ psia},$$

and

$$P_{E7} = P_{E8} + \Delta P_{E7--E8} = 6.7 \text{ psia}$$ (first-stage compressor discharge pressure).

The first-stage compressor inlet pressure is again determined from Eq. 28 where

$$\dot{m}_i = \dot{m}_{E6} = 1019.7 \text{ lbm/sec},$$

$$T_i = T_{E6} = T_{E5} = T_{E4} = 560\ °R,$$

and

$$Q = 4{,}112{,}000 \text{ ft}^3\text{/min}$$ (capacity of four compressors).

Hence,

$$P_{E6} = 3.1 \text{ psia}$$

and

$$PR = P_{E7}/P_{E6} = 2.2.$$

Again entering Figure 40 with PR = 2.2 and Q = 1,028,000 ft^3/min, the compressor efficiency is approximately

$$\eta_c = 0.68.$$

Therefore, from Eq. 26

$$T_{E7} = T_{E8} = 765.2\ °R.$$

Since the pressure loss from station E5 to E6 is negligible,

$$P_{E5} = P_{E6} = 3.1\ \text{psia}.$$

Therefore, CV.C.10 must throttle the pressure from 3.4 psia to 3.1 psia. This concludes the analysis of the required exhaust system configuration

4.4.3.4 Configuration Summary. The air supply system configuration utilizes the four first-stage air supply compressors, operation of all four RC1 cooling stages, and one refrigeration turbine. Airflow is delivered to the mixing header through flow path legs 1 and 2. After mixing, airflow is metered to the engine by eleven open venturis.

The exhaust system configuration utilizes a two-stage exhaust gas compressor configuration consisting of four first-stage compressors and two second-stage compressors. Test cell cooling air is induced directly into the test cell from atmosphere. Exhaust gas cooling is accomplished in EC1 with intercooling between the first-stage and second-stage compressors by WC12.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Mitchell, J. G., "New Test Capability For Propulsion System Testing", AIAA Paper 73-1283, AIAA/SAE 9th Propulsion Conference, Las Vegas, Nevada, November 1973.

2. Mitchell, J. G., "The Aeropropulsion Systems Test Facility", AIAA Paper 72-1034, AIAA 7th Aerodynamic Testing Conference, Palo Alto, California, September 1972.

3. Bates, W. R. and Edwards, Z. B., "The Aeropropulsion Systems Test Facility", AIAA Paper 77-913, AIAA/SAE 13th Propulsion Conference, Orlando, Florida, July 1977.

4. Lawley, M. W., Bond, D. C., and Rickard, J. R., "ASTF Test Instrumentation System", paper published in the Record of ICIASF '79, IEEE Publication 79CH 1500-8 AES, September 1979.

5. Mueller, B., Spinager, T., Wallstein, D., "Static Variable Frequency Starting and Drive System For Large Synchronous Motors", IEEE Publication 79CH, 1484-51A, IEEE/IAS 14th Annual Meeting, Cleveland, Ohio, September 1979.

6. Test Facilities Handbook. Eleventh Edition. Arnold Air Force Station, Tennessee; Arnold Engineering Development Center, 1979.

7. Huang, Francis F., Engineering Thermodynamics, Macmillan Publishing Co., Inc., New York, 1976.

8. U.S. Standard Atmosphere, 1962. National Aeronautics and Space Administration, United States Air Force, United States Weather Bureau, Washington, DC, December 1962.

9. Zucker, Robert D., Fundamentals of Gas Dynamics, Matrix Publishers, Inc., Champaign, Illinois, 1977.

10. Military Specification, MIL-E-50070, "Engines, Aircraft, Turbojet and Turbofan, General Specifications For", 15 October 1973.

11. Smith, R. E., Jr, and Wolff, H. E., "Accurate Measurement of Airflow Rate During Tests of Air-Breathing Propulsion Systems", AEDC-TR-68-22, March 1968.

12. Olson, Reuben M., Engineering Fluid Mechanics, Second Edition, International Textbook Company, Scranton, Pennsylvania, 1968.

13. Moran, A. H., Private Communication, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, March 1982.

14. Steam Tables. "Thermodynamic Properties of Water Including Vapor, Liquid and Solid Phases", John Wiley and Sons Inc., 1969.

15. Randall, R. E. "Basis for Selecting the Configuration and Capabilities of the Aeropropulsion Systems Test Facility", ASTF-ER-47, October 1974.

16. Process Calculations For the Aeropropulsion Systems Test Facility (ASTF), Volume 111-J.1, Section 1, July 31, 1973.

APPENDIXES

APPENDIX A. TABLES

TABLE 1

AIR SUPPLY COMPRESSOR/DRIVE MOTOR UNIT
OPERATING CONDITIONS

	First Stage Units	Second Stage Units
COMPRESSORS		
Rated Operating Conditions (ref to dry air)		
Inlet Volume, CFM	242,000	150,000
Inlet Temperature, °F	80	80
Inlet Pressure, psia	13.8	13.8
Pressure Ratio, Discharge Total Pressure / Inlet Total Pressure	3.19	3.19
Speed, RPM	3,600	3,600
Min. Adiabatic Efficiency, %	84	84
Extreme Operating Conditions		
Min. Inlet Air Temperature, °F	-10	-10
Max. Inlet Air Temperature, °F	105	105
Min. Inlet Air Pressure, psia	4.8	4.8
Max. Inlet Air Pressure, psia	14.5	50
Max. Discharge Pressure, psia	50	150
DRIVE MOTORS		
Horsepower	27,500	52,500
Speed, RPM	3,600	3,600
Full Load Efficiency, %	97.98	97.95

TABLE 2

REFRIGERATION TURBINE OPERATING CONDITIONS

Parameter	Low Flow		Rated Flow		High Flow	
	Turbine	Compressor	Turbine	Compressor	Turbine	Compressor
Inlet Pressure, psia	49	14.5	38	14.5	27	14.5
Inlet Temperature, °F	-24	75	-6	75	-9	75
Discharge Pressure, psia	16.6	16	12.8	21.9	15	19.4
Discharge Temperature, °F	-71	94	-108	165	-65	136
Flow, lbm/sec	60	141	288	319	300	266
Speed, RPM	1820		4000		3300	
Horsepower	933	918	9870	9740	5600	5550
Efficiency, %	40	76	85	76	80	76

TABLE 3

HEATER H1 OPERATING CONDITIONS

Parameter	Minimum[1] Heat Load	Maximum[2] Outlet Temp	Design Point and[3] Max Heat Load
Air Flow Rate, lbm/sec	200	290	1,100
Air Inlet Temp, ^{o}F	190	190	190
Air Outlet Temp, ^{o}F	307	850	700
Air Inlet Pressure, psia	150 max 35 min	150 max 35 min	50

[1]Conditions corresponding to minimum heat load to the process air.

[2]Conditions for obtaining maximum outlet air temperature.

[3]Conditions corresponding to design point and maximum heat load.

TABLE 4

HEATER H2 OPERATING CONDITIONS

Parameter	Minimum[1] Heat Load	Maximum[2] Heat Load	Maximum[3] Outlet Temp	Design Point Conditions
Air Flow Rate, lbm/sec	200	1,100	400	1,100
Air Inlet Temp, ^{o}F	680	680	680	680
Air Outlet Temp, ^{o}F	786	1,150	1,200	1,100
Air Inlet Pressure, psia	150 max 35 min	150 max 35 min	150 max 35 min	50

[1]Conditions corresponding to minimum heat load to process air.

[2]Conditions corresponding to maximum heat load to process air.

[3]Conditions for obtaining maximum outlet air temperature.

TABLE 5

EXHAUST GAS COMPRESSOR/DRIVE MOTOR UNIT OPERATING CONDITIONS

	First Stage	Second/Third Stage
EXHAUSTERS		
Rated Operating Conditions (ref to dry air)		
Inlet Volume Flow*, CFM	1,000,000	1,000,000
Inlet Temperature, °F	100	100
Pressure Ratio, $\frac{\text{Discharge Total Pressure}}{\text{Inlet Total Pressure}}$	3.5	3.5
Min Adiabatic Efficiency*, %	82	82
Speed, RPM	2,290	2,290
Extreme Design Conditions		
Min Inlet Temperature, °F	35	-15
Max Inlet Temperature, °F	180	180
Min Inlet Pressure, psia	0.35	--
Max Inlet Pressure, psia	--	9.0
Min Discharge Pressure, psia	0.86	--
Max Discharge Temperature, °F	500	500
Max Discharge Pressure, psia	--	14.6

TABLE 5 (continued)

	First Stage	Second/Third Stage
DRIVE MOTORS		
Horsepower	27,500	44,000
Speed, RPM	3,600	3,600
Full Load Efficiency, %	97.5	97.5

*For inlet pressures of 1.2 psia to 9.0 psia

TABLE 6

EXHAUST GAS INTERCOOLER DESIGN AND OPERATING CONDITIONS

Intercooler	Design Inlet	Design Outlet	Actual Inlet Conditions Possible (Range)
<u>WC11 and WC12</u>			
Gas Flow, Including Water Vapor, lbm/sec	900	as obtained	0 to 1820
Gas Pressure, psia	12.2	11.7 min.	1 to 13
Gas Temperature, ^{o}F	433	142 max.	100 to 500
Specific Humidity, gr/lb dry gas	1960	as obtained	--
<u>WC21</u>			
Gas Flow, Including Water Vapor, lbm/sec	660	as obtained	0 to 1380
Gas Pressure, psia	12.0	11.29	4 to 15
Gas Temperature, ^{o}F	424	140 max.	100 to 500
Specific Humidity, gr/lb dry gas	1960	as obtained	--

TABLE 7

CONFIGURATION AND CONTROL VALVE TABULATION

Valve No.	Nominal Dia (ft)	Type Actuator	Stroke Time (sec) Norm/Emerg	Max. Temp. (°F) Ups/Dns[1]	Min. Temp. (°F) Ups/Dns	Max. Press (psia) Ups/Dns	Min. Press (psia) Ups/Dns
Butterfly Valves							
CV.C.1A*[2]	2	Hydraulic	1/--	408/650	-24/100	150/150	0/0
CV.C.1B*	4	Hydraulic	1/--	408/650	-24/100	150/150	0/0
CV.C.1C*	8	Hydraulic	1/--	408/650	-24/100	150/150	0/0
CV.C.2A*	2	Hydraulic	1/--	408/408	-24/-150	150/16	0/13.7
CV.C.2B*	4	Hydraulic	1/--	408/408	-24/-150	150/16	0/13.7
CV.C.2C*	7	Hydraulic	1/--	408/408	-24/-150	150/16	0/13.7
CV.C.3A*	2	Hydraulic	1/--	850/850	-15/-100	150/150	0/0
CV.C.3B*	4	Hydraulic	1/--	850/850	-15/-100	150/150	0/0
CV.C.3C*	7	Hydraulic	1/--	850/850	-15/-100	150/150	0/0
CV.C.4A*	1.5	Hydraulic	1/--	850/1200	-15/-15	150/16	0/13.7
CV.C.4B*	3	Hydraulic	1/--	850/1200	-15/-15	150/16	0/13.7
CV.C.4C*	5.5	Hydraulic	1/--	850/1200	-15/-15	150/16	0/13.7

TABLE 7 (continued)

Valve No.	Nominal Dia (ft)	Type Actuator	Stroke Time (sec) Norm/Emerg	Max. Temp. (°F) Ups/Dns[1]	Min. Temp. (°F) Ups/Dns	Max. Press (psia) Ups/Dns	Min. Press (psia) Ups/Dns
CV.C.5A*	2	Hydraulic	1/--	1200/1200	-15/-15	150/150	0/0
CV.C.5B*	4	Hydraulic	1/--	1200/1200	-15/-15	150/150	0/0
CV.C.5C*	7	Hydraulic	1/--	1200/1200	-15/-15	150/150	0/0
CV.C.6A*	1.5	Hydraulic	1/--	1200/1200	-15/-15	150/16	0/13.7
CV.C.6B*	3	Hydraulic	1/--	1200/1200	-15/-15	150/16	0/13.7
CV.C.6C*	5.5	Hydraulic	1/--	1200/1200	-15/-15	150/16	0/13.7
CV.EC1.1A*	6	Hydraulic	10/--	180/180	-15/-15	25/16	0/13.7
CV.EC1.1B*	12.5	Hydraulic	10/--	180/180	-15/-15	25/16	0/13.7
CV.C1.1*	2.5	Hydraulic	5/--	105/650	-15/-100	14.5/150	13.7/0
CV.C2.1*	2.5	Hydraulic	5/--	105/650	-15/-100	14.5/150	13.7/0
CV.C1.3*	2.5	Electric	30/--	650/650	-100/-100	150/150	0/0
CV.C2.3*	2.5	Electric	30/--	650/650	-100/-100	50/50	0/0
CV.A21.1	3	Hydraulic	1/--	408/408	-15/-15	150/16	2.5/13.7
CV.A22.1	3	Hydraulic	1/--	408/408	-15/-15	150/16	2.5/13.7

TABLE 7 (continued)

Valve No.	Nominal Dia (ft)	Type Actuator	Stroke Time (sec) Norm/Emerg	Max. Temp. (°F) Ups/Dns[1]	Min. Temp. (°F) Ups/Dns	Max. Press (psia) Ups/Dns	Min. Press (psia) Ups/Dns
CV.C1.2*	3	Electric	30/--	650/650	-100/-100	150/150	0/0
CV.C2.2*	3	Electric	30/--	650/650	-100/-100	50/50	0/0
CV.A11.1	4	Hydraulic	1/--	408/408	-15/-15	50/16	2.5/13.7
CV.A12.1	4	Hydraulic	1/--	408/408	-15/-15	50/16	2.5/13.7
CV.A13.1	4	Hydraulic	1/--	408/408	-15/-15	50/16	2.5/13.7
CV.A14.1	4	Hydraulic	1/--	408/408	-15/-15	50/16	2.5/13.7
CV.E111.1	6	Hydraulic	1/--	180/180	-15/-15	14.5/14.5	0.9/0
CV.E112.1	6	Hydraulic	1/--	180/180	-15/-15	14.5/14.5	0.9/0
CV.E113.1	6	Hydraulic	1/--	180/180	-15/-;5	14.5/14.5	0.9/0
CV.E114.1	6	Hydraulic	1/--	180/180	-15/-15	14.5/14.5	0.9/0
CV.E121.1	6	Hydraulic	1/--	180/180	-15/-15	14.5/14.5	0.9/0
CV.E122.1	6	Hydraulic	1/--	180/180	-15/-15	14.5/14.5	0.9/0
CV.E123.1	6	Hydraulic	1/--	180/180	-15/-15	14.5/14.5	0.9/0
CV.E124.1	6	Hydraulic	1/--	180/180	-15/-15	14.5/14.5	0.9/0

TABLE 7 (continued)

Valve No.	Nominal Dia (ft)	Type Actuator	Stroke Time (sec) Norm/Emerg	Max. Temp. (^{o}F) Ups/Dns[1]	Min. Temp. (^{o}F) Ups/Dns	Max. Press (psia) Ups/Dns	Min. Press (psia) Ups/Dns
CV.E211.1	6	Hydraulic	1/--	180/180	-15/-15	14.5/14.5	3.6/0.9
CV.E212.1	6	Hydraulic	1/--	180/180	-15/-15	14.5/14.5	3.6/0.9
CV.E213.1	6	Hydraulic	1/--	180/180	-15/-15	14.5/14.5	3.6/0.9
CV.E311.1	6	Hydraulic	1/--	105/108	-15/-15	14.5/14.5	13.5/3.6
CV.RC3.1*	15	Hydraulic	10/--	105/425	-15/-100	14.5/50	13.7/0
AV.C.1*	1.5	Electric	30/--	605/605	-100/-100	150/16	0/13.7
AV.A21.1	3.5	Hydraulic	30/2	408/408	-15/-15	150/150	2.5/2.5
AV.A22.1	3.5	Hydraulic	30/2	408/408	-15/-15	150/150	2.5/2.5
AV.TC1.1	4	Hydraulic	30/0.25	408/260	-24/-24	150/50	0/0
AV.TC2.1	4	Hydraulic	30/0.25	408/260	-24/-24	150/50	0/0
AV.TC3.1	4	Hydraulic	30/0.25	408/260	-24/-24	150/50	0/0
AV.TC4.1	4	Hydraulic	30/0.25	408/260	-24/-24	150/50	0/0
AV.TC5.1	4	Hydraulic	30/0.25	408/260	-24/-24	150/50	0/0
AV.A11.1	4.5	Hydraulic	30/2	408/408	-15/-15	50/50	2.5/2.5

TABLE 7 (continued)

Valve No.	Nominal Dia (ft)	Type Actuator	Stroke Time (sec) Norm/Emerg	Max. Temp. (°F) Ups/Dns[1]	Min. Temp. (°F) Ups/Dns	Max. Press (psia) Ups/Dns	Min. Press (psia) Ups/Dns
AV.A12.1	4.5	Hydraulic	30/2	408/408	-15/-15	50/50	2.5/2.5
AV.A13.1	4.5	Hydraulic	30/2	408/408	-15/-15	50/50	2.5/2.5
AV.A14.1	4.5	Hydraulic	30/2	408/408	-15/-15	50/50	2.5/2.5
AV.A.4	5	Electric	60/--	408/408	-15/-15	150/150	2.5/2.5
AV.A.5	5	Electric	60/--	408/408	-15/-15	150/150	2.5/2.5
AV.C1.3*	6	Electric	60/--	650/1020	-100/-15	150/150	0/0
AV.A11.2	7	Electric	60/--	105/105	-15/-15	14.5/14.5	13.2/4.8
AV.A12.2	7	Electric	60/--	105/105	-15/-15	14.5/14.5	13.2/4.8
AV.A13.2	7	Electric	60/--	105/105	-15/-15	14.5/14.5	13.2/4.8
AV.A14.2	7	Electric	60/--	105/105	-15/-15	14.5/14.5	13.2/4.8
AV.A.2	7	Electric	60/--	105/105	-24/-15	50/50	2.5/4.8
AV.A.3	7	Electric	60/--	105/408	-24/-24	50/150	2.5/-
AV.A.6	8	Electric	60/--	408/408	-15/-24	150/150	2.5/0
AV.A.7	8	Electric	60/--	244/408	-15/-15	50/150	2.5/2.5

TABLE 7 (continued)

Valve No.	Nominal Dia (ft)	Type Actuator	Stroke Time (sec) Norm/Emerg	Max. Temp. (°F) Ups/Dns[1]	Min. Temp. (°F) Ups/Dns	Max. Press (psia) Ups/Dns	Min. Press (psia) Ups/Dns
AV.A.1	9	Electric	60/--	105/105	-15/-15	14.5/50	13.2/4.8
AV.E.7	10	Electric	60/--	105/180	-15/-15	14.5/14.5	13.5/13.6
AV.ECl.1	10	Electric	120/--	2500/400	-65/-65	25/25	0/0
AV.ECl.2	10	Electric	120/--	400/180	-65/-15	25/25	0/0
AV.Cl.1	10	Electric	60/--	650/650	-100/-100	150/150	0/0
AV.E.6	13	Electric	60/--	180/180	-15/-15	14.5/14.5	3.6/3.6
AV.E111.1	13	Electric	60/--	180/180	-15/-15	14.5/14.5	0/0
AV.E112.1	13	Electric	60/--	180/180	-15/-15	14.5/14.5	0/0
AV.E113.1	13	Electric	60/--	180/180	-15/-15	14.5/14.5	3.6/3.6
AV.E114.1	13	Electric	60/--	180/180	-15/-15	14.5/14.5	3.6/3.6
AV.E121.1	13	Electric	60/--	180/180	-15/-15	14.5/14.5	3.6/3.6
AV.E122.1	13	Electric	60/--	180/180	-15/-15	14.5/14.5	3.6/3.6
AV.E123.1	13	Electric	60/--	180/180	-15/-15	14.5/14.5	3.6/3.6
AV.E124.1	13	Electric	60/--	180/180	-15/-15	14.5/14.5	3.6/3.6

TABLE 7 (continued)

Valve No.	Nominal Dia (ft)	Type Actuator	Stroke Time (sec) Norm/Emerg	Max. Temp. (°F) Ups/Dns[1]	Min. Temp. (°F) Ups/Dns	Max. Press (psia) Ups/Dns	Min. Press (psia) Ups/Dns
AV.E211.1	13	Electric	60/--	180/180	-15/-15	14.5/14.5	0.9/0.9
AV.E212.1	13	Electric	60/--	180/180	-15/-15	14.5/14.5	0.9/0.9
AV.E213.1	13	Electric	60/--	180/180	-15/-15	14.5/14.5	0.9/0.9
AV.E311.1	13	Electric	60/--	180/180	-15/-15	14.5/14.5	0.9/3.6
AV.TC.1*	13	Electric	60/--	105/408	-150/-150	50/16	0/13.7
AV.TC.2*	13	Electric	60/--	105/650	-150/-150	50/150	0/0
AV.C2.1	15	Electric	70/--	650/650	-100/-100	150/150	0/0
AV.RC3.1	15	Electric	60/--	650/650	-100/-100	50/50	0/0
AV.E.8	16	Electric	60/--	425/425	-15/-15	16/14.5	3.6/3.6
AV.E.9	16	Electric	60/--	425/425	-15/-15	16/16	3.6/13.7
AV.E.1	18	Electric	60/--	180/180	-15/-15	14.5/14.5	0.9/0.9
AV.E.3	18	Electric	60/--	180/180	-15/-15	14.5/14.5	0.9/0.9
AV.E.4	32	Electric	60/--	180/180	-15/-15	14.5/14.5	0/0.9
AV.H1.1	4	Electric	60/--	408/408	-15/-15	150/150	0/0

TABLE 7 (continued)

Valve No.	Nominal Dia (ft)	Type Actuator	Stroke Time (sec) Norm/Emerg	Max. Temp. (°F) Ups/Dns[1]	Min. Temp. (°F) Ups/Dns	Max. Press (psia) Ups/Dns	Min. Press (psia) Ups/Dns
AV.H1.2	4	Electric	60/--	408/408	-15/-15	150/150	0/0
AV.H1.3	4	Electric	60/--	408/408	-15/-15	150/150	0/0
AV.H1.4	4	Electric	60/--	408/408	-15/-15	150/150	0/0
AV.H2.1	4	Electric	60/--	850/850	-15/-15	150/150	0/0
AV.H2.2	4	Electric	60/--	850/850	-15/-15	150/150	0/0
AV.H2.3	4	Electric	60/--	850/850	-15/-15	150/150	0/0
AV.H2.4	4	Electric	60/--	850/850	-15/-15	150/150	0/0
<u>Special Valves</u>							
CV.TC1.1*	4	Hydraulic	60/--	850/850	-15/-15	150/150	0/0
CV.TC2.1*	4	Hydraulic	60/--	850/850	-15/-15	150/150	0/0
CV.TC3.1*	4	Hydraulic	60/--	850/850	-15/-15	150/150	0/0
CV.TC4.1*	4	Hydraulic	60/--	850/850	-15/-15	150/150	0/0
CV.TC5.1*	4	Hydraulic	60/--	850/850	-15/-15	150/150	0/0
CV.C.10*	See Note 3	Hydraulic	1/--	850/850	-15/-15	150/150	0/0

TABLE 7 (continued)

Valve No.	Nominal Dia (ft)	Type Actuator	Stroke Time (sec) Norm/Emerg	Max. Temp (°F) Ups/Dns[1]	Min. Temp (°F) Ups/Dns	Max. Press (psia) Ups/Dns	Min. Press (psia) Ups/Dns
AV.C1.2	24	Hydraulic	1/--	850/850	-15/-15	150/150	0/0
AV.C2.2	26	Hydraulic	1/--	850/850	-15/-15	150/150	-/0

[1] Ups - Upstream; Dns - Downstream

[2] Valves controlled by Automatic Test Control System (ATCS)

[3] A 45-foot diameter assembly with ten louver elements (CV.C10A - 10H, 10J, 10K) 5.5 feet by 14 feet each

TABLE 8

ATCS CONTROL PARAMETERS

Control Parameter	Control Purpose
Engine Inlet Pressure	Establish simulated Mach No. and altitude
Engine Inlet Temperature	
Test Cell Ambient Pressure	
Test Cell Cooling Air Flow	Protect engine and test cell instrumentation
Test Cell Secondary Air Flow	
Supply Leg 2 Pressure	Maintain constant mass flow in legs 2, 3, and 4 to maintain steady state air supply compressor and heater operation
Supply Leg 3/Supply Leg 2 (mass flow ratio)	
Supply Leg 4/Supply Leg 3 (mass flow ratio)	

