To Carl, Jr.
With best wishes.
Dad
26 Nov 59.

Complete scavenging of the jet exhaust products of combustion is one of the basic requirements of the closed-circuit arrangement, together with a supply of "make-up" air to compensate for that removed by the exhaust system.

Aerodynamic and thermodynamic problems of the scavenge system - tunnel combination are considered, and some results are included from special experimental studies undertaken in connection with the engineering design.

Design and Development of the Jet Exhaust Gas Scavenging System for the AEDC Propulsion Wind-Tunnel Facility

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SOME OF the basic design requirements originally established for the Propulsion Wind Tunnels of the Arnold Engineering Development Center (AEDC) were that they should provide facilities for:

(a) Wind-tunnel testing of complete full-scale operating propulsion systems as installed in aircraft or missiles over as full a range as possible of the altitude-Mach Number simulation.

(b) Aerodynamic testing of complete models with "burning jets" and components of aircraft and missiles.

(c) Development testing of ram-jets with complete internal and external flow.

(d) Future tests of rockets.

Analytical studies were made (1949–1950) to determine the most useful and practical size and shape of test section for the facility within certain fixed funding. The studies included power-plant installations of aircraft and missiles in the development stage at the time, and estimated future arrangements for the next 5- and 10-year periods. Based on the results of these studies and estimated numbers of test runs for various configurations, a maximum test section size of approximately 16 ft. square in cross section and 40 ft. long was established. The facility was specified to be of the continuous-flow closed-circuit type to cover the Mach range from about 0.5 to 3.5 (later extended to 5). Supply power available at the time limited the compressor drive horsepower initially to 216,000 and provided for a proposed altitude range of sea level to 100,000 ft.; structural considerations limited the maximum total temperature level to about 650°F. Temperature-pressure matching would then be available up to Mach Number of about 3, beyond which the tunnel would operate too cold for simulated altitude conditions.

Other studies and investigations resulted in the present configurations and general arrangement of Propulsion Wind Tunnel (PWT). This facility actually consists of two separate wind tunnels (see Figs. 1 and 2), each with its own compressor but coupled to a common drive system. The complete drive system, using four electric motors, can be coupled to one tunnel or the other, or half of the drive can be coupled to each tunnel simultaneously. The Transonic Circuit was designed to cover a Mach range from about 0.5 to 1.6, while the Supersonic Circuit was designed to start at $M = 1.5$ and extend to approximately $M = 5.0$. Estimated altitude-Mach Number performance of the PWT obtained from some recently published data is indicated in Fig. 3.

One of the unique features of this facility is the closed-circuit configuration with complete scavenging of the jet exhaust products of combustion, a feature not existing in any other closed transonic or supersonic tunnel. This combination makes it possible to simulate a wide range of altitude conditions and Reynolds Numbers, compared with the existing open-circuit configurations exhausting directly to atmosphere. The closed circuit requires, of course, a supply of "make-up" air to compensate for that removed by the exhaust system. An additional feature arose in the case of the PWT, particularly for the Transonic Circuit, in that a "plenum evacuation system" external to the tunnel had to be incorporated for removing the boundary-layer air by

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Mr. Wenzinger was responsible for the general arrangements and detailed aero- and thermodynamic designs of the facility discussed here. One of the Institute's Founder Members and holder of Electrical and Mechanical Engineering degrees from Swarthmore College, he became associated with Sverdrup & Parcel in 1949 after 16 years with NACA at Langley Field. While with NACA, now NASA, his best known contributions were associated with development of many of the high-lift and lateral-control devices in use on today's aircraft. His World War II service included duty as Officer-in-Charge of the Aeronautical Laboratory, Navy Taylor Model Basin (with additional duties in BuAer), and as a member of a special Naval Mission to Europe to investigate aerodynamic and propulsion activities of the Germans and French.

suction from the perforated walls that were especially developed for the test section, and that air then compressed and reinjected into the tunnel circuit downstream. This permits testing of high blockage configurations without "choking" the test section, and, in addition, reductions can be controlled of the wave reflections at the test section walls.