TABLE 9

POWER TRANSFORMER RATING AND LOAD DATA

Transformer No.	Load Rating (MVA) OA/FA/FOA	Voltage Rating (KV) Primary	Voltage Rating (KV) Secondary	Winding Connection Primary	Winding Connection Secondary
Air Supply Area					
A1, 1st Stage Comp	50/66.7/83.8	161	13.8/13.8	Delta	Wye/Wye
A2, 2nd Stage Comp	50/66.7/83.3	161	13.8/13.8	Delta	Wye/Wye
A3, Support Systems	35/46.6/58.3	161	6.9/6.9	Delta	Wye/Wye
A4, VFSS Input	39.54/--/--	161	5.18/5.18	Delta	Delta/Wye
AA, VFSS Output	41.66/--/--	2.73/2.73/ 2.73/2.73	13.8	Wye/Del Del/Wye	Wye
Exhaust Area					
E1, VFSS Input	39.54/--/--	161	5.18/5.18	Delta	Delta/Wye
E2, 1st Stage Exh Input	50/66.7/83.3	161	13.8/13.8	Delta	Wye/Wye
E3, 1st Stage Exh Input	50/66.7/83.3	161	13.8/13.8	Delta	Wye/Wye
E4, 2nd Stage Exh Input	40/53.3/66.7	161	13.8/13.8	Delta	Wye/Wye
E5, 3rd Stage Exh Input	40/53.3/66.7	161	13.8/13.8	Delta	Wye/Wye
E6, Support Systems	30/40/50	161	6.9/6.9	Delta	Wye/Wye
EA, VFSS Output	41.66/--/--	2.73/2.73/ 2.73/2.73	13.8	Wye/Del Del/Wye	Wye

TABLE 10

COOLING TOWER SYSTEM PUMP DATA

Pump Category	Pump No.	Head, Ft.	Capacity, GPM	Motor Horsepower
Return Basin	P1	135	5,000	200
	P2	135	10,000	450
	P3	135	15,000	700
	P4	135	25,000	1000
	P5	135	50,000	2250
	P6	135	50,000	2250
	P7	135	50,000	2250
Cooling Tower Basin	P11	250	5,000	400
	P12	250	10,000	800
	P13	250	15,000	1250
	P14	250	25,000	2000
	P15	250	50,000	4000
	P16	250	50,000	4000
	P17	250	50,000	4000

TABLE 11

PROCESS AIR VALVE HYDRAULIC SYSTEMS

Hydraulic Subsystem No.	Process Air Valves Served	Flow Rate (GPM)	Hydraulic Console No.
1	CV.A11.1 CV.A12.1 CV.A13.1 CV.A14.1 AV.A11.1 AV.A12.1 AV.A13.1 AV.A14.1	352	HC.A1.1
2	CV.A21.1 CV.A22.1 AV.A21.1 AV.A22.1	206	HC.A2.1
3	CV.C.1A CV.C.1B CV.C.1C CV.C1.1 CV.C2.1	749	HC.C.1 and HC.C.2
4	CV.C.2A CV.C.2B CV.C.2C	574	HC.C.3 and HC.C.4

TABLE 11 (continued)

Hydraulic Subsystem No.	Process Air Valves Served	Flow Rate (GPM)	Hydraulic Console No.
5	CV.C.3A CV.C.3B CV.C.3C	647	HC.C.5 and HC.C.6
6	CV.C.4A CV.C.4B CV.C.4C	42	HC.C.12
7	CV.C.5A CV.C.5B CV.C.5C	647	HC.C.14 and HC.C.15
8	CV.C.6A CV.C.6B CV.C.6C	419	HC.C.16
9	AV.TC1.1 AV.TC2.1 AV.TC3.1 AV.TC4.1 AV.TC5.1 CV.TC1.1 CV.TC2.1	226	HC.TC.1

TABLE 11 (continued)

Hydraulic Subsystem No.	Process Air Valves Served	Flow Rate (GPM)	Hydraulic Console No.
9 (cont'd)	CV.TC3.1 CV.TC4.1 CV.TC5.1 CV.RC3.1		
10	CV.C.10A CV.C.10B	400	HC.C.7
11	CV.C.10C CV.C.10D	400	HC.C.8
12	CV.C.10E CV.C.10K	400	HC.C.9
13	CV.C.10H CV.C.10J	400	HC.C.10
14	CV.C.10F CV.C.10G	400	HC.C.11
15	CV.EC1.1A CV.EC1.1B	80	HC.EC1.1

TABLE 11 (continued)

Hydraulic Subsystem No.	Process Air Valves Served	Flow Rate (GPM)	Hydraulic Console No.
16	CV.E111.1 CV.E112.1 CV.E113.1 CV.E114.1	220	HC.E.1
17	CV.E121.1 CV.E122.1 CV.E123.1 CV.E124.1	220	HC.E.2
18	CV.E211.1 CV.E212.1 CV.E213.1 CV.E311.1 AV.E4	353	HC.E.3

TABLE 12

STANDARD AIR SUPPLY OPERATING CONFIGURATIONS

Test Cell Inlet Temperature Range, °F	Compressor Configuration	Mixing Legs	Leg Temperature, °F
-108 to 200	Single-stage	Leg 1 (via ref. turbines)	-108 to -24
		Leg 2 (by passing ref turbines and heaters)	- 24 to 200
	Single-stage[1] plus atmospheric	Leg 1	-108 to -24
		Leg 2	- 24 to 200
		Leg 5	38
-24 to 630	Single-stage	Leg 2	- 24 to 200
		Leg 3	200 to 630
	Single-stage[1] plus atmospheric	Leg 2	- 24 to 200
		Leg 3	200 to 630
		Leg 5	38
200 to 1020	Single-stage	Leg 3 (via one heater)	200 to 630
		Leg 4 (via both heaters)[2]	630 to 1020
-24 to 630	Two-stage	Leg 2	- 24 to 200
		Leg 3	200 to 630
200 to 1020	Two-stage	Leg 3	200 to 630
		Leg 4[2]	630 to 1020

[1]Test cell C2 only

[2]Test Cell C1 only

TABLE 13

TEST SCENARIO NO.1 EQUIVALANT PRESSURE LOSS

COEFFICIENTS AND EQUIVALANT DIAMETERS

	K	D_e (feet)
AIR SUPPLY SYSTEM STATIONS		
A1 to A2	2.74	7
A3 to A3'	4.6	4.5
A3' to A4	9.64	9
A4 to A5	1.63	9
A5 to A9	2.24	8
A9 to A6	1.13	8
A6 to A7	13.86	8
A7 to A8	3.25	9
A9 to A10	6.6	9
A11 to A13	1.4	9
A12 to A13	1.5	9
A13 to A14	2.15	9
A15 to 2	0.43	22
EXHAUST SYSTEM STATIONS		
E1 to E2	0.14	24
E2 to E3	0.04	24
E3 to E4	37.5	65
E4 to E5	33.21	65
E5 to E6	0.28	65
E7 to E8	4.7	32
E9 to E10	0.22	10

TABLE 14

TEST SCENARIO NO.2 PRESSURE LOSS SUMMARY

	Pressure Loss (psi)
AIR SUPPLY SYSTEM STATIONS	
A1 to A2	0.3
A3 to A4	1.9
A4 to A5	2.3
A5 to A6	0.8
A6 to A7	0.5
A6 to A9	0.4
A8 to A12	0.1
A10 to A11	0.1
A11 to A12	0
A12 to A13	0.1
EXHAUST SYSTEM STATIONS	
E1 to E2	0.1
E2 to E3	0
E3 to E4	0
E5 to E6	0
E7 to E8	0
E8 to E9	0.4
E9 to E10	0.1
E11 to E12	0.1

APPENDIX B. FIGURES

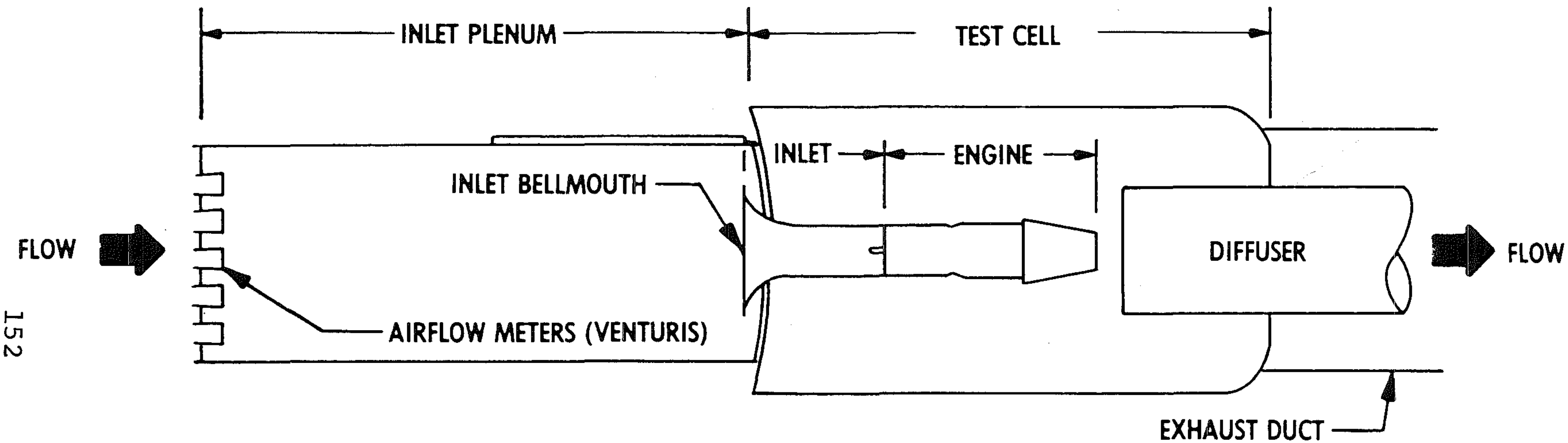


Figure 1. Direct-Connect Test Arrangement

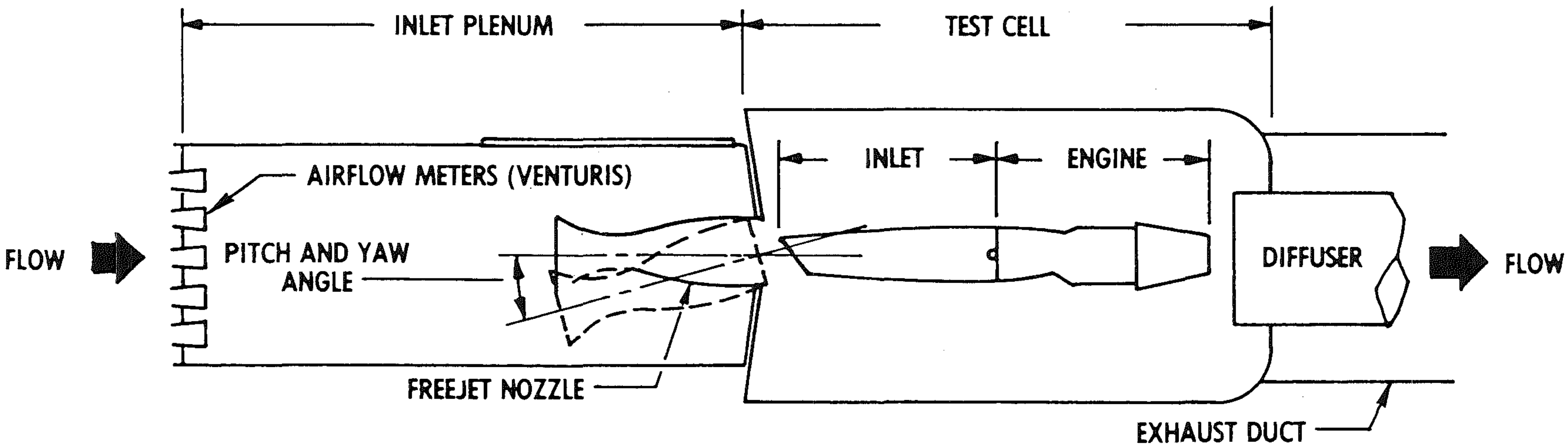


Figure 2. Freejet Test Arrangement.

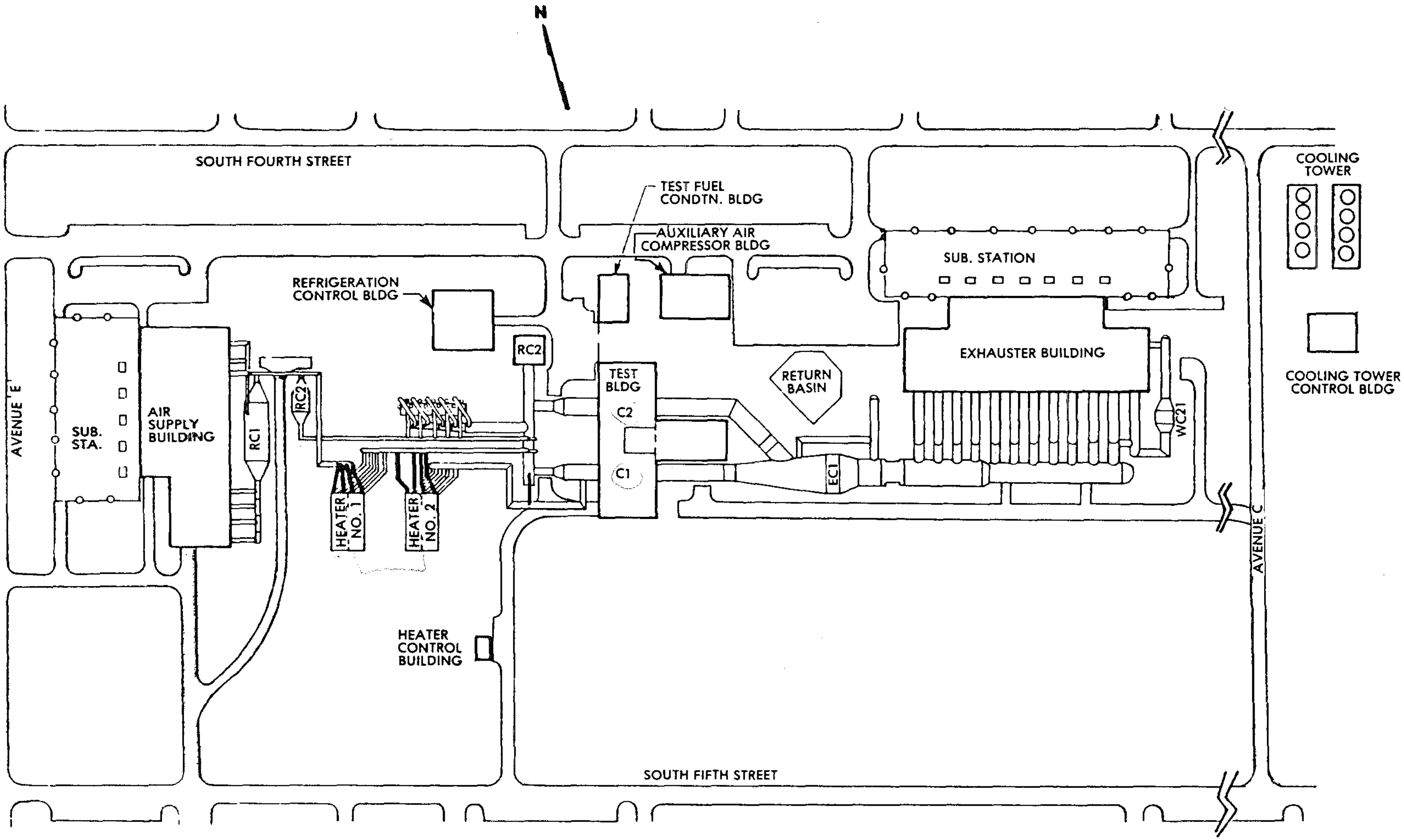
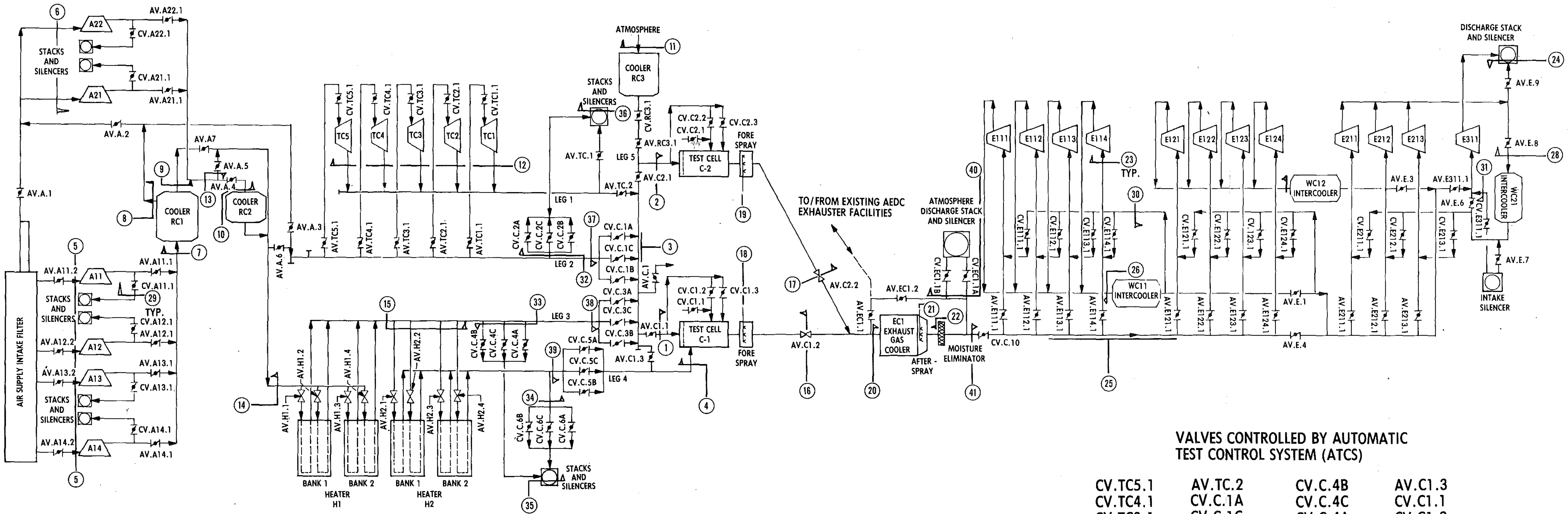


Figure 3. Facility Site Plan View.



VALVES CONTROLLED BY AUTOMATIC TEST CONTROL SYSTEM (ATCS)

CV.TC5.1	AV.TC.2	CV.C.4B	AV.C1.3
CV.TC4.1	CV.C.1A	CV.C.4C	CV.C1.1
CV.TC3.1	CV.C.1C	CV.C.4A	CV.C1.2
CV.TC2.1	CV.C.1B	CV.C.5A	CV.C1.3
CV.TC1.1	CV.C.3A	CV.C.5C	CV.EC1.1A
CV.C2.1	CV.C.3C	CV.C.5B	CV.EC1.1B
CV.C2.2	CV.C.3B	CV.C.6B	CV.C.10
CV.C2.3	CV.C.2A	CV.C.6C	
CV.RC3.1	CV.C.2C	CV.C.6A	
AV.TC.1	CV.C.2B	AV.C.1	

Figure 4. Facility Systems Schematic.

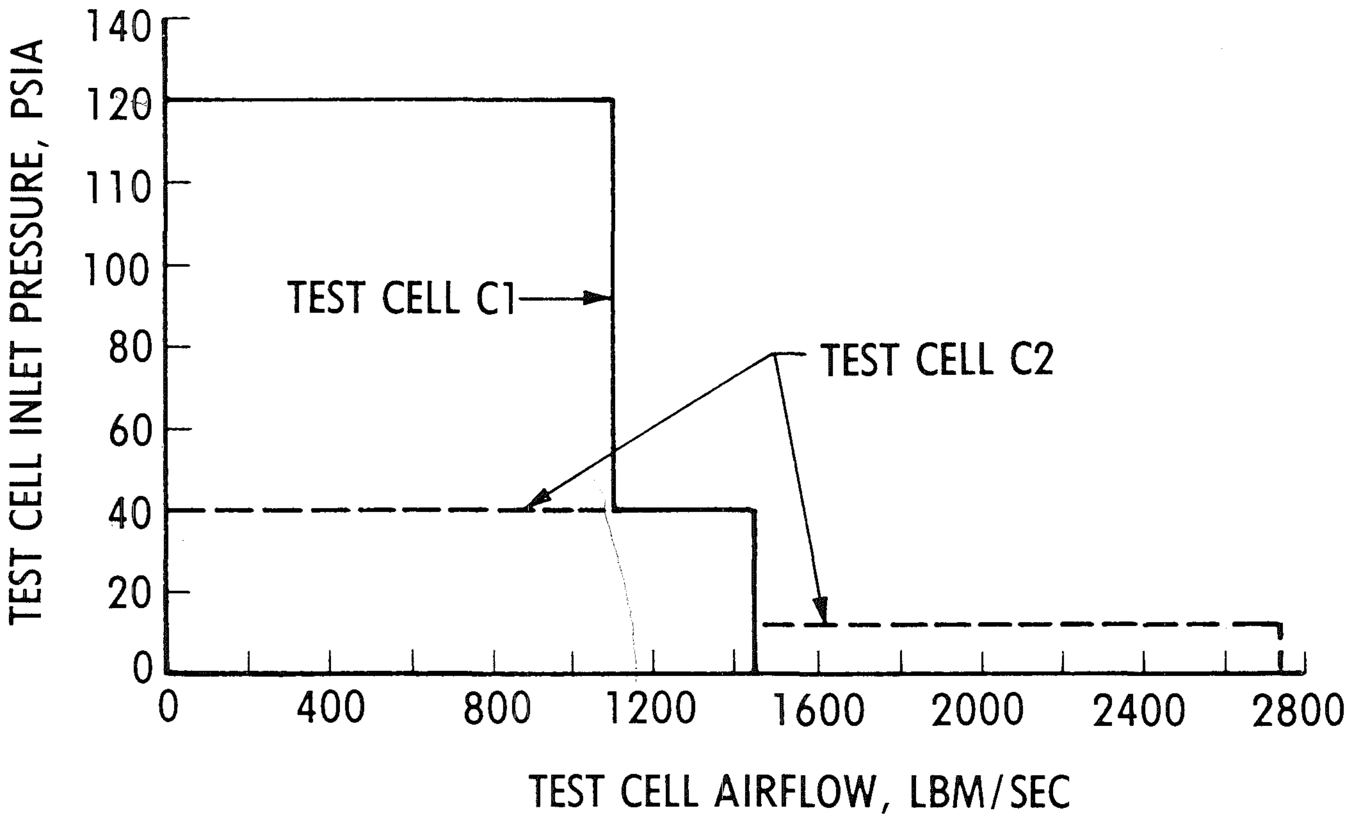


Figure 5. Air Supply System Pressure Capability.

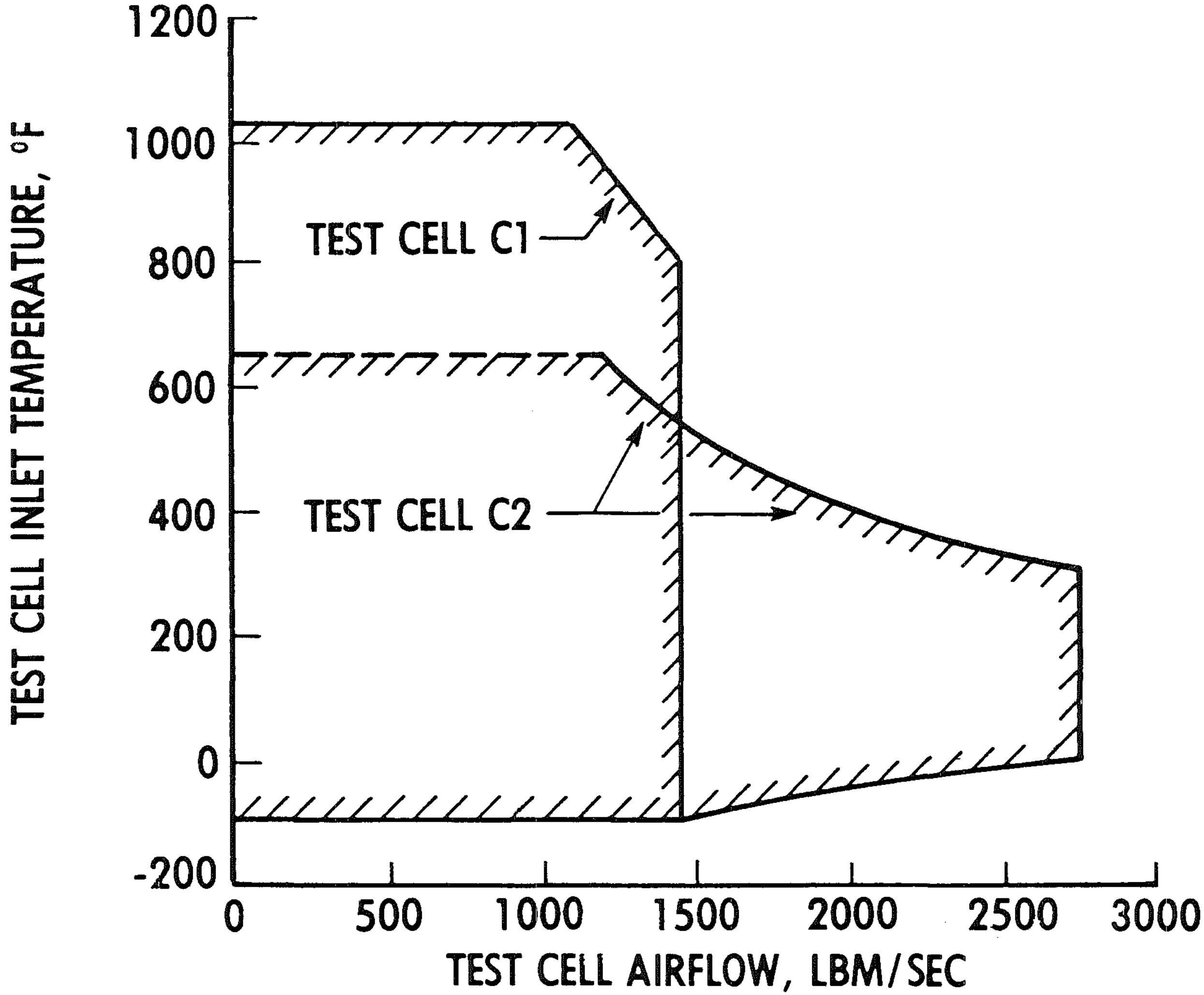


Figure 6. Air Supply System Temperature Capability.

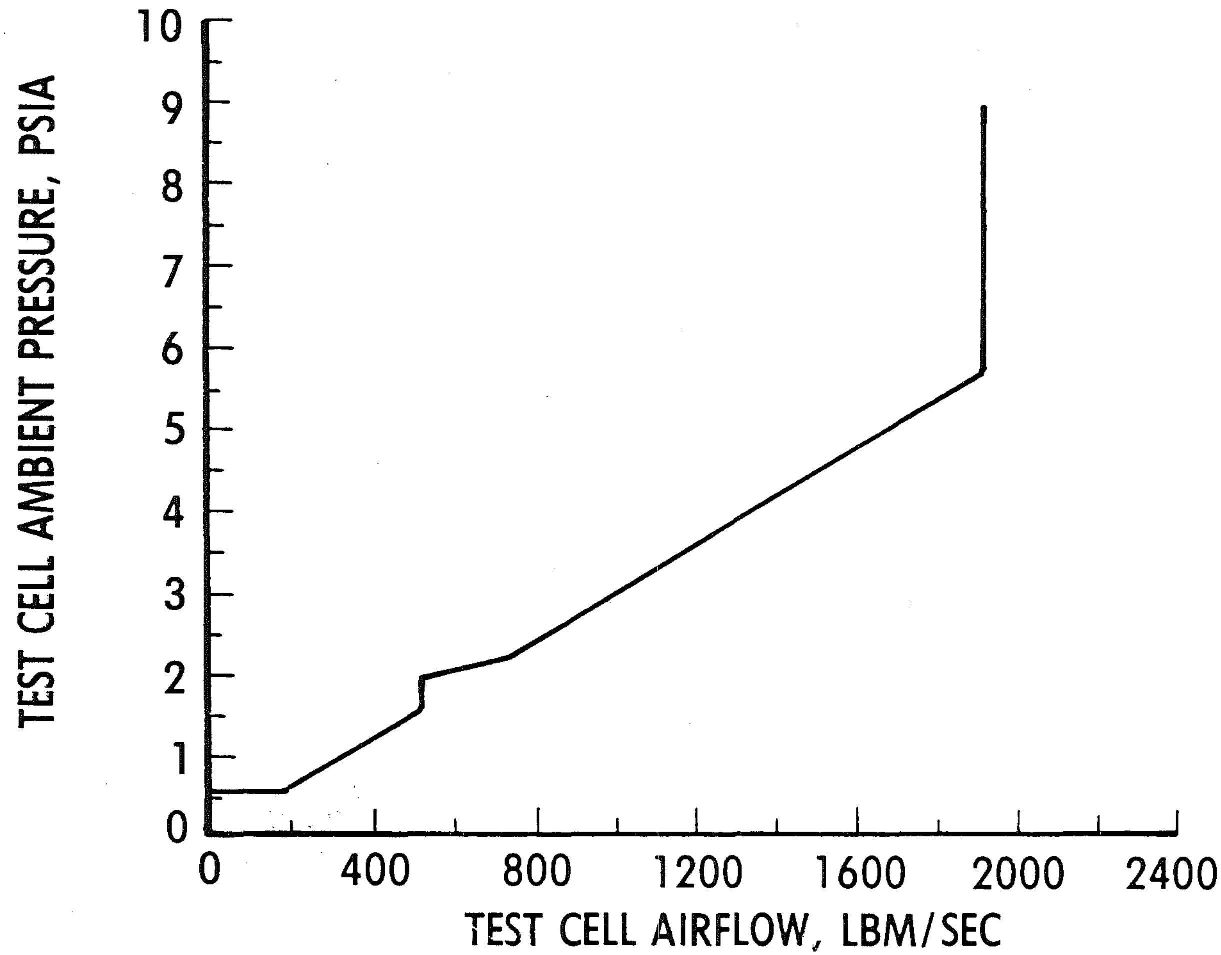


Figure 7. Exhaust System Performance Capability for Turbojet Tests: Test Cell C1

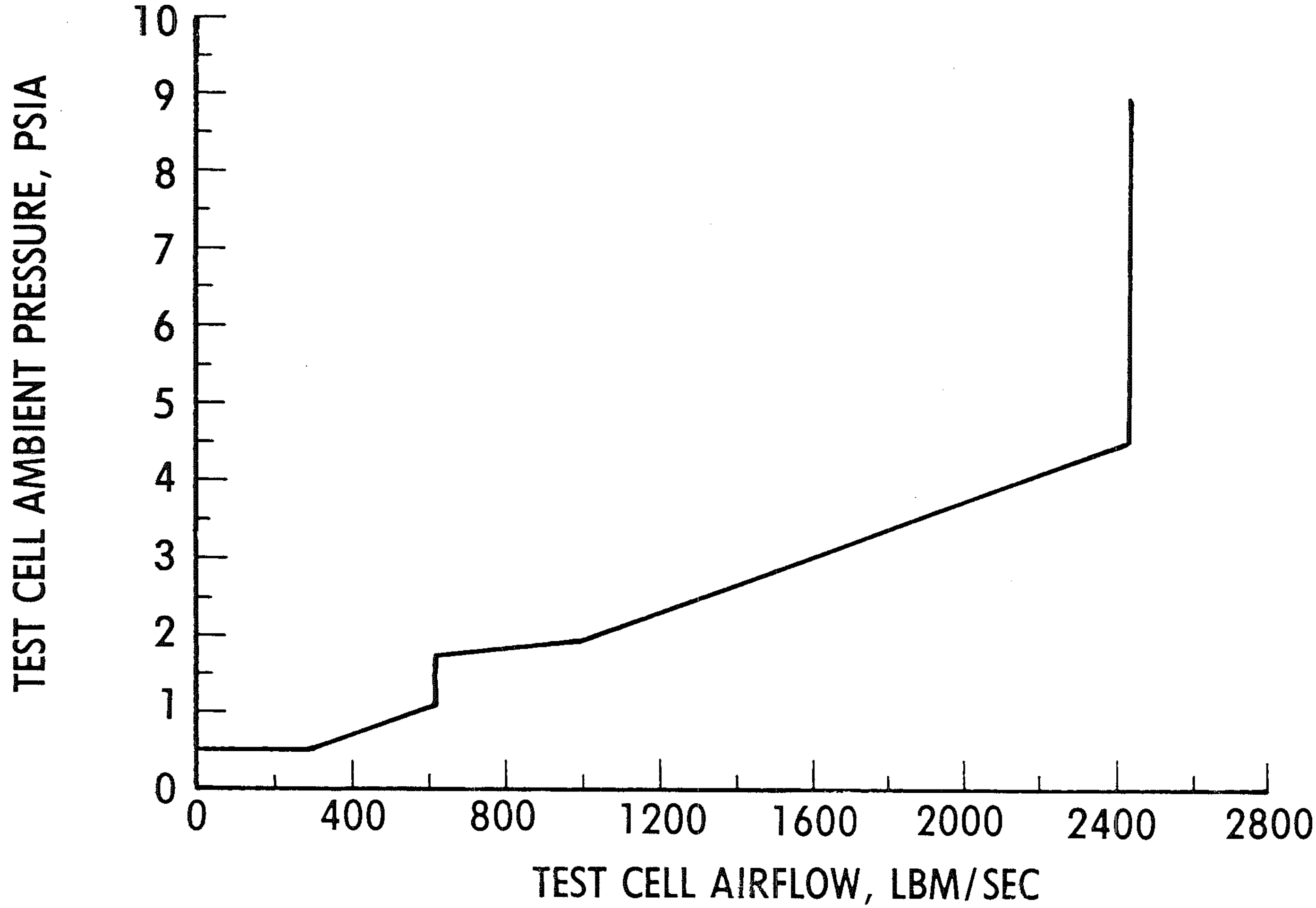


Figure 8. Exhaust System Performance Capability for Turbofan Tests: Test Cell C2.

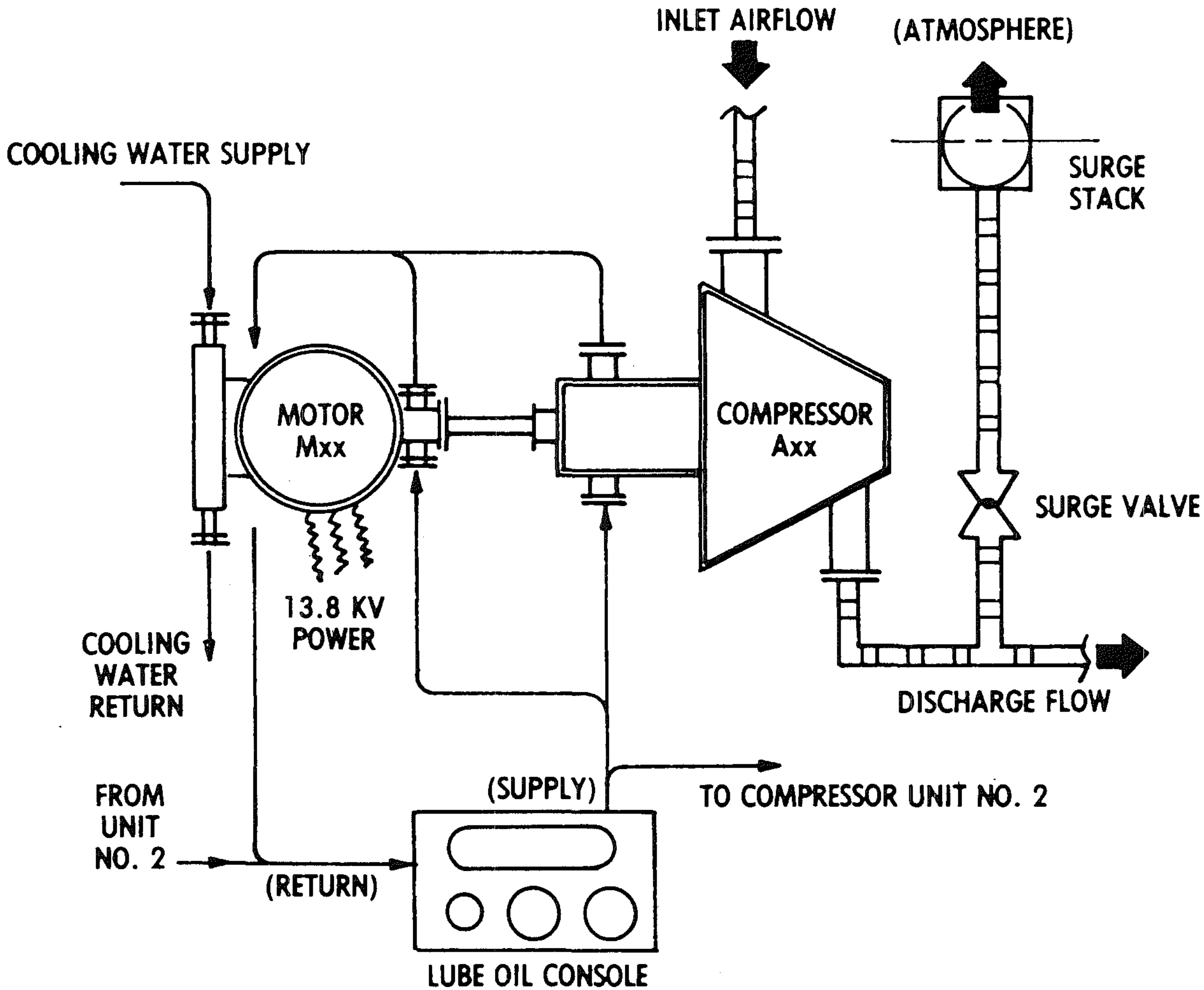


Figure 9. Typical Air Supply Compressor Arrangement.

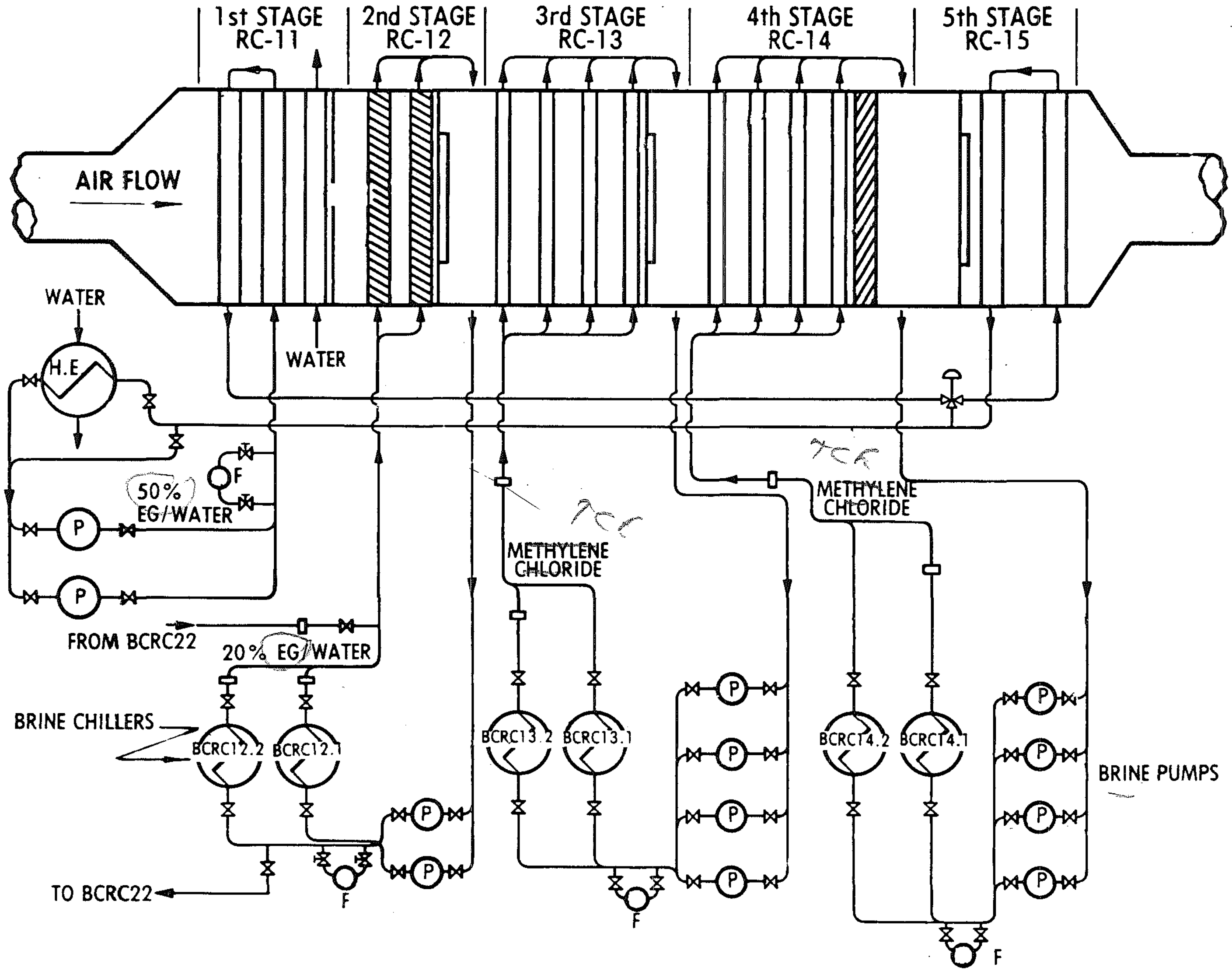


Figure 10. Cooler RC1 Schematic.

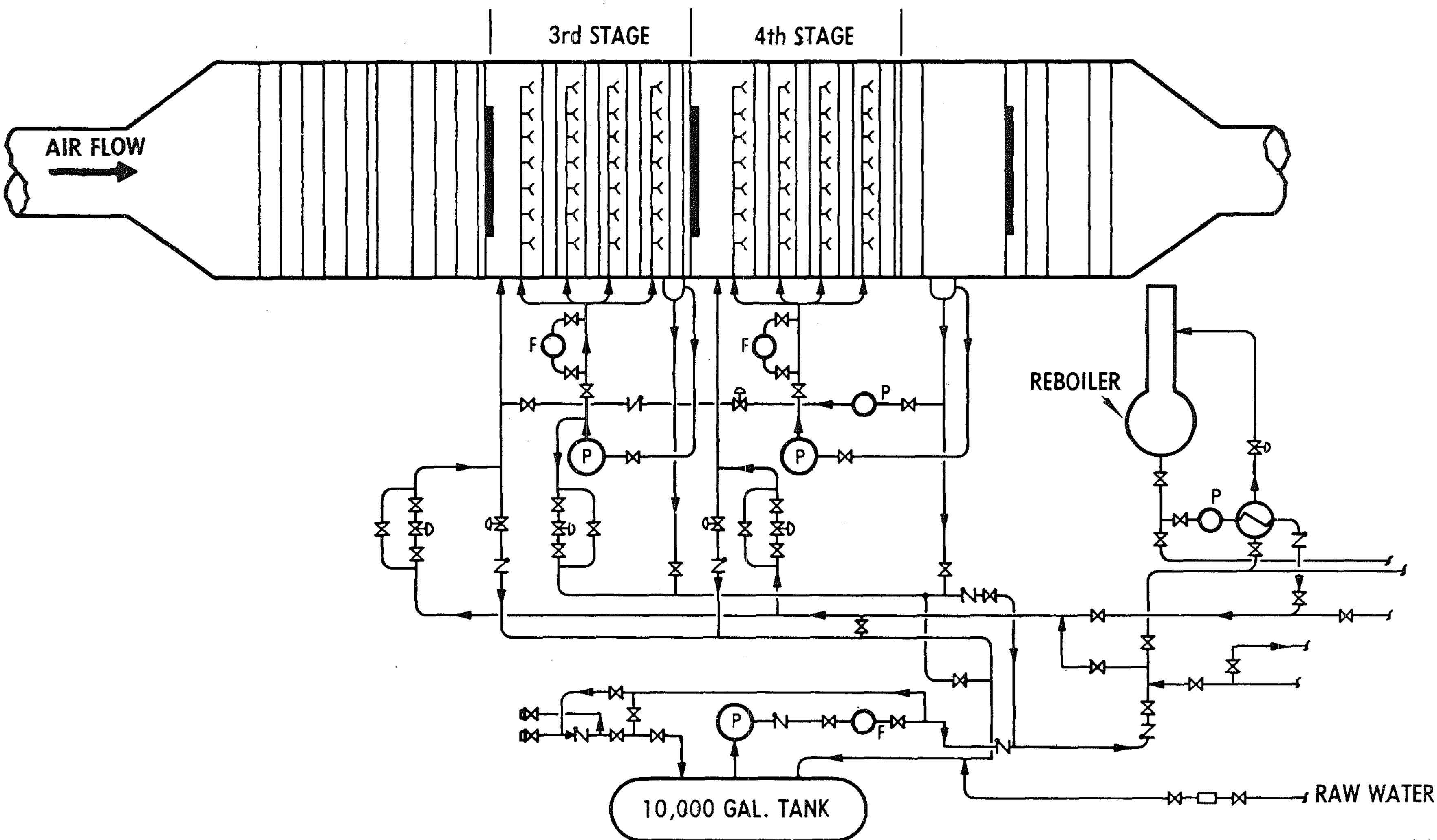


Figure 11. Cooler RC1 De-icing Spray System.

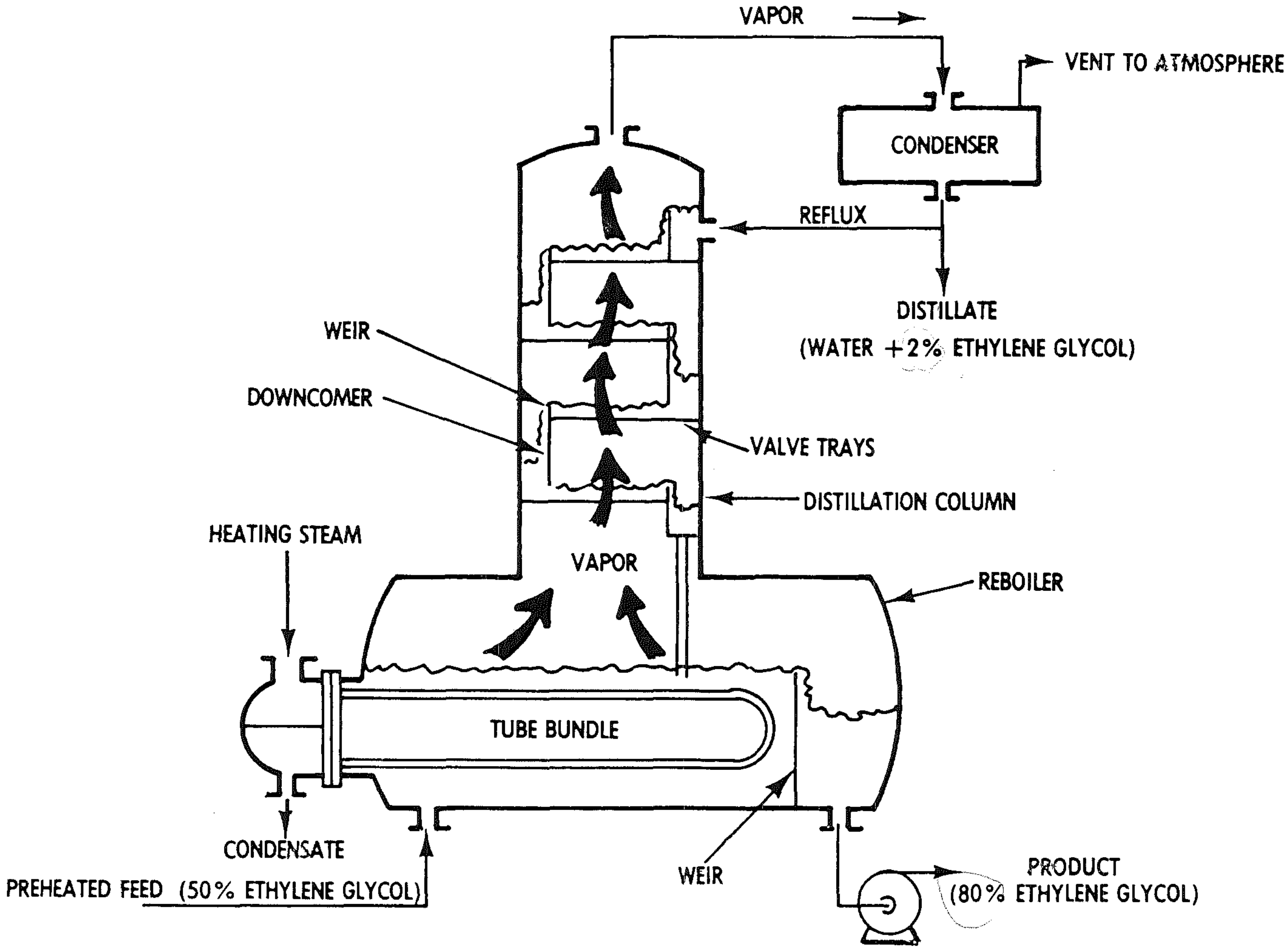


Figure 12. Ethylene Glycol Concentration Unit.