Engineering Design Problems

The problems encountered in the scavenge system may be considered in two broad categories—those having to do with the flow of the exhaust jet and the tunnel mainstream and those having to do with what may be termed the mechanics of the system.

Specific problems of an aerodynamic nature may be listed as:

(a) Scoop inlet design.

(b) Scoop inlet position (with respect to exhaust jet outlet).

(c) Diffusion of scavenged gases within the scoop.

(d) Conveyance of scavenged gases from PWT to exhaust compressor system.

(e) Design of scoop-tunnel diffuser combination.

(f) Make-up air injection.

Some problems of a mechanical nature are:

(a) Cooling of scavenged gases.

(b) Mounting of the scoop within the tunnel.

Experimental Studies

Jet Exhaust Spreading

The exhaust scoop was one of the main items to be designed and developed, and the primary performance requirements established for it were:

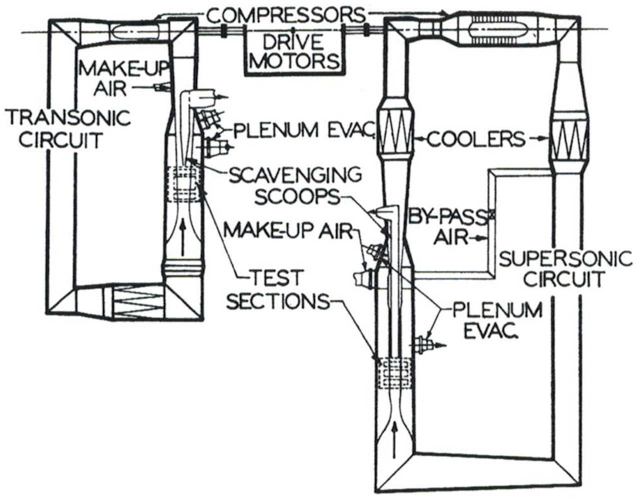

Fig. 1. The Transonic and Supersonic Circuits of the AEDC Propulsion Wind Tunnel.

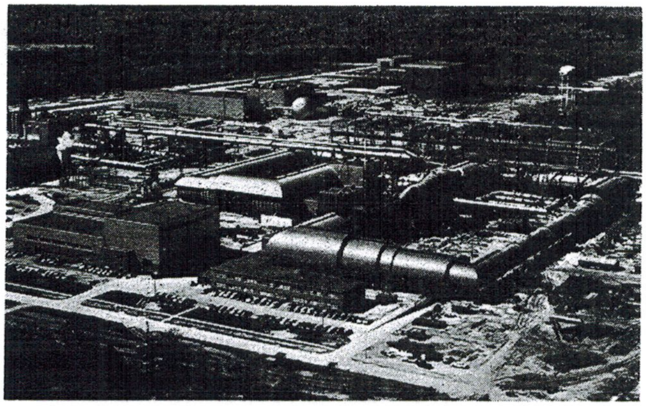

Fig. 2. Aerial view of the AEDC Propulsion Wind Tunnel.

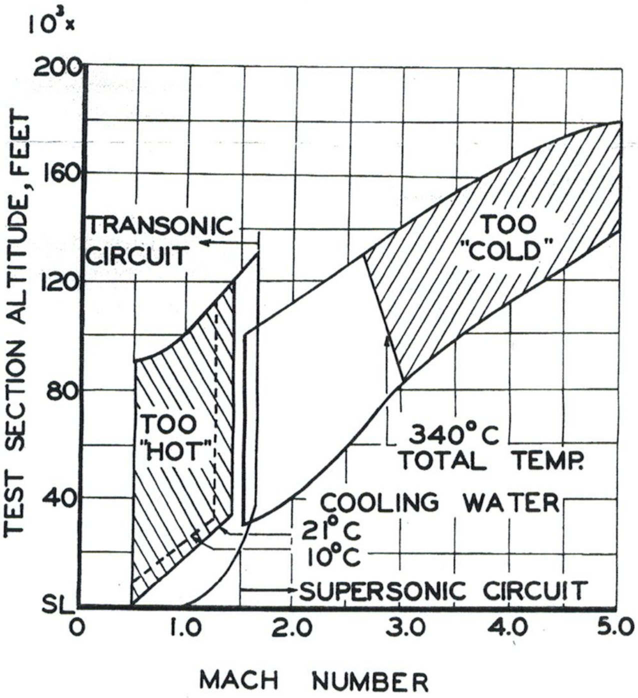

Fig. 3. Altitude-Mach Number performance of the PWT.