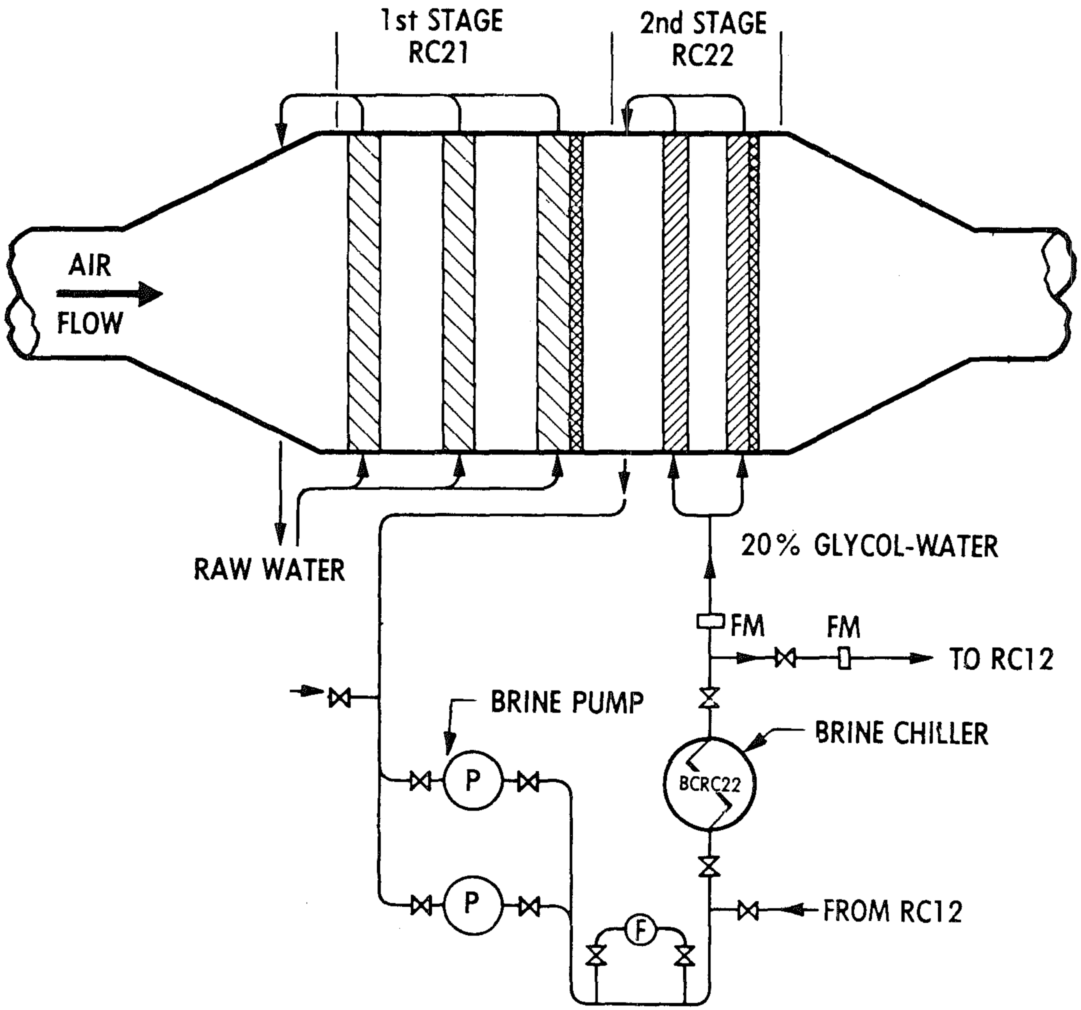


Figure 13. Cooler RC2 Schematic.

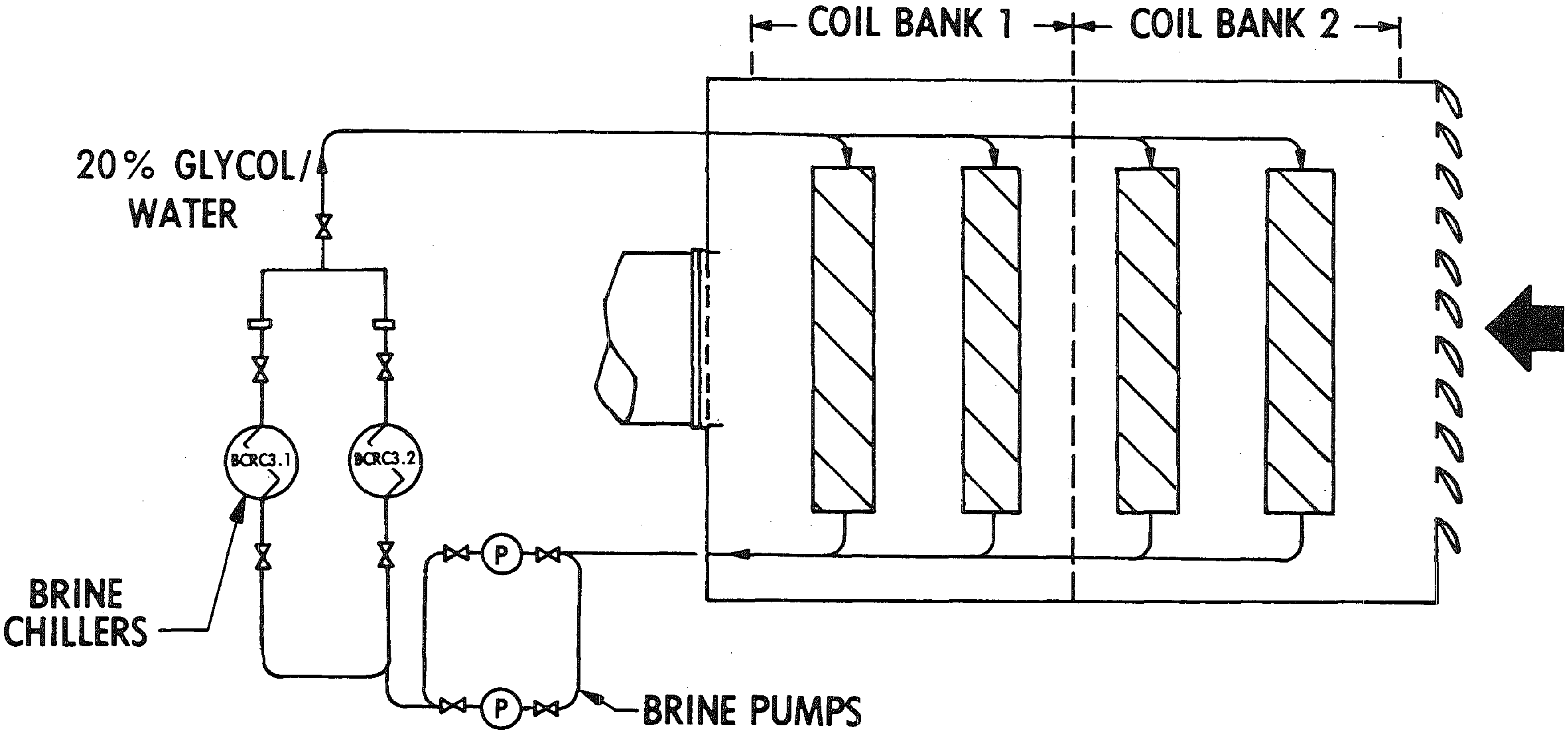


Figure 14. Cooler RC3 Schematic.

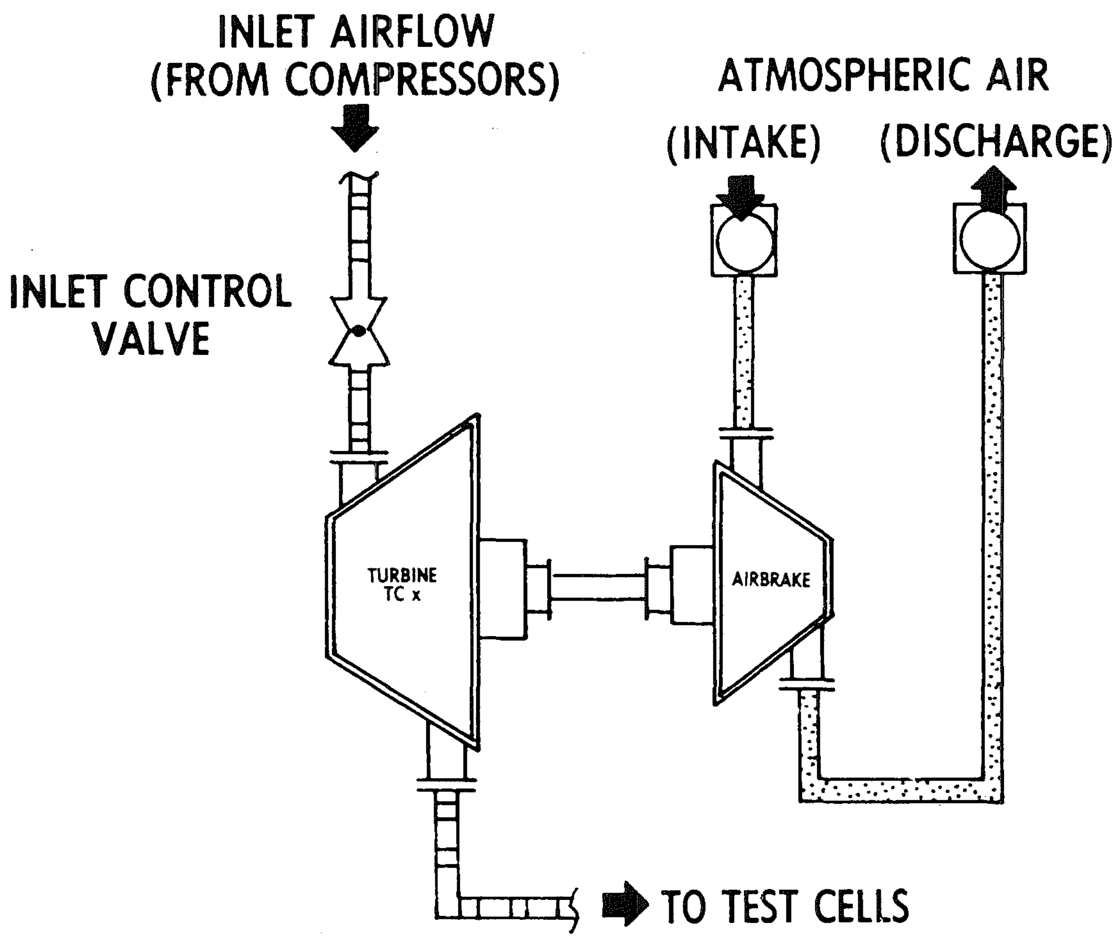


Figure 15. Typical Refrigeration Turbine Arrangement.

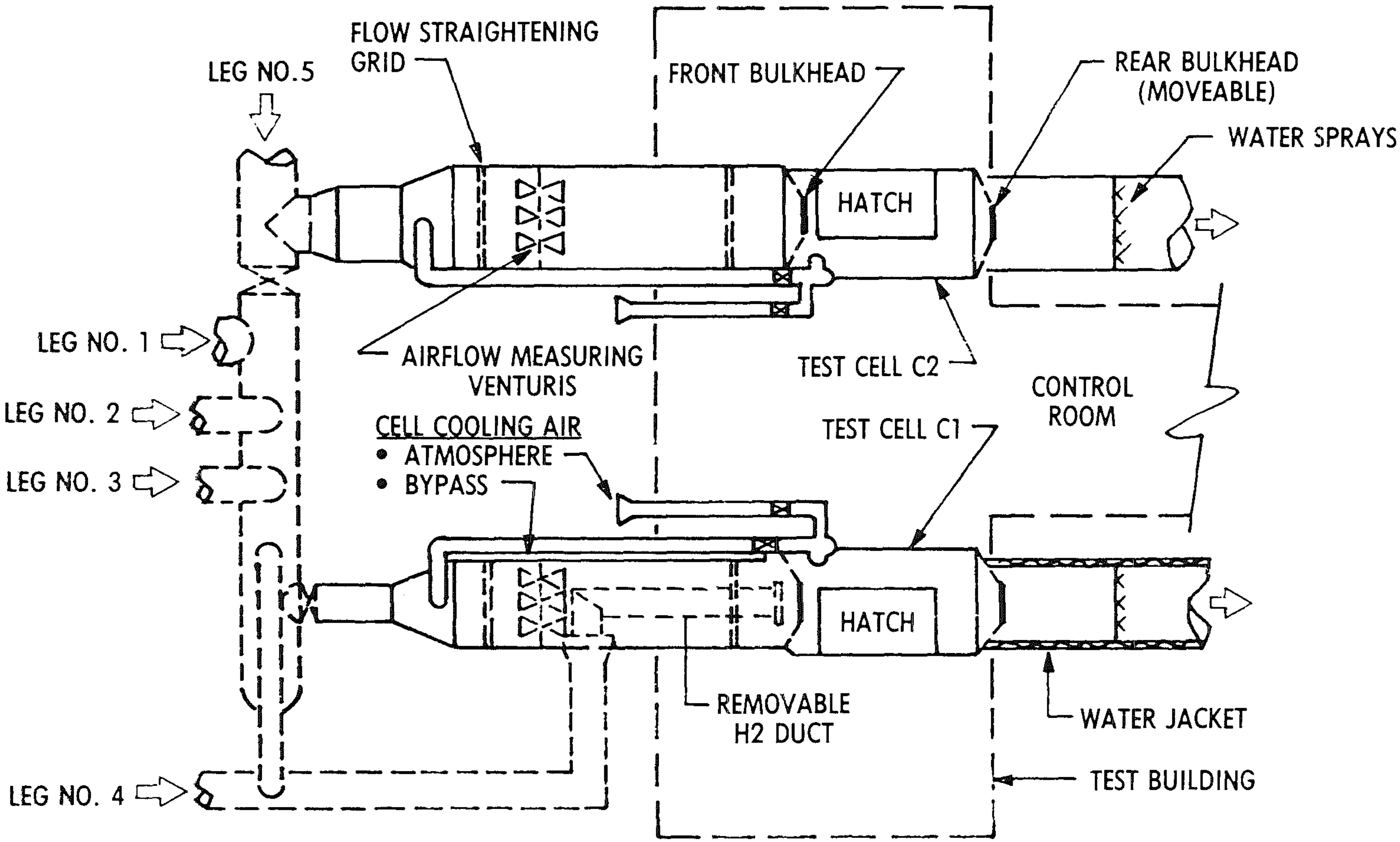


Figure 16. Test Area System Arrangement.

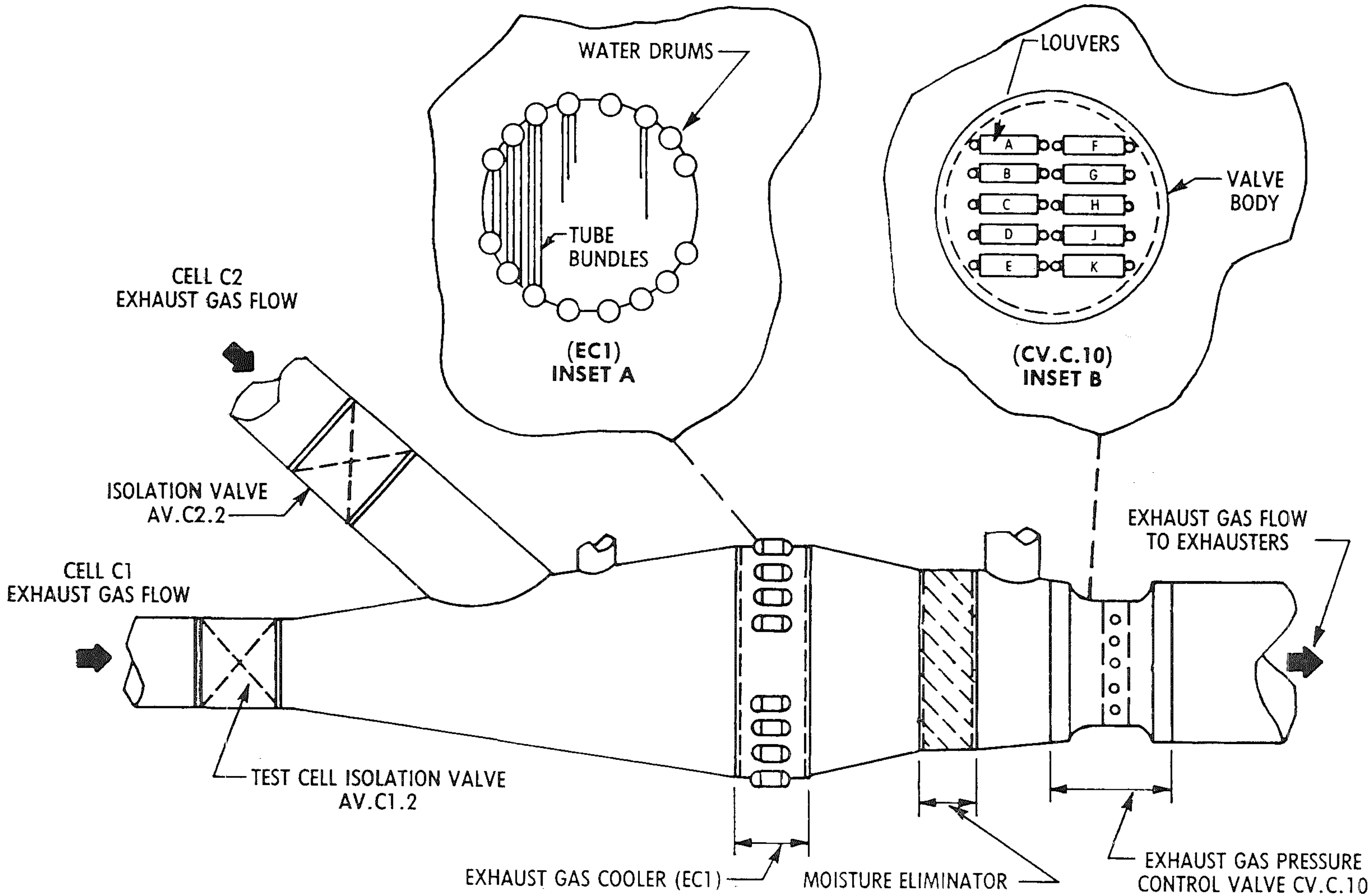


Figure 17. Exhaust Gas System Transition Section Illustration.

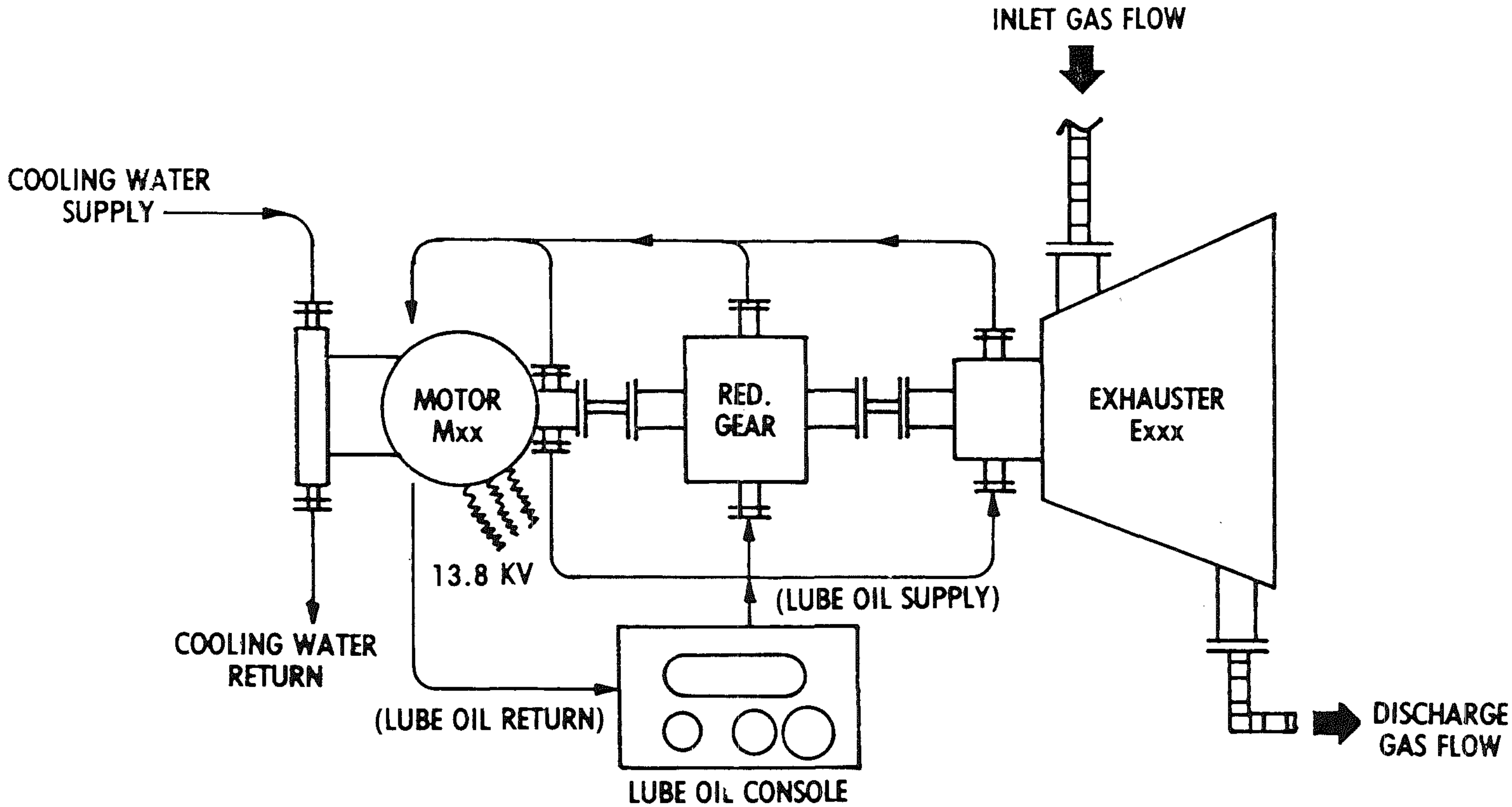


Figure 18. Typical Exhauster Arrangement.

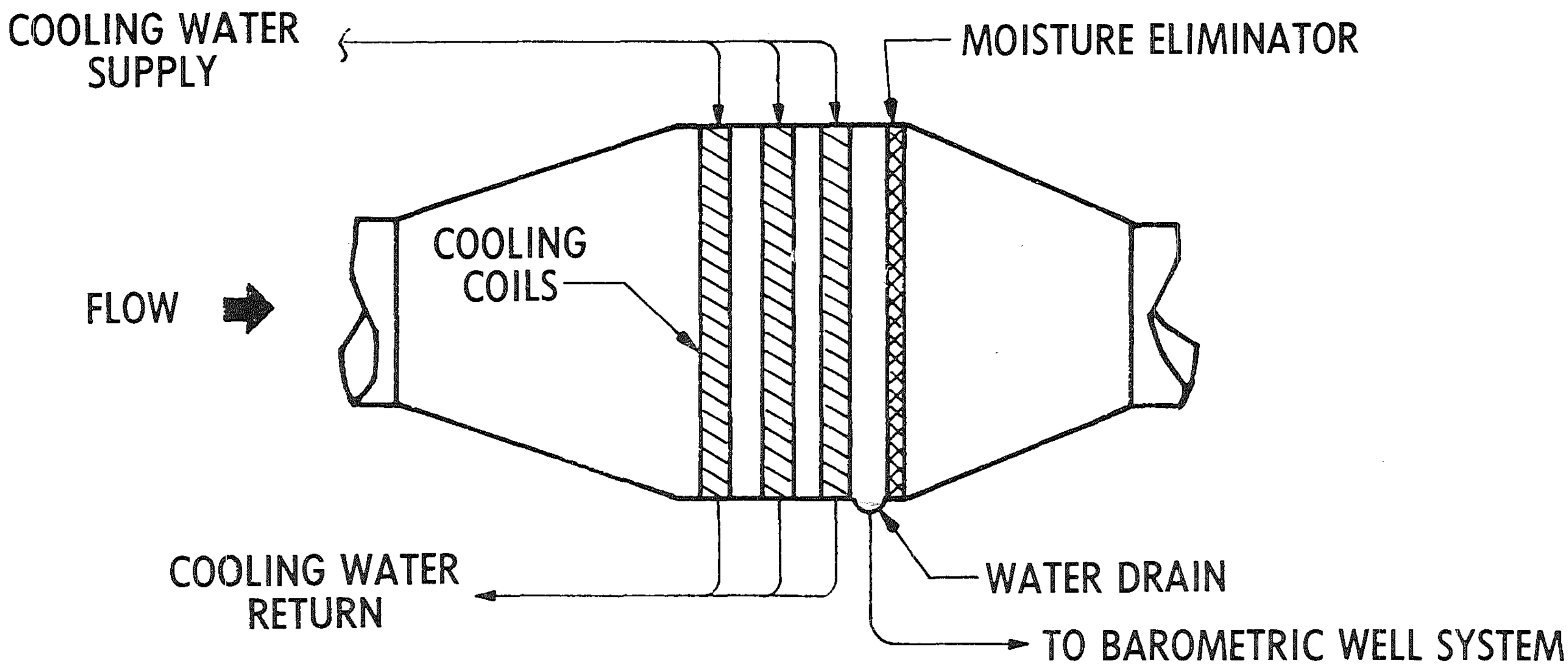


Figure 19. Exhaust Gas Intercooler Schematic.

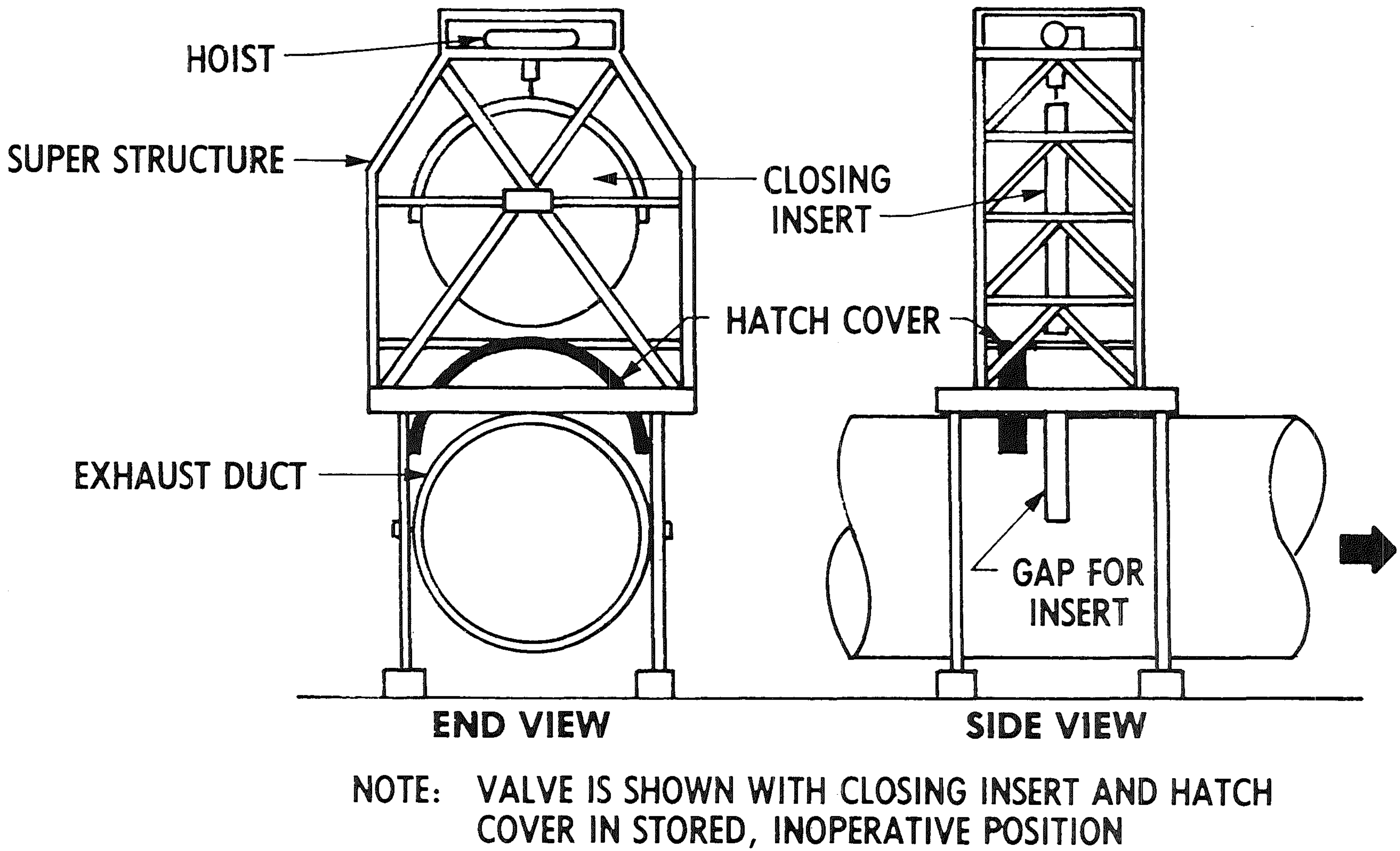


Figure 20. Test Cell Isolation Valve Illustration.

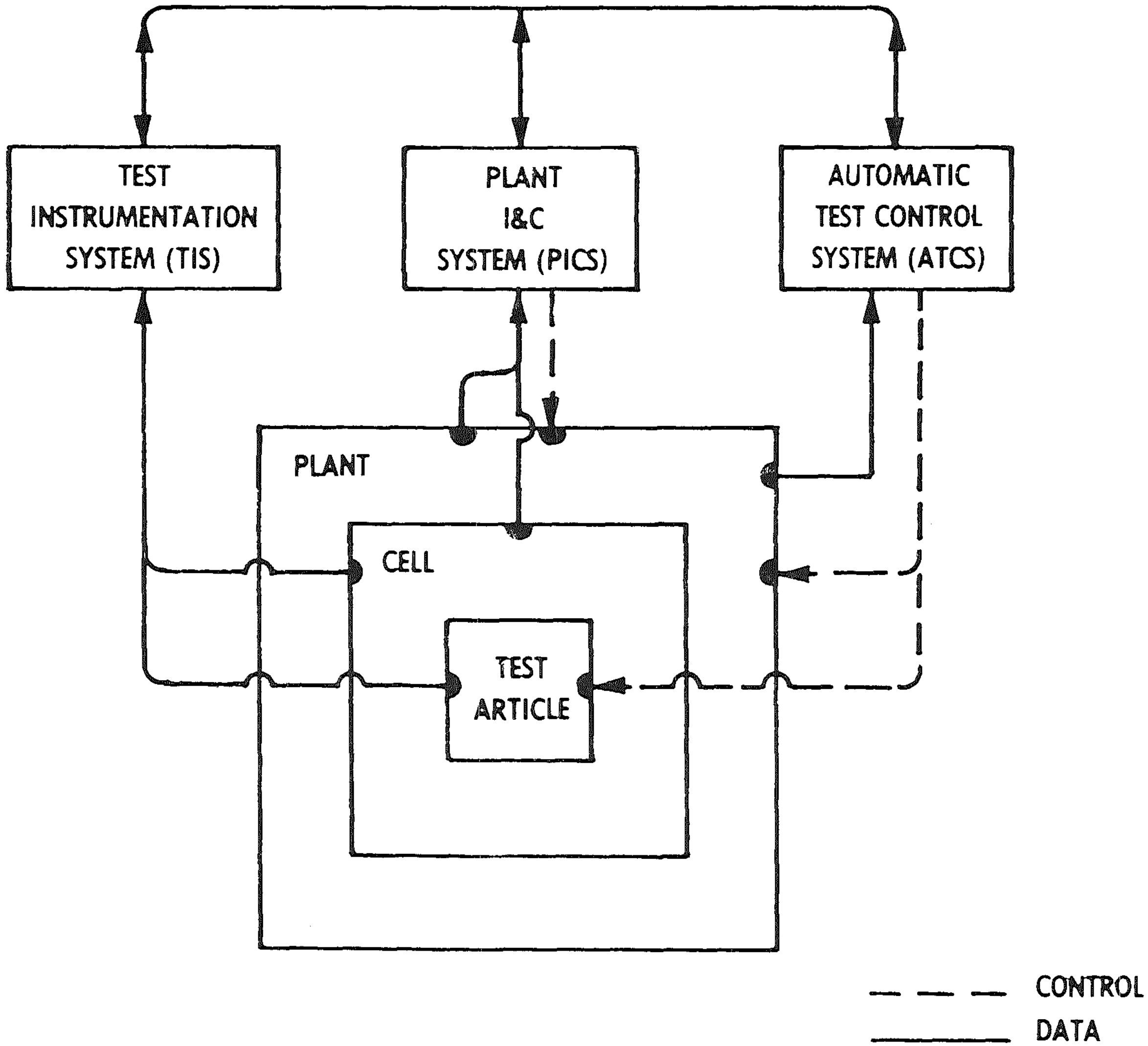


Figure 21. ASTF Instrumentation and Control Interface Diagram.

FIGURE 22. PLANT INSTRUMENTATION AND CONTROL SYSTEM (PICS) INTERFACE DIAGRAM.

ABBREVIATIONS AND ACRONYMS

I&C	--	Instrumentation and Control
COMM	--	Communication
INT'LK	--	Interlock
TACS	--	Test Article Control System
TADS	--	Test Article Data System
TIS	--	Test Instrumentation System
ATCS	--	Automatic Test Control System
CONTR	--	Control
CRM	--	Control Room
FML	--	Facility Monitoring and Logging System
CLS	--	Catastrophe Logging System
PRCS	--	Pressure Ratio Control System
RMAS	--	Rotating Machinery Anslysis System
CWRCS	--	Cooling Water Remote Control System
SPS	--	Secondary Pumping Station
CP	--	Control Panel

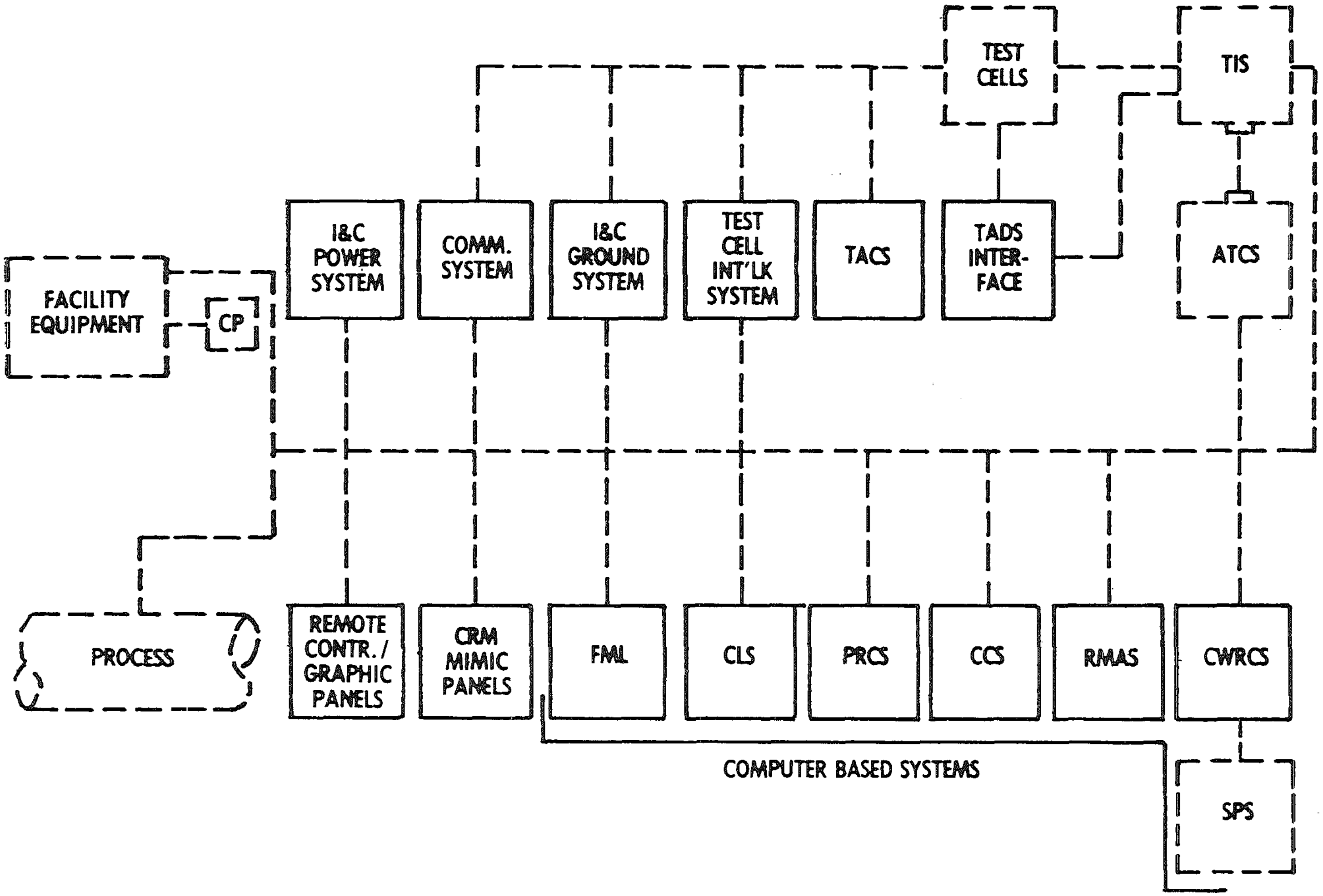

TEST CELLS
TIS
I&C POWER SYSTEM
COMM. SYSTEM
I&C GROUND SYSTEM
TEST CELL INT'LK SYSTEM
TACS
TADS INTER-FACE
ATCS
FACILITY EQUIPMENT
CP
PROCESS
REMOTE CONTR./ GRAPHIC PANELS
CRM MIMIC PANELS
FML
CLS
PRCS
CCS
RMAS
CWRCS
COMPUTER BASED SYSTEMS
SPS

Figure 22.

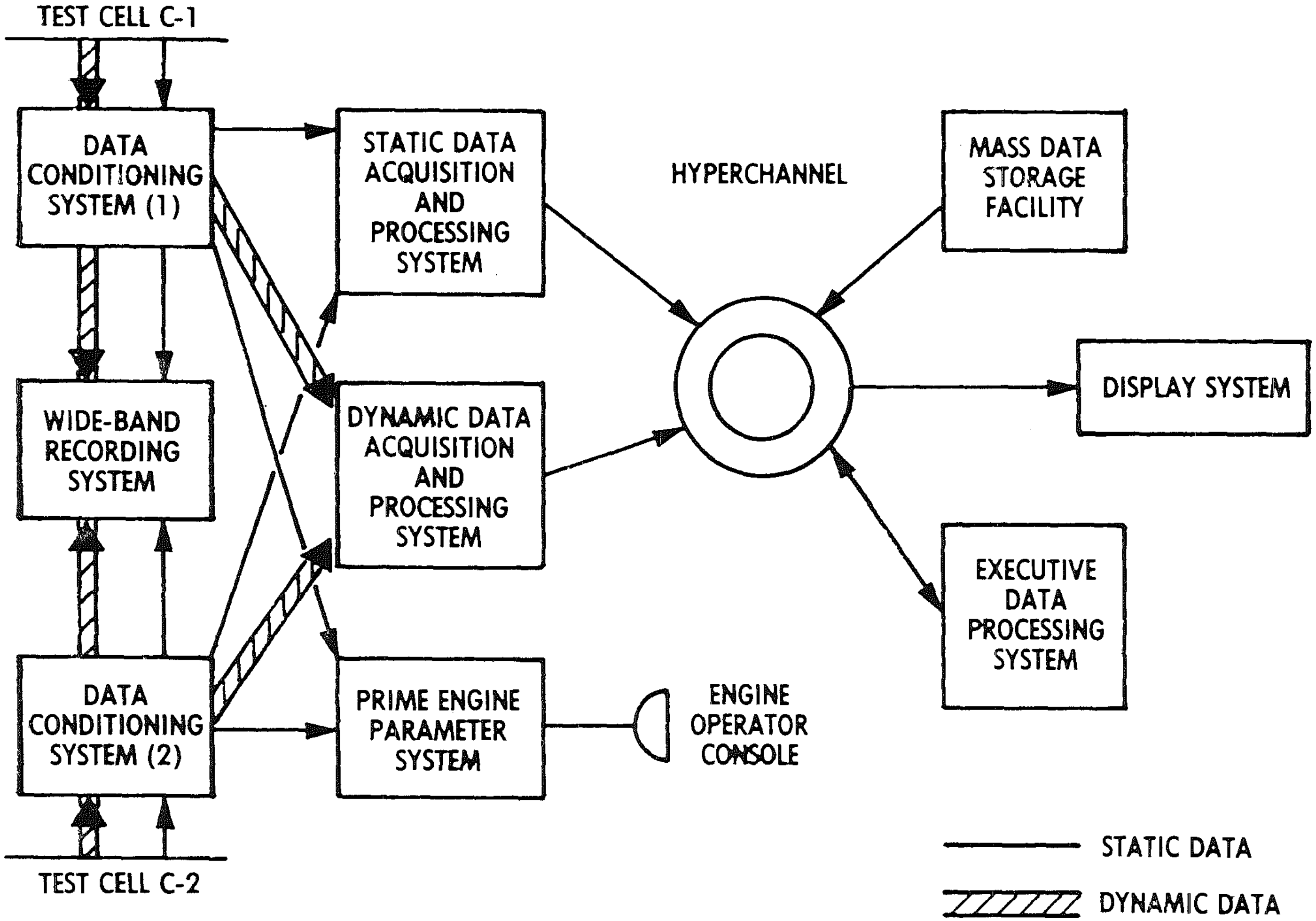


Figure 23. Test Instrumentation System Block Diagram.

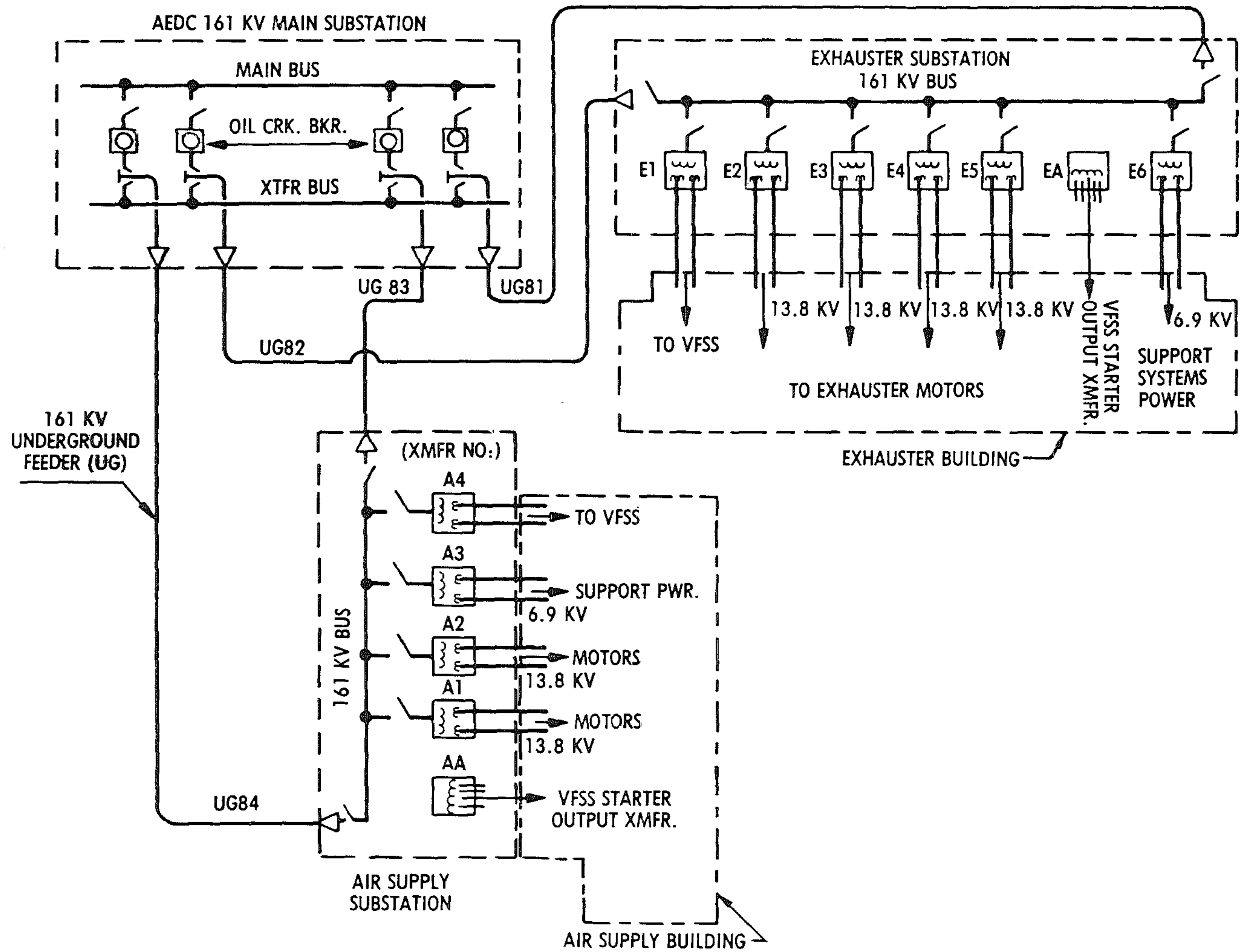


Figure 24. 161 KV Electrical Distribution System.

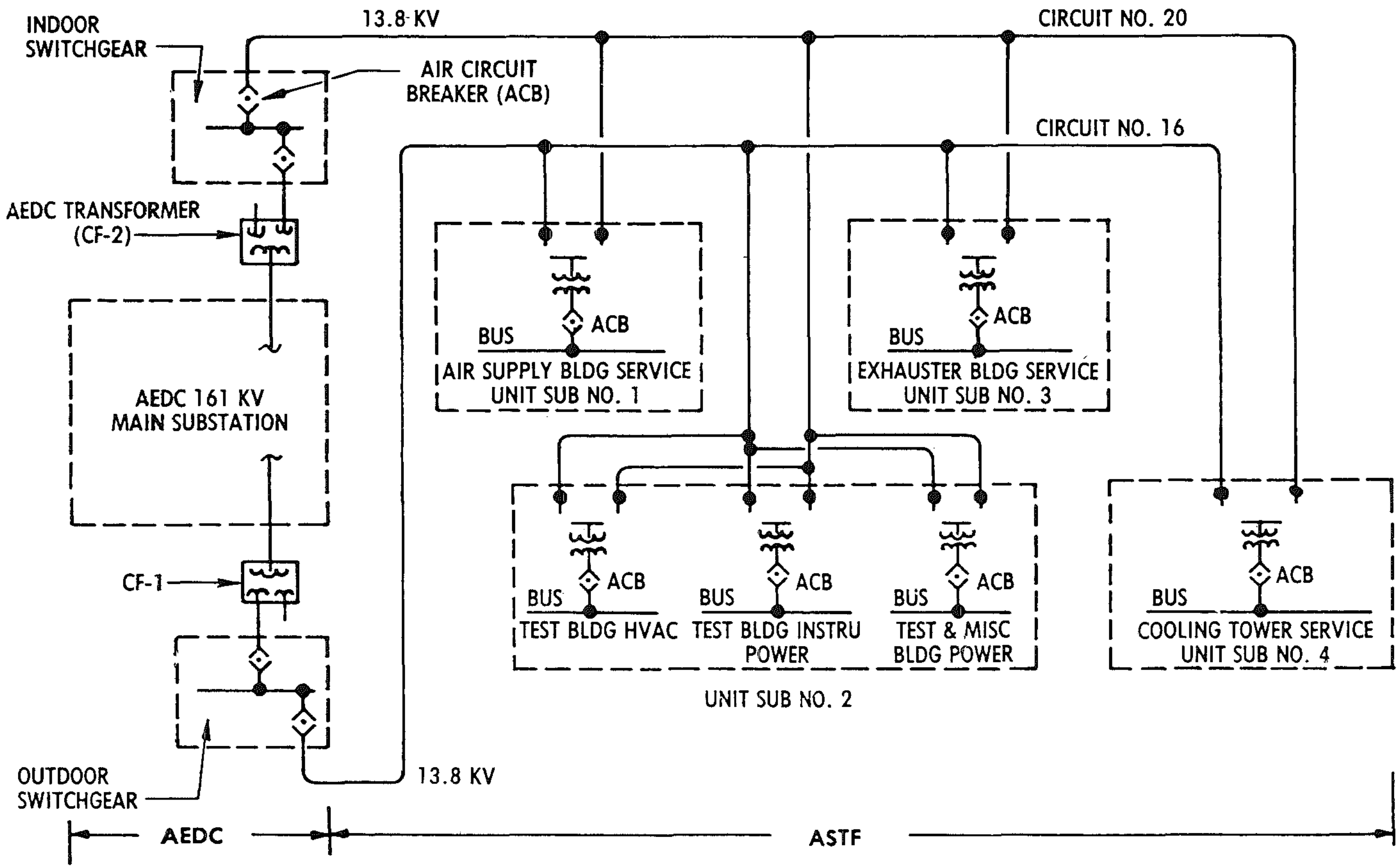


Figure 25. 13.8 KV Electrical Distribution System.