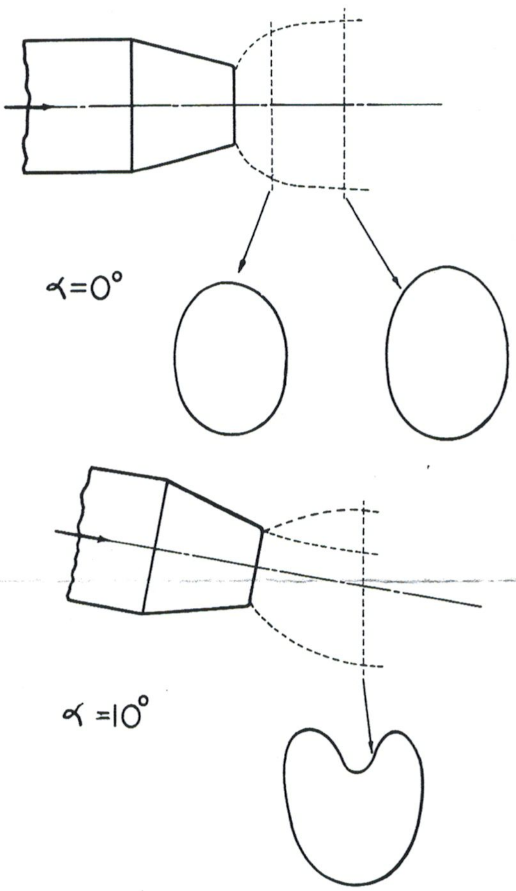

Fig. 4. Exhaust jet profiles and boundaries.

(a) Complete scavenging of the exhaust gases.

(b) Size compatible with anticipated turbojets, ramjets, and rockets.

(c) Adjustment in pitch to accommodate engine angles of pitch to 10°.

(d) Minimum effect on tunnel diffuser.

Test programs were carried out at the United Aircraft Research Department during 1951–1952 and included both hot and cold model turbo- and ram-jets at subsonic and low supersonic tunnel Mach Numbers. Several scoop-to-jet diameter ratios, several scoop locations, and several scoop inlet configurations were tested. Additional tests were made at the Jet Propulsion Laboratory of the California Institute of Technology (1953) to determine the spreading characteristics primarily of hot supersonic jets exhausting into a supersonic stream.

Some typical results from the tests are shown in Fig. 4 for the jet at 0° and 10° angle of attack. The expansion of the jet at different axial stations downstream of the nozzle exit is illustrated quite clearly. The contours obtained at 0° and 10° angle of attack differ considerably, in large measure because of vortices shed by the model at angle of attack.

Test results at 1.5 jet diameters downstream for the simulated turbojet are plotted in Fig. 5 as the ratio of the diameter of the spread jet to the diameter of the nozzle exit versus the Mach Number of the expanded jet. The experimental curve is seen to lie considerably above the theoretical curve indicating the rather high degree of mixing between the exhaust jet and the tunnel airstream.

Analysis of surveys of the jet and of schlieren photographs taken as part of the tests led to the following important conclusions:

(a) Scoop-jet diameter ratios as large as 1.75 may be required in the Transonic Tunnel for hot jets. Cold jets are less critical in importance.

(b) Scoop positions as close as 1.5 jet exit diameters downstream of the jet exit may be used without apparent interference effects on the model at the low Mach Numbers.

(c) Simple conical or parallel-conical scoop inlets appear satisfactory.

(d) Adequate cooling of the lips of the scoop inlet is of great importance.