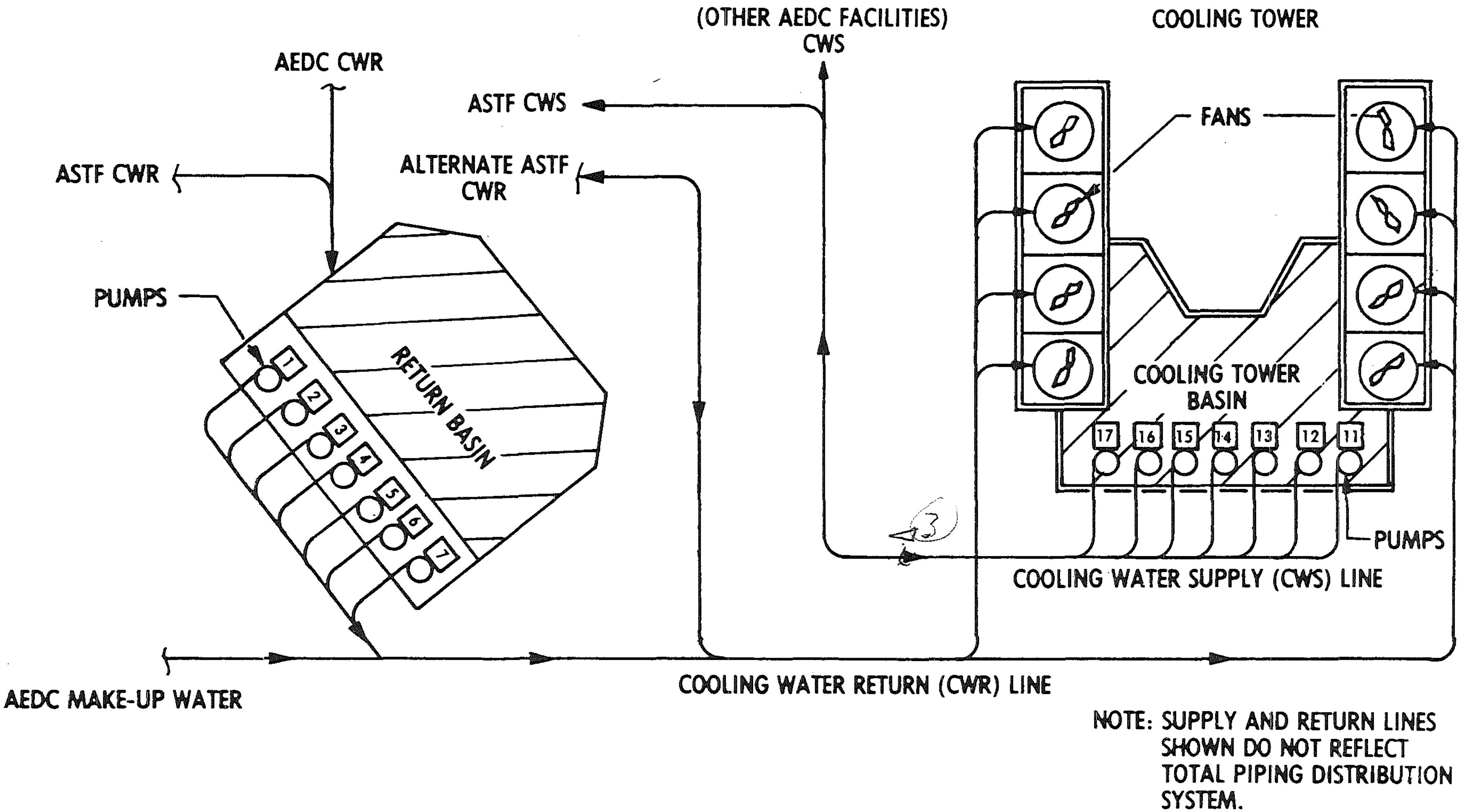


Figure 26. Cooling Tower System Schematic, Closed Loop.

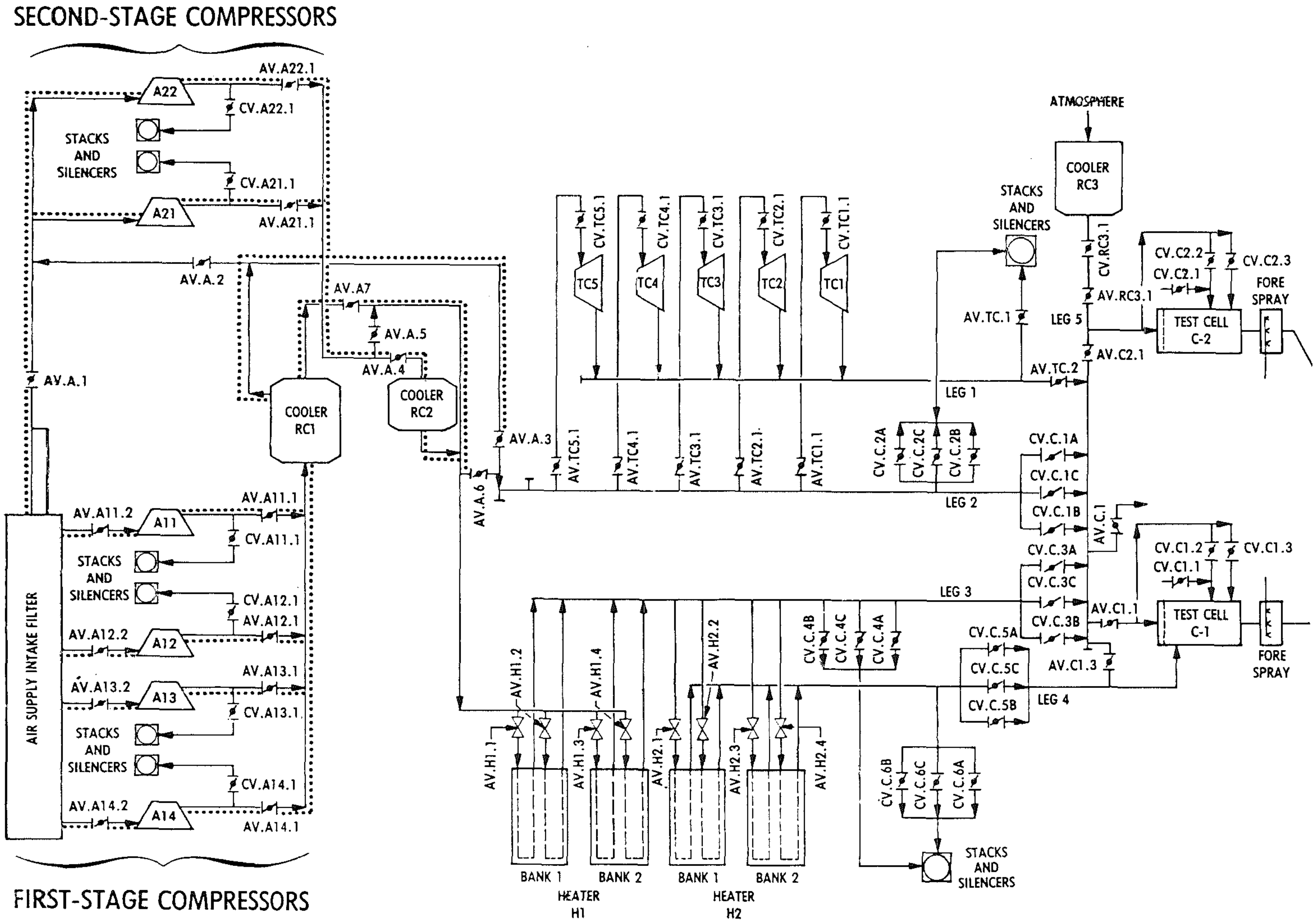


Figure 27. Air Supply Compressor Single-Stage Configuration.

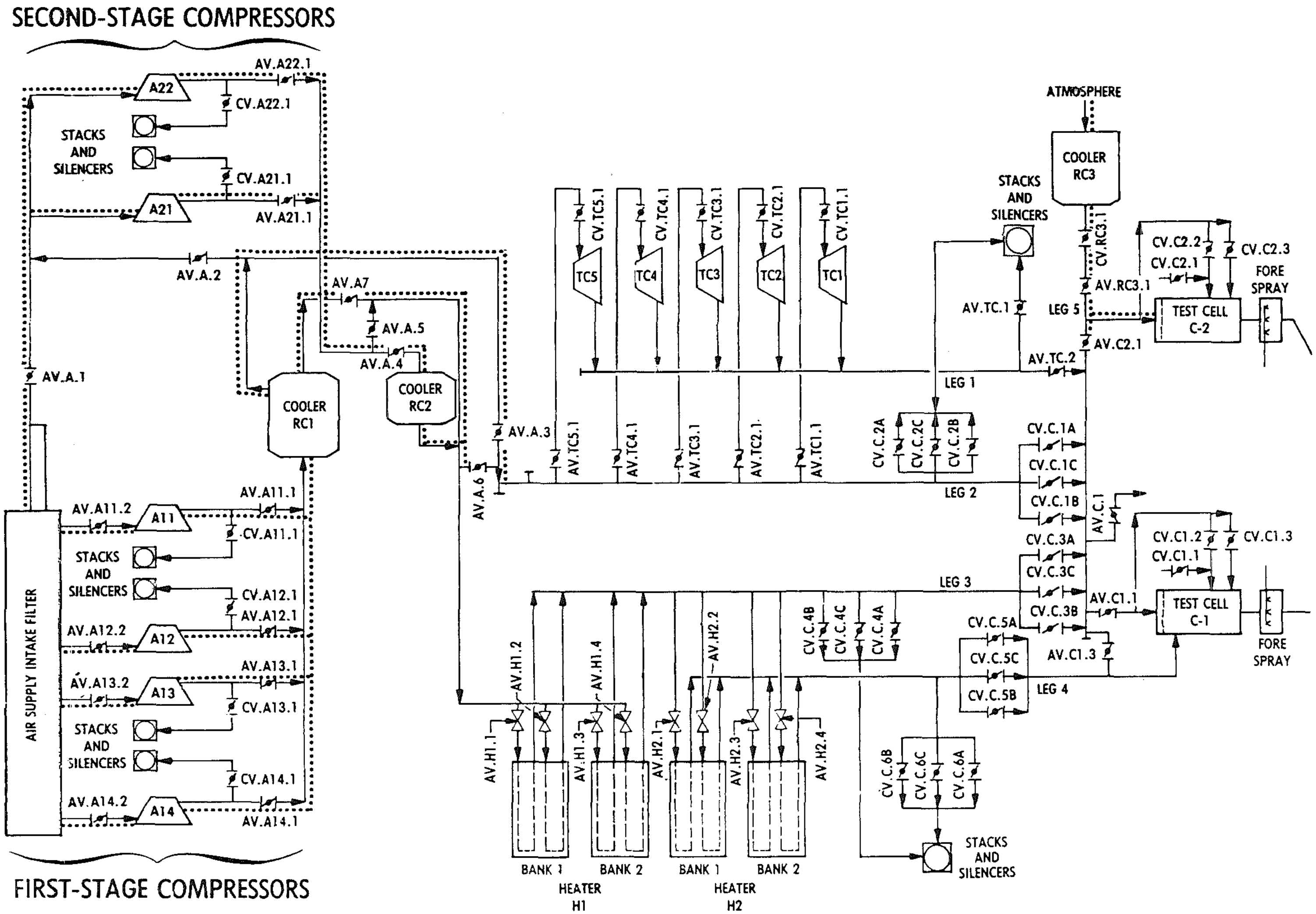


Figure 28. Air Supply Compressor Single-Stage Configuration with Atmospheric Inlet

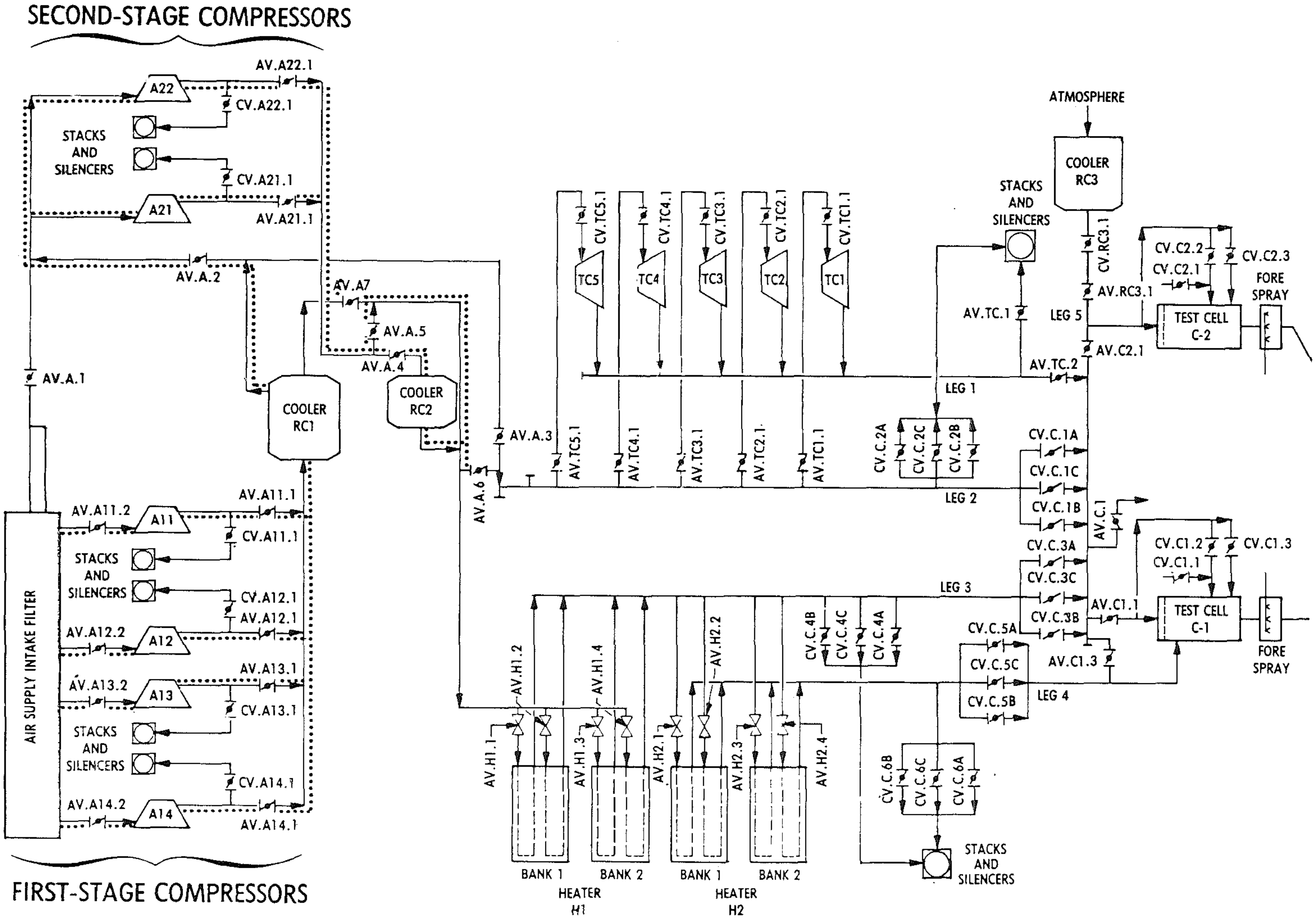


Figure 29. Air Supply Compressor Two-Stage Configuration.

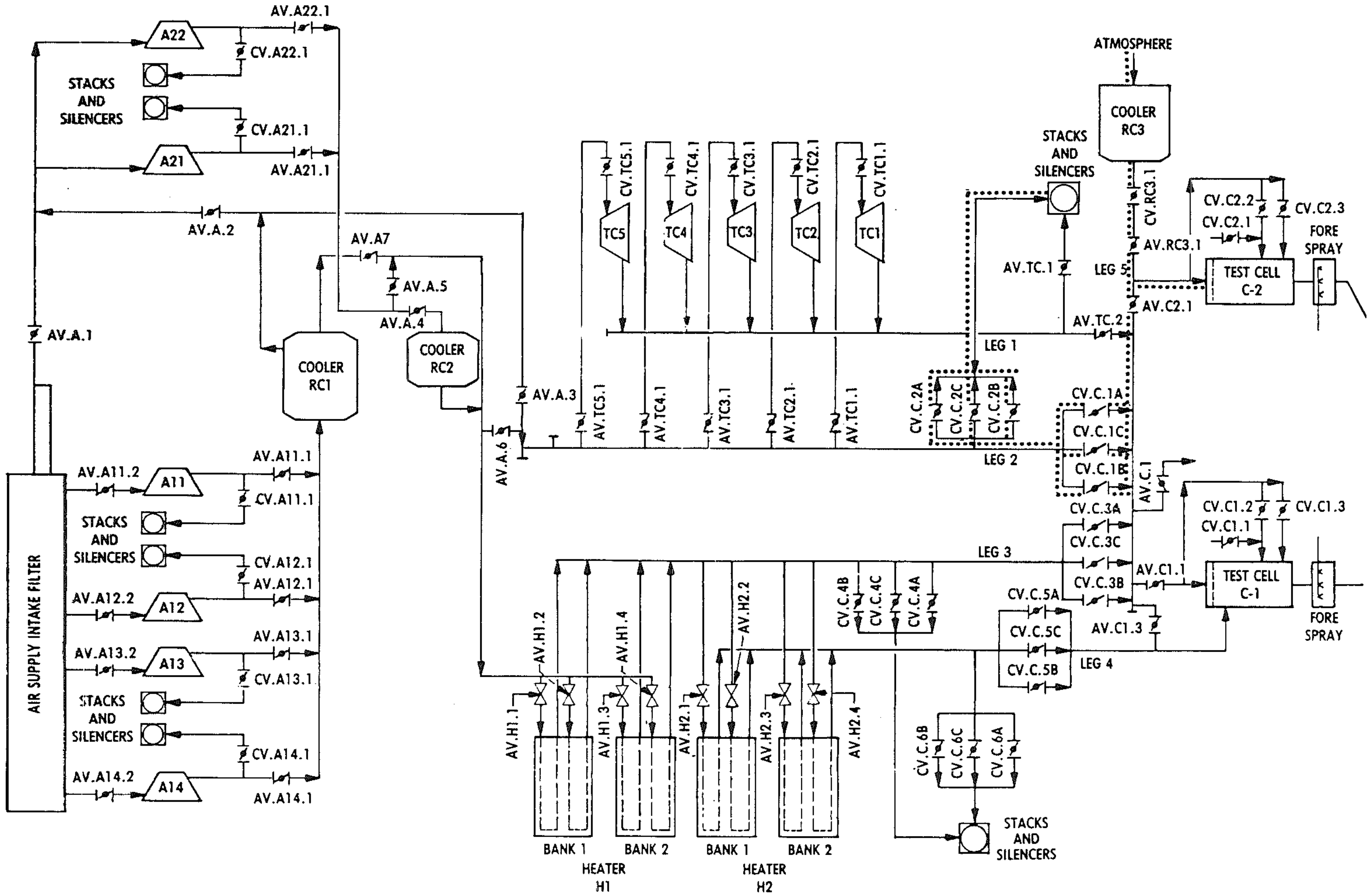


Figure 30. Atmospheric Intake (only) Configuration.

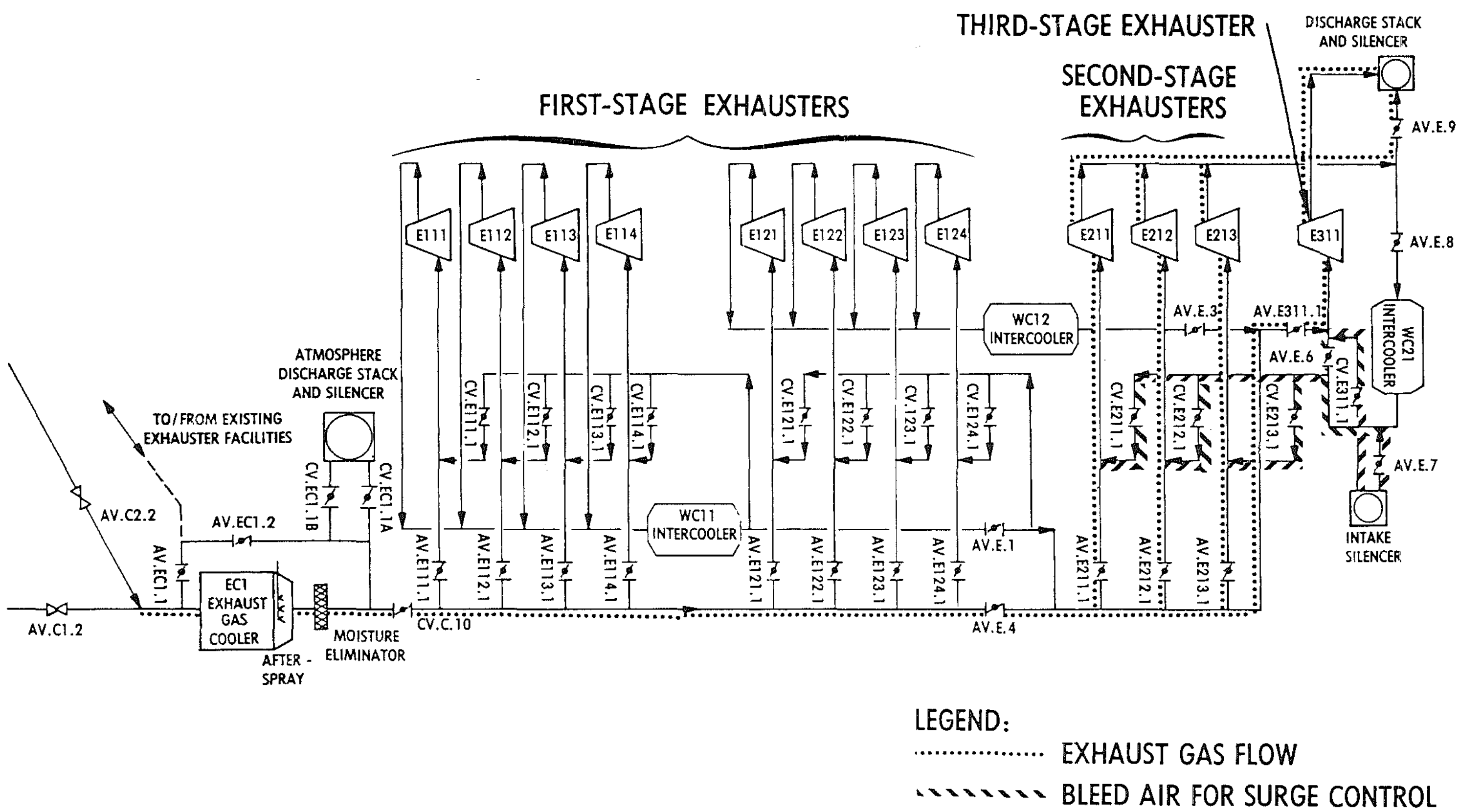


Figure 31. Exhauster Single-Stage Configuration.

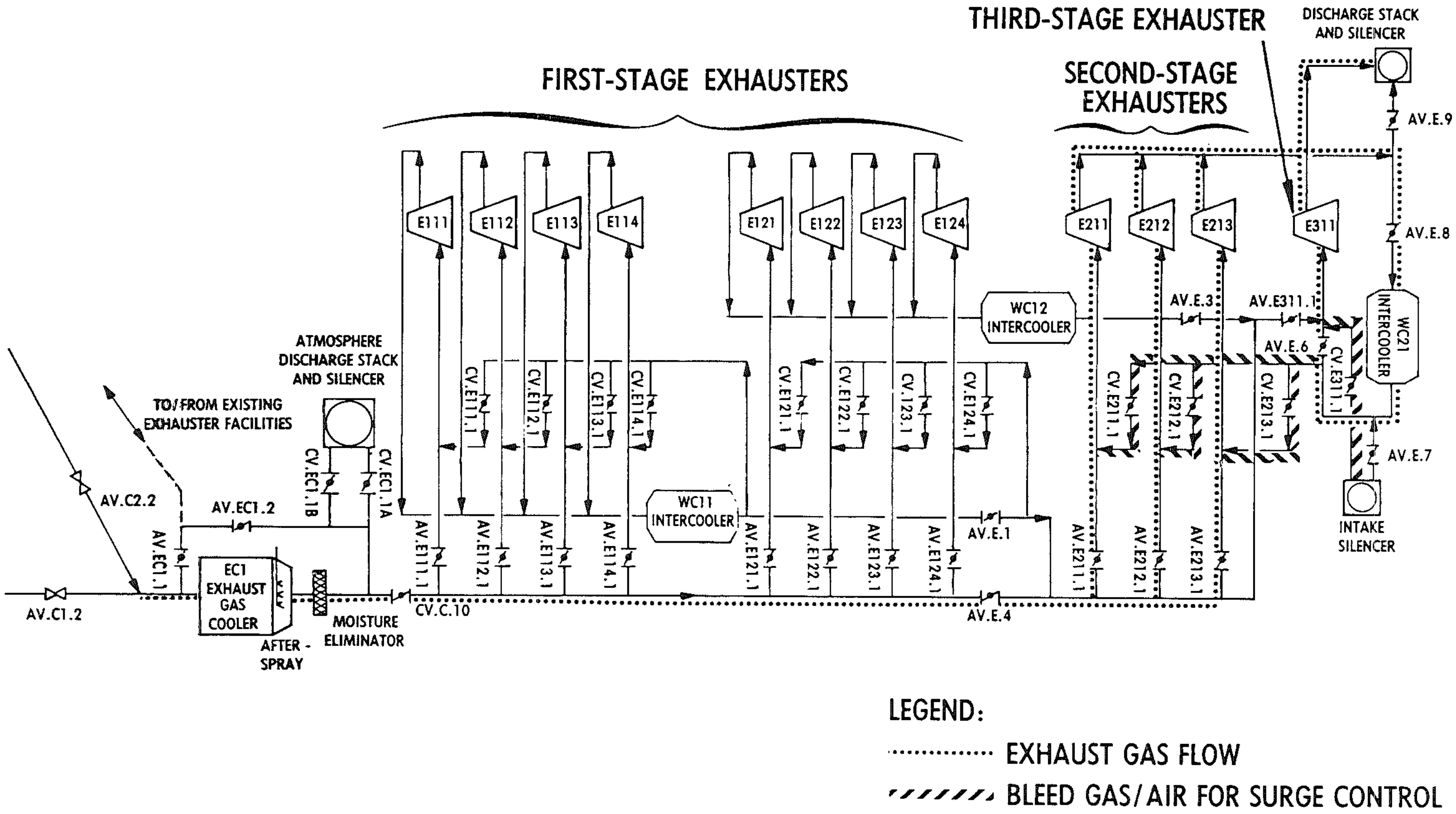


Figure 32. Exhauster Two-Stage Configuration: Second and Third-Stage Exhausters.