(e) The simple conical-inlet scoop indicated reasonably high total head recoveries.

Scavenge Scoop - Diffuser Combination

Since the high power requirements of the PWT were a very important item of equipment and operating costs, all losses in the tunnel circuits had to be kept to a practical minimum. Considerable information was available regarding the performance of variable-geometry diffusers, but none of the data or existing theories was adequate to predict the effects of the scavenge scoop on diffuser performance. Experimental investigations were therefore conducted at various laboratories (University of Minnesota, Naval Ordnance Laboratory, United Aircraft Corp., University of Texas) to determine the optimum performance and configuration for the design of the scavenge scoop - variable geometry diffuser combination primarily for the PWT Supersonic Circuit.

Effects upon diffuser performance were determined for items such as Mach Number range, Reynolds Number, scavenge-scoop configuration, second-throat configuration, etc., and with and without a model in the tunnel test section. As a result of these investigations, suitable arrangements were developed for both the PWT Transonic and Supersonic Circuits. The com-

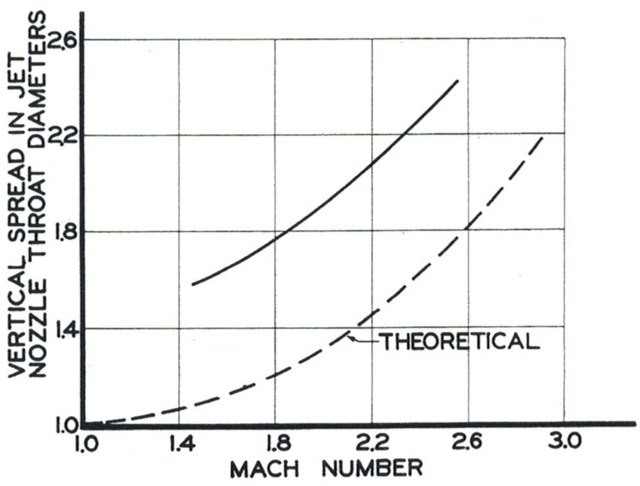

Fig. 5. Jet spread with expanded-jet Mach Number.

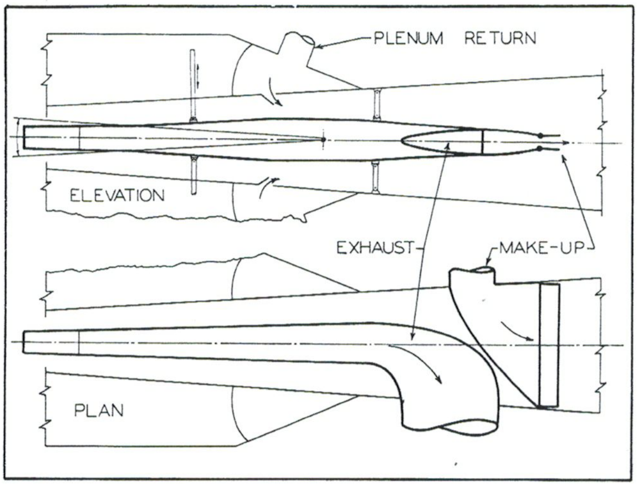

Fig. 6. PWT Transonic Circuit scavenge scoop - tunnel diffuser.

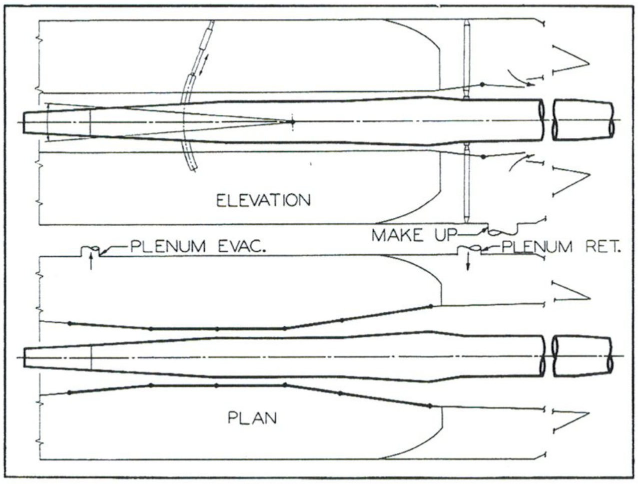

Fig. 7. PWT Supersonic Circuit scavenge scoop - tunnel variable geometry diffuser.

binations decided upon as most satisfactory for the requirements are outlined in Fig. 6 with fixed diffuser for the Transonic Circuit, and in Fig. 7 with variable-geometry diffuser for the Supersonic Circuit.