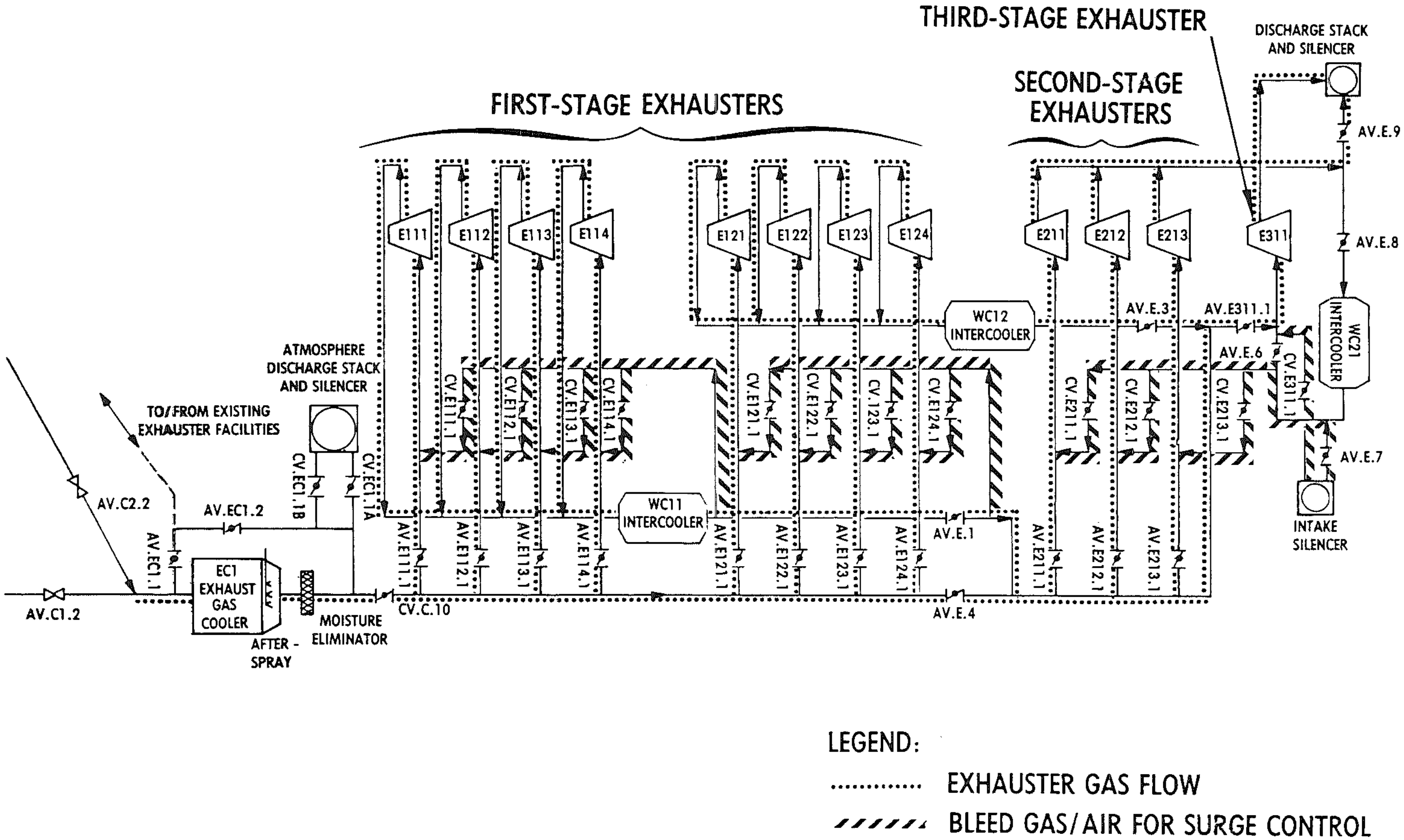


Figure 33. Exhauster Two-Stage Configuration: First, Second, and Third Stage Exhausters.

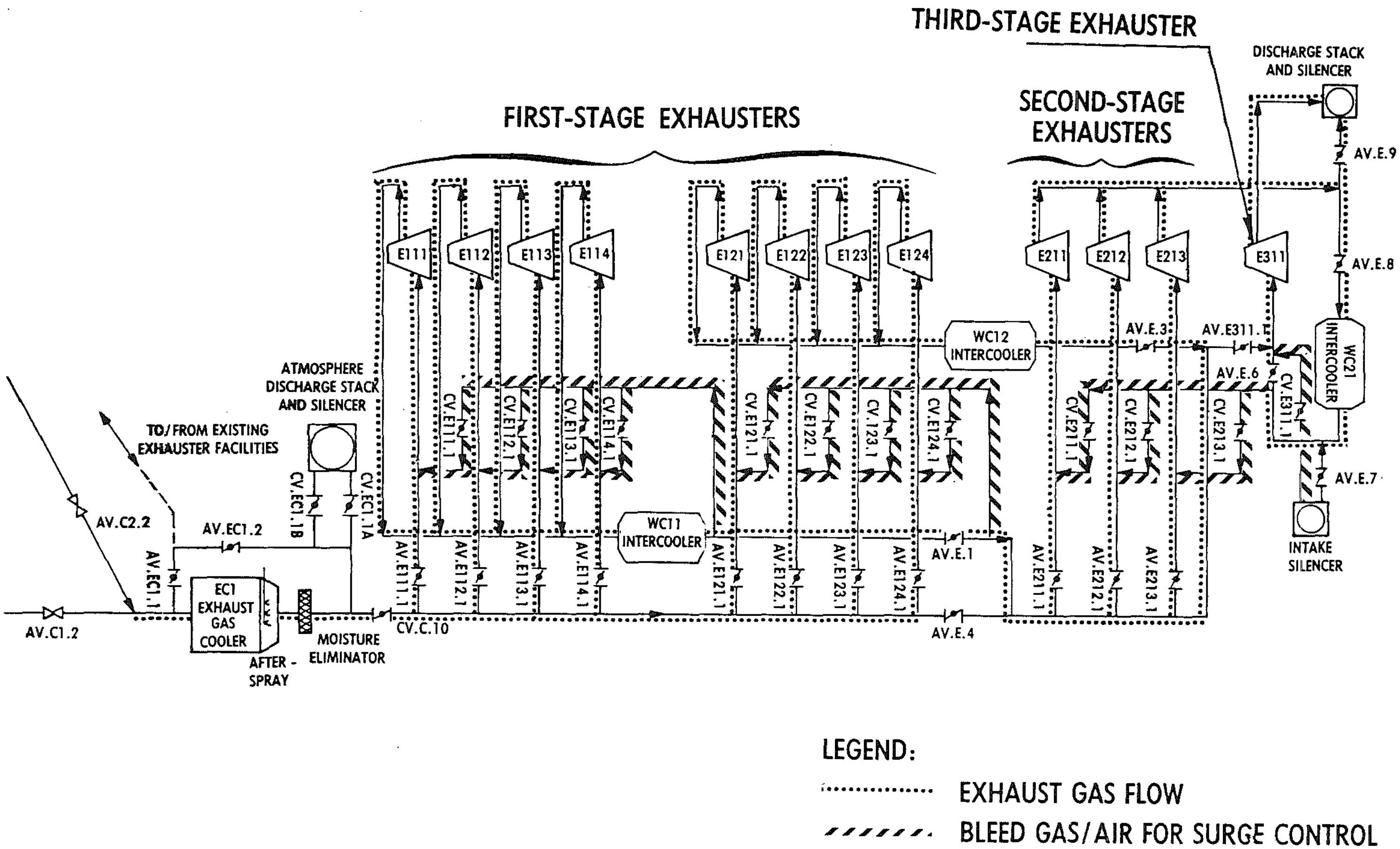


Figure 34. Exhauster Three-Stage Configuration.

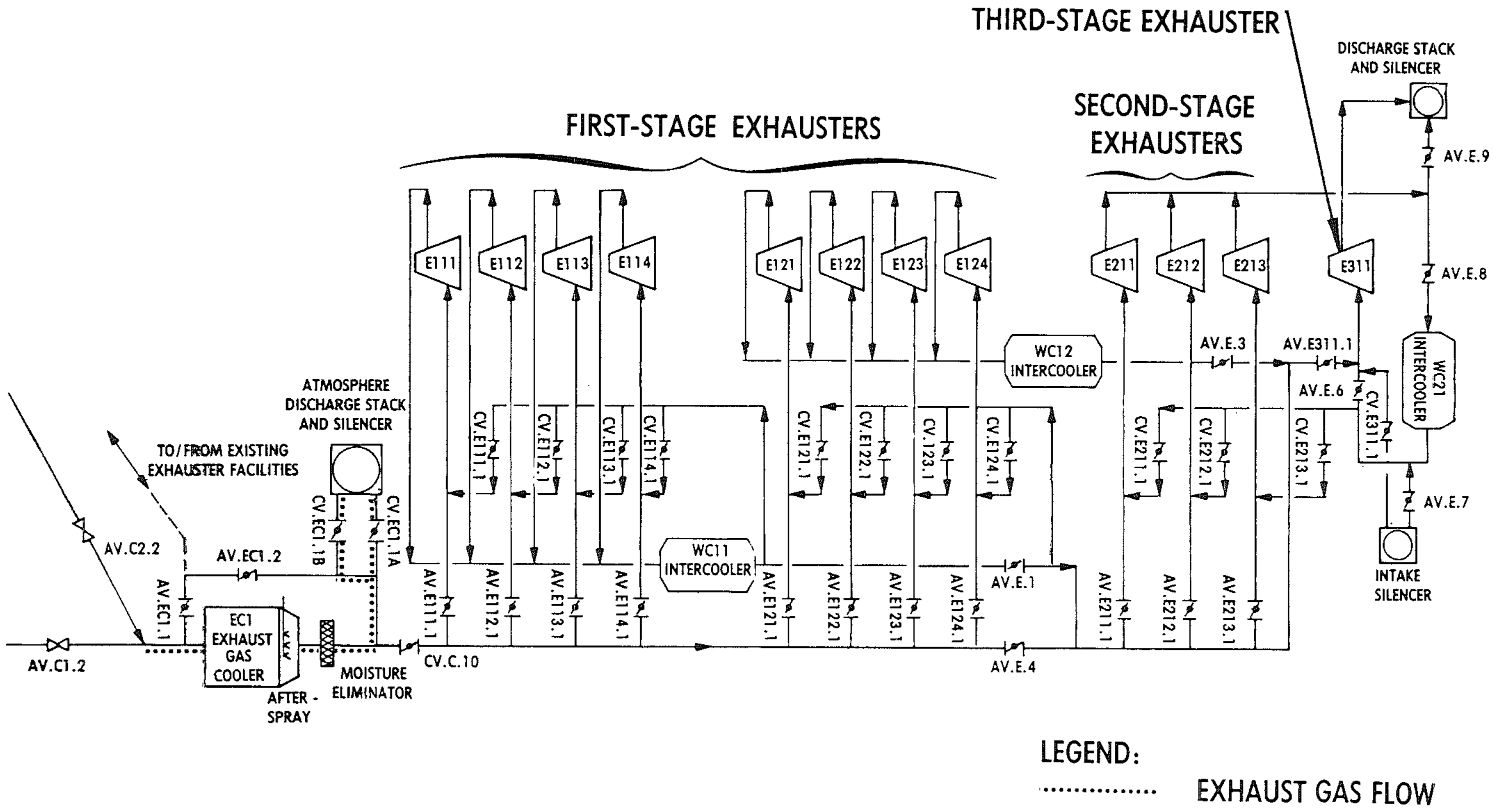
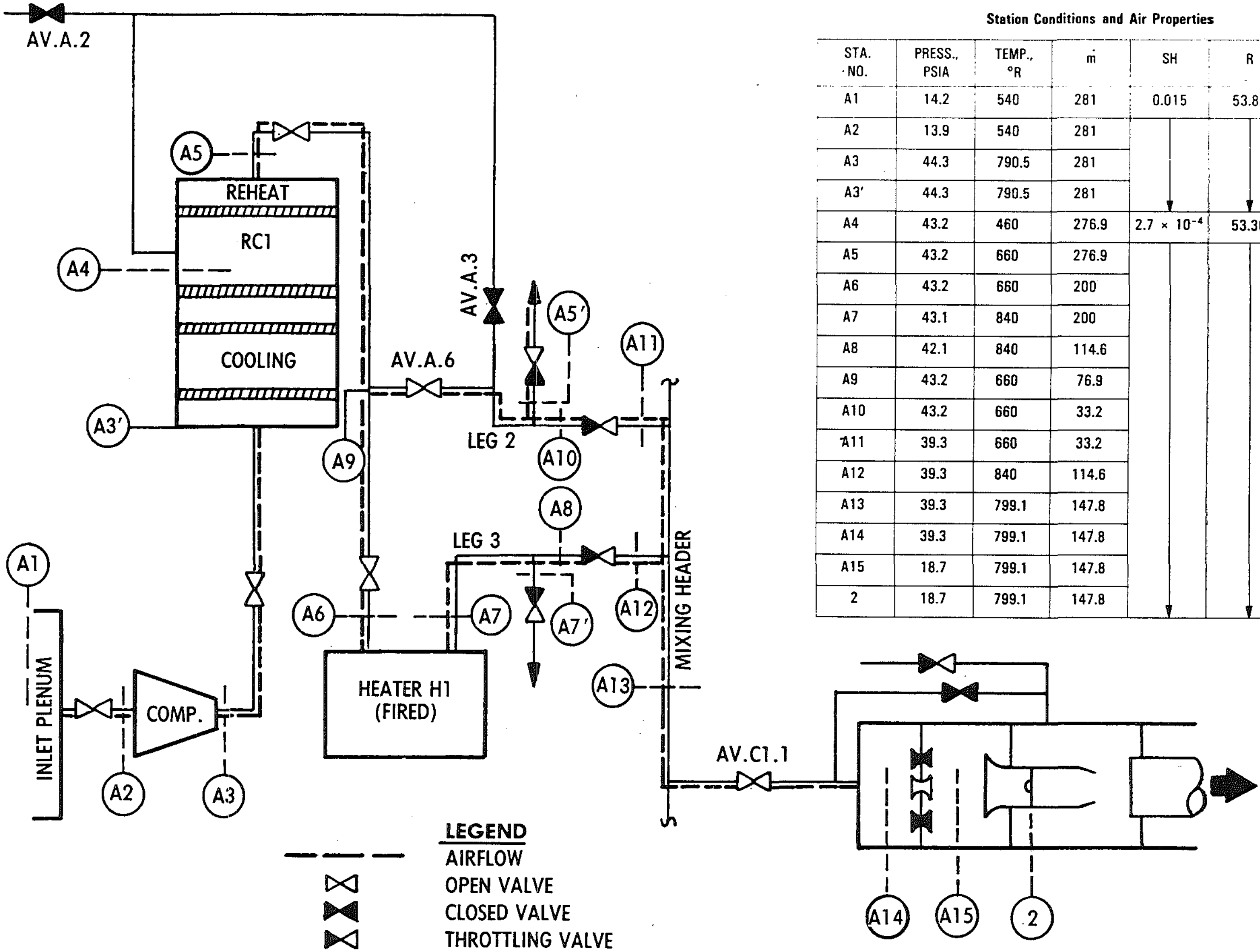


Figure 35. Atmospheric Discharge Configuration.



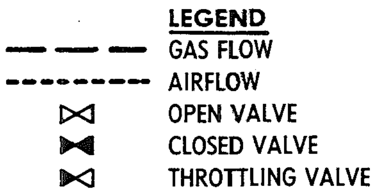
Station Conditions and Air Properties

STA. NO.	PRESS., PSIA	TEMP., °R	ṁ	SH	R	C_p	γ
A1	14.2	540	281	0.015	53.82	0.244	1.395
A2	13.9	540	281				
A3	44.3	790.5	281				
A3′	44.3	790.5	281				
A4	43.2	460	276.9	2.7×10^{-4}	53.36	0.24	1.4
A5	43.2	660	276.9				
A6	43.2	660	200				
A7	43.1	840	200				
A8	42.1	840	114.6				
A9	43.2	660	76.9				
A10	43.2	660	33.2				
A11	39.3	660	33.2				
A12	39.3	840	114.6				
A13	39.3	799.1	147.8				
A14	39.3	799.1	147.8				
A15	18.7	799.1	147.8				
2	18.7	799.1	147.8				

Figure 36. Air Supply System Configuration for Test Scenario No.1.

Station Conditions and Gas Properties

STA. NO.	PRESS., PSIA	TEMP., °R	$\dot{m}$	SH	R	C_p	γ
E1	6.4	3411.4	172.2	0.08	58.62	0.33	1.264
E2	6.4	2960	184.3	0.156	60.37	0.34	1.296
E3	6.4	2960	184.3	0.156	60.37	0.34	1.296
E4	6.4	840	184.3	0.156	60.37	0.34	1.296
E5	6.4	583	199.4	0.251	62.30	0.35	1.297
E6	6.4	583	199.4	0.251	62.30	0.35	1.297
E7	4.06	583	199.4	0.251	62.30	0.35	1.297
E8	4.06	583	317.3	0.251	62.30	0.35	1.297
E9	14.21	804.4	317.3	0.251	62.30	0.35	1.297
E10	14.2	804.4	317.3	0.251	62.30	0.35	1.297



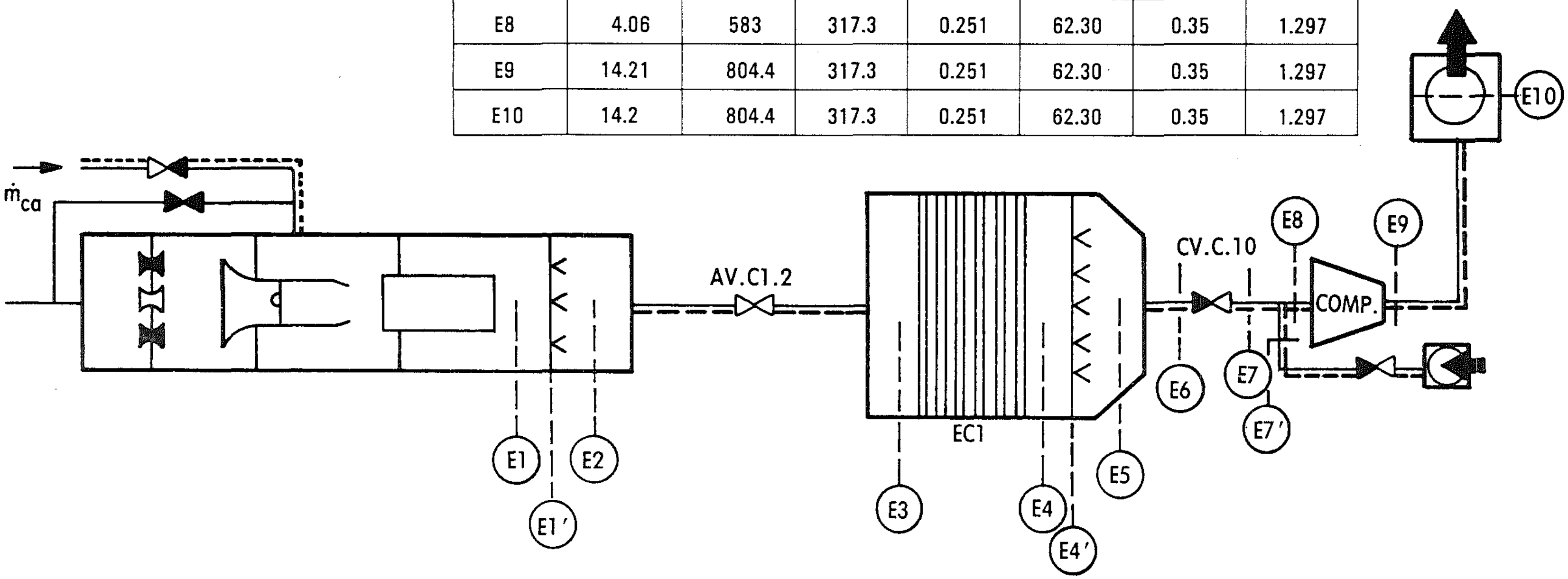


Figure 37. Exhaust System Configuration for Test Scenario No.1.

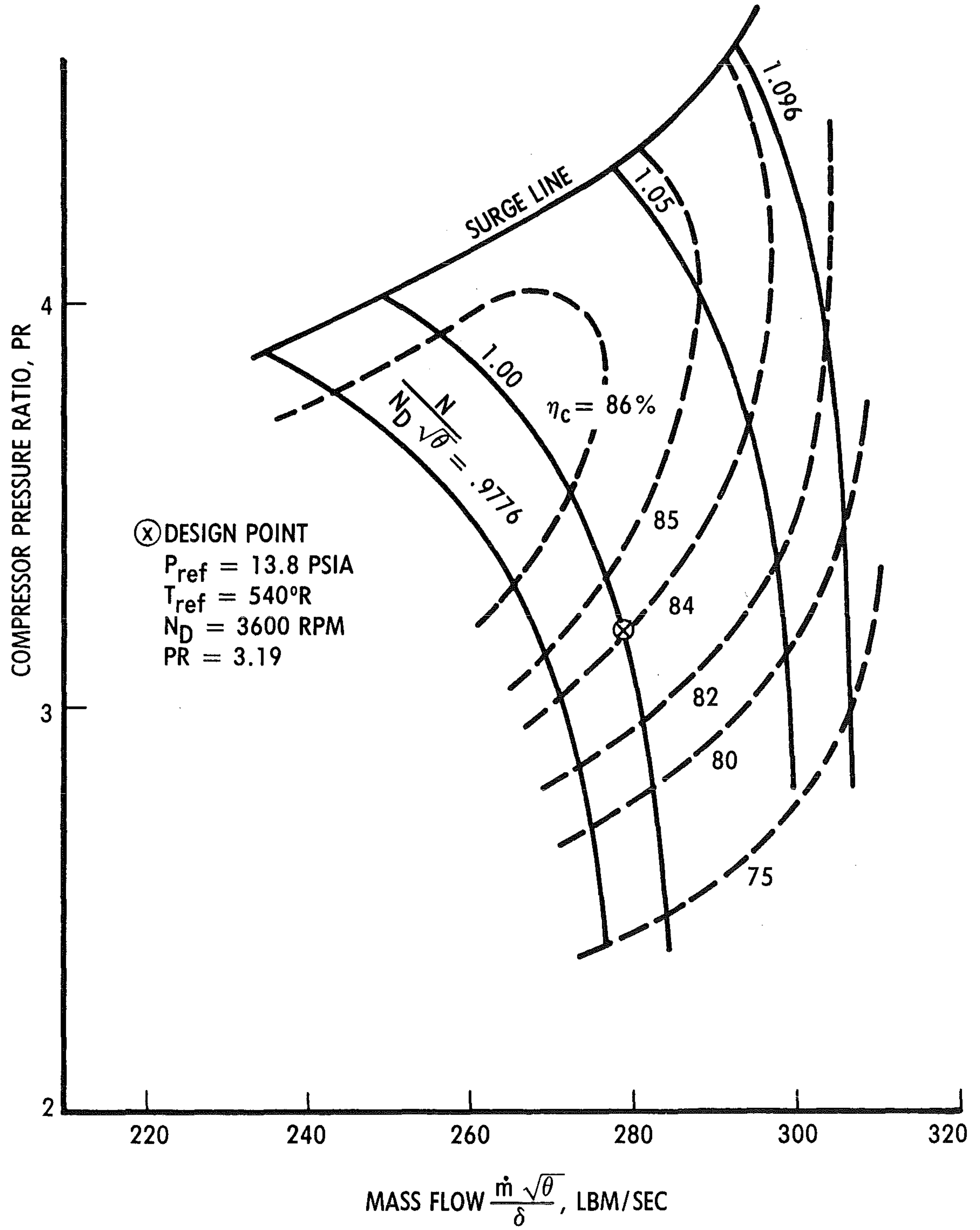


Figure 38. First-Stage Compressor Performance Map.

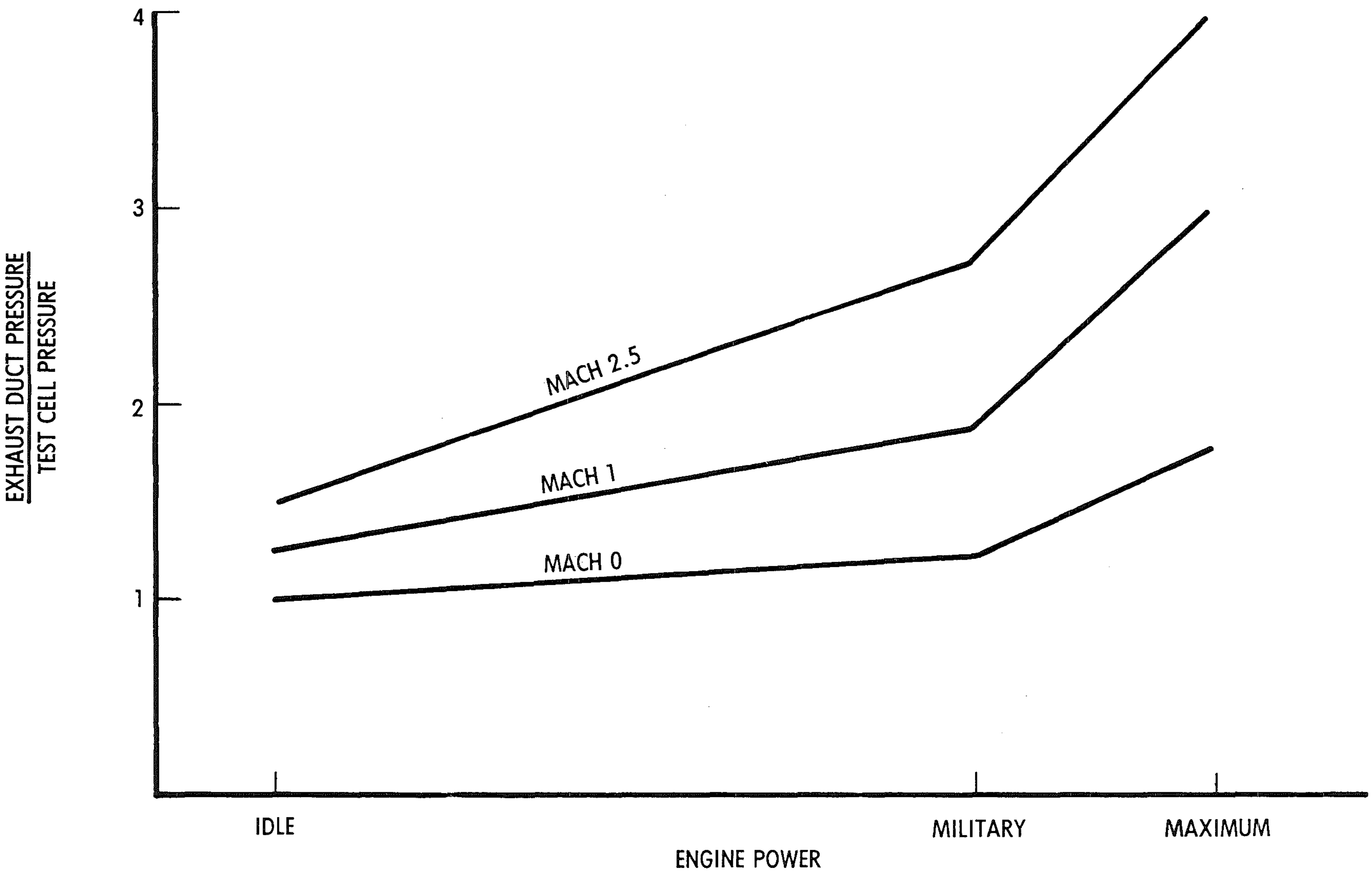


Figure 39. Representative Exhaust Diffuser Recovery Ratio for Turbojet and Mixed-Flow Turbofan Engines.

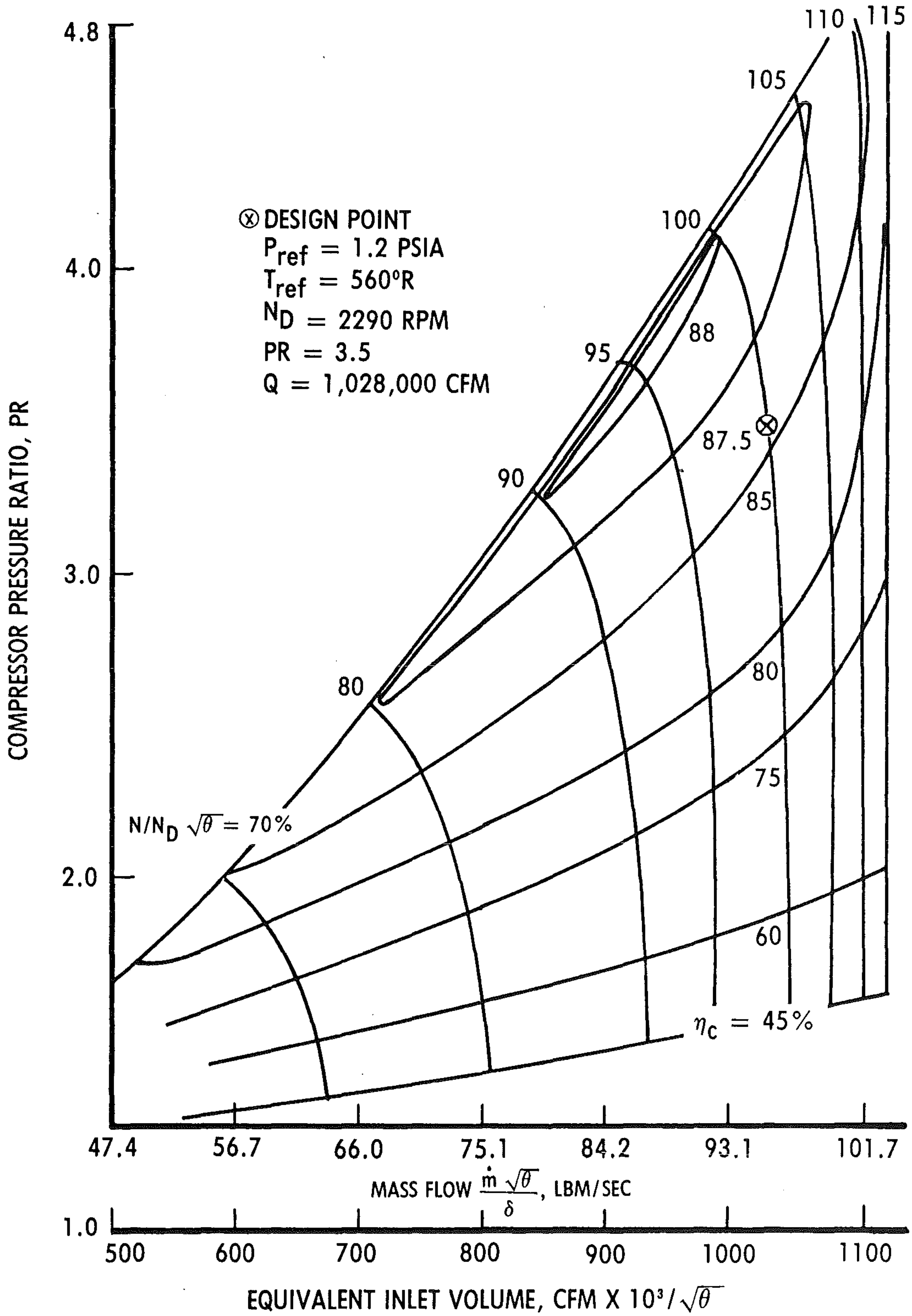
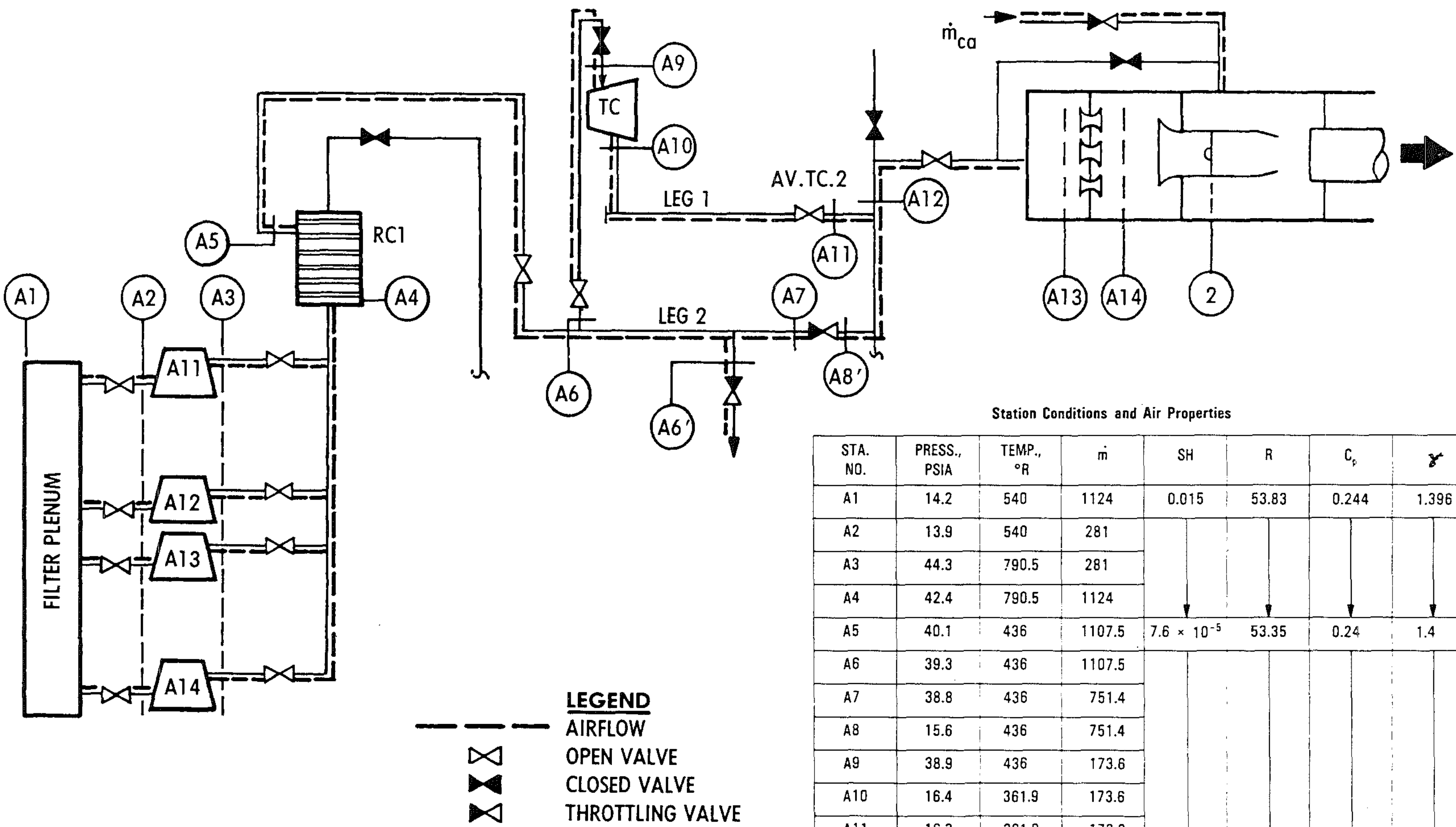


Figure 40. Exhaust Gas Compressor Performance Map.



Station Conditions and Air Properties

STA. NO.	PRESS., PSIA	TEMP., °R	$\dot{m}$	SH	R	C_p	γ
A1	14.2	540	1124	0.015	53.83	0.244	1.396
A2	13.9	540	281				
A3	44.3	790.5	281				
A4	42.4	790.5	1124				
A5	40.1	436	1107.5	7.6×10^{-5}	53.35	0.24	1.4
A6	39.3	436	1107.5				
A7	38.8	436	751.4				
A8	15.6	436	751.4				
A9	38.9	436	173.6				
A10	16.4	361.9	173.6				
A11	16.3	361.9	173.6				
A12	16.3	422.1	925				
A13	16.2	422.1	925				
A14	4.5	422.1	925				
2	4.5	422.1	925				

Figure 41. Air Supply System Configuration for Test Scenario No.2.

Station Conditions and Gas Properties

STA. NO.	PRESS., PSIA	TEMP., °R	$\dot{m}$	SH	R	C_p	γ
E1	3.5	753.4	1019.7	0.016	53.81	0.245	1.393
E2	3.4	753.4					
E3	3.4	560					
E4	3.4	560					
E5	3.1	560					
E6	3.1	560					
E7	6.7	765.2					
E8	6.7	765.2					
E9	6.3	560					
E10	6.2	560					
E11	14.3	768.9					
E12	14.2	768.9					

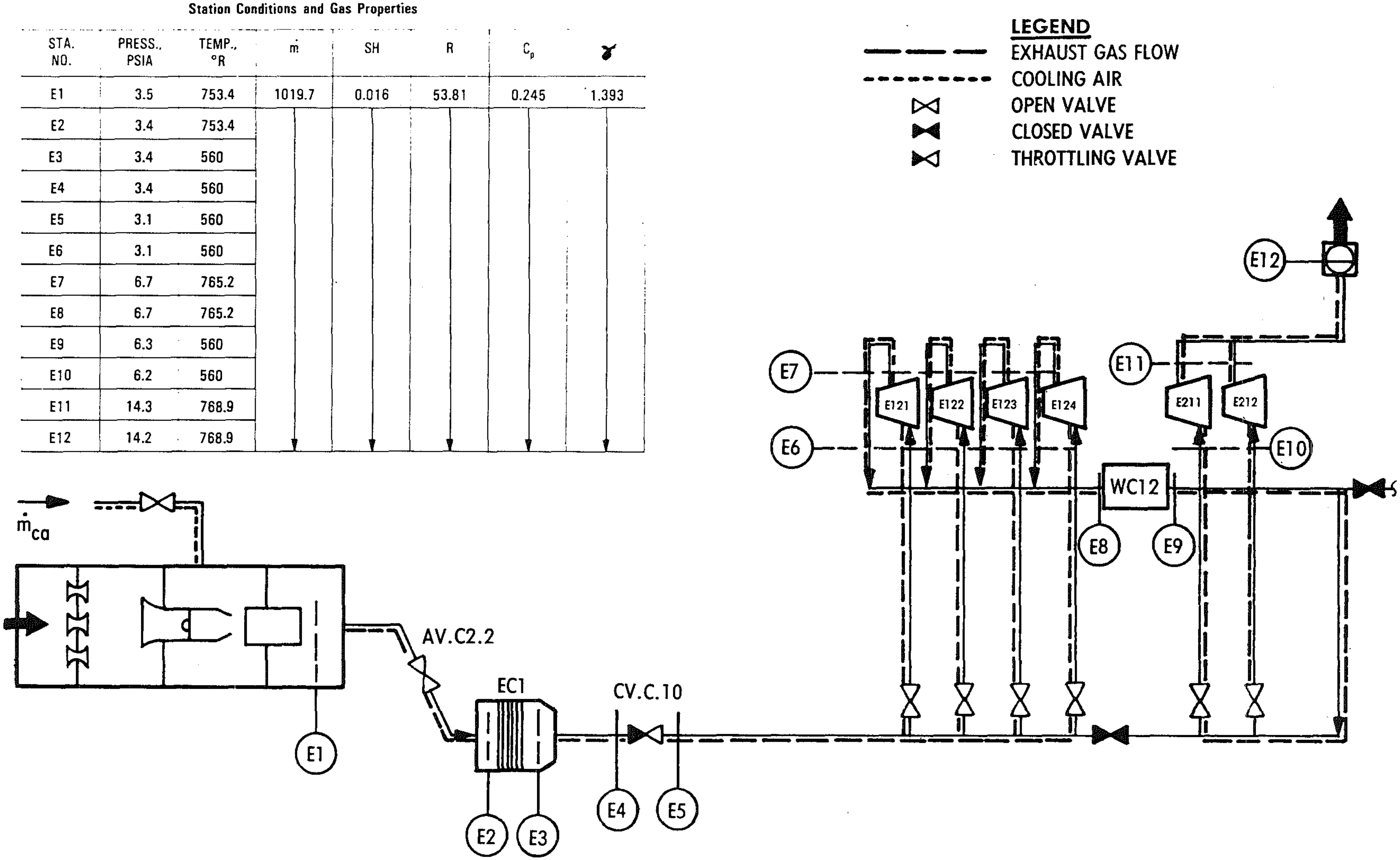


Figure 42. Exhaust System Configuration for Test Scenario No.2.

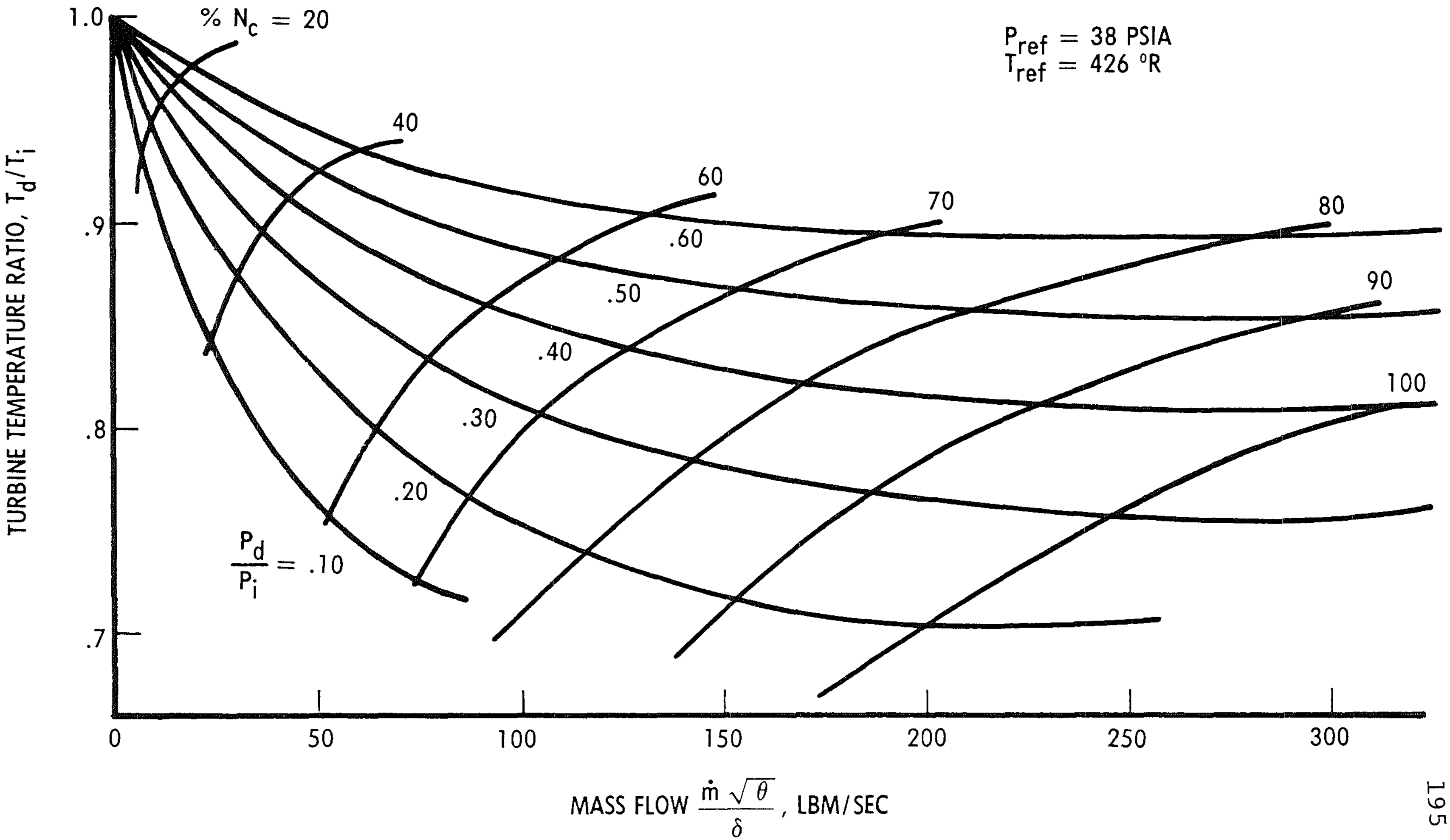


Figure 43. Refrigeration Turbine Performance Map.

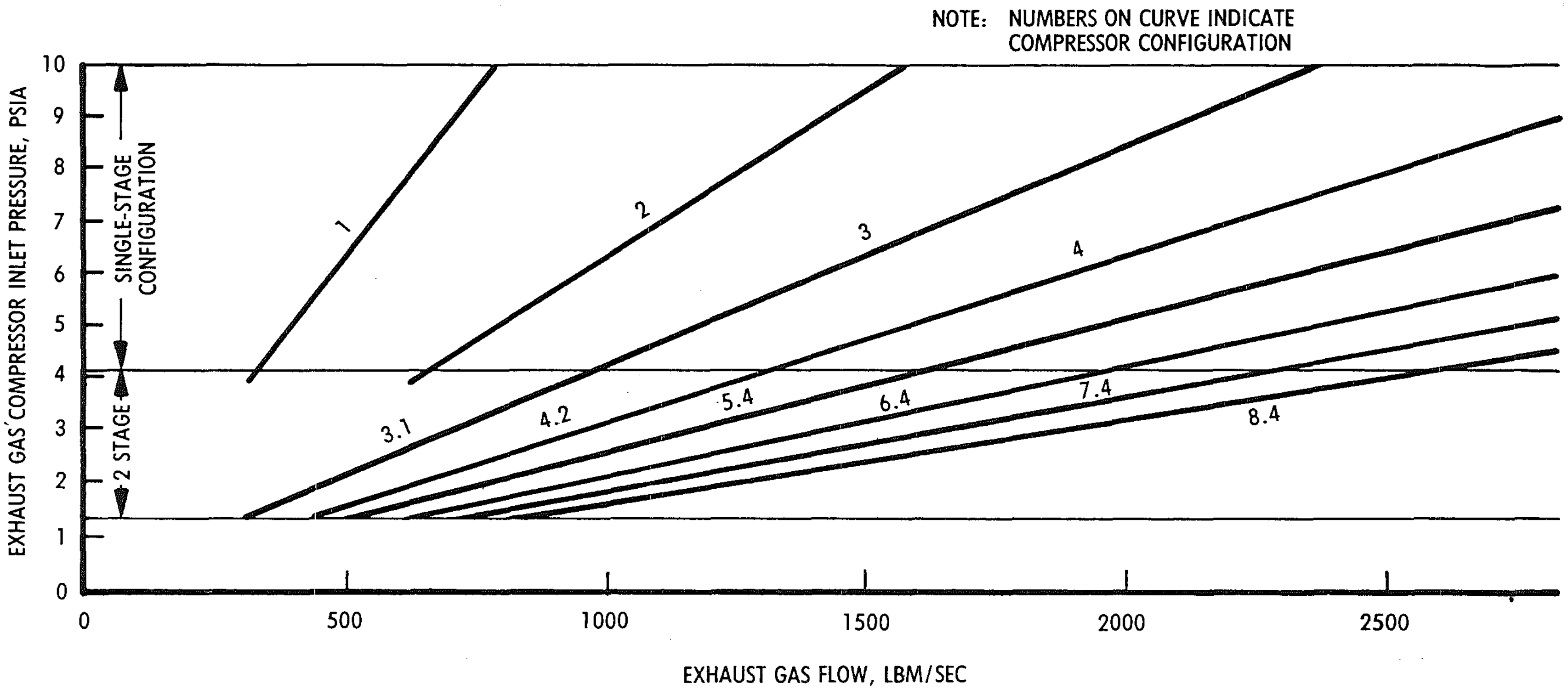


Figure 44. Exhaust Gas System Performance Limits for Turbofan Engine Testing.