Make-Up Air

All products of combustion are to be removed by the scavenge system in order to avoid contamination, and all air-fuel mixture exhausted by the propulsion unit before starting must also be removed to minimize any danger of explosion in the circuit. A certain amount of tunnel air is thus removed by scavenging, and the entire mass must be replaced with fresh air. This mass of air must be conditioned and introduced into the tunnel so as not to cause excessive losses in the basic tunnel circuit.

In addition, although not directly concerned with the scavenge system, the boundary-layer air previously mentioned as being removed from the test section walls must also be reintroduced into the tunnel without causing excessive losses. The two systems are thus somewhat interrelated in this respect, and that part of the problem was analyzed and the solution arrived at for the combination of effects. Figs. 6 and 7 also indicate the basic arrangements used for reinjection in both the Transonic and the Supersonic Circuits.

When products of combustion are not being removed from the airstream as in the case of purely aerodynamic tests, then the scoop, exhaust, and make-up air systems are used only to set and adjust the pressure and humidity levels in the wind-tunnel circuit. In this case, it was found that it may be desirable to use a different shape of scoop inlet to provide for somewhat more efficient diffuser recovery.

Cooling and Structural Considerations

General

The exhaust jets issuing from the operating propulsion units were considered to be at a high temperature, approximately 3,500°F., and also to contain some combustible gases which could ignite under certain conditions. This means, of course, that the scavenged gases must be cooled and the entire scavenging system itself protected from high temperatures. Items to be considered were scoop inlet, scoop diffuser, connecting ducting to exhausters, and exhauster units.

A chart was prepared which provided the basis for a large portion of the thermodynamic calculations for spray cooling and dehumidification. This chart is illustrated as Fig. 8 and is interpreted as follows: The initial exhaust gas condition is indicated by the intersection of the 3,500°F. curve with the "water of combustion" curve. As spray cooling is applied, the temperature of the exhaust gases will decrease while their specific humidity will increase as shown by the curve. This process will continue until the saturation temperature corresponding to the pressure in the cooling chamber is reached. Further cooling will then proceed along one of the curves labeled "saturation curves" and will continue as long as the cooling water is able to absorb heat.

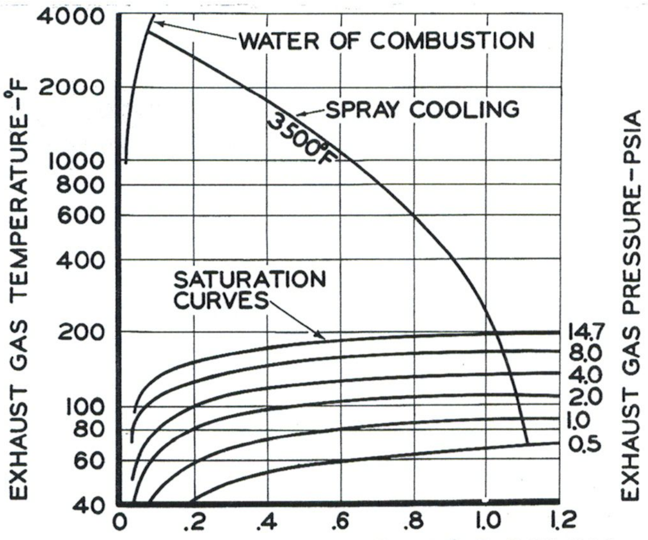

Fig. 8. Jet exhaust gas conditions during spray cooling.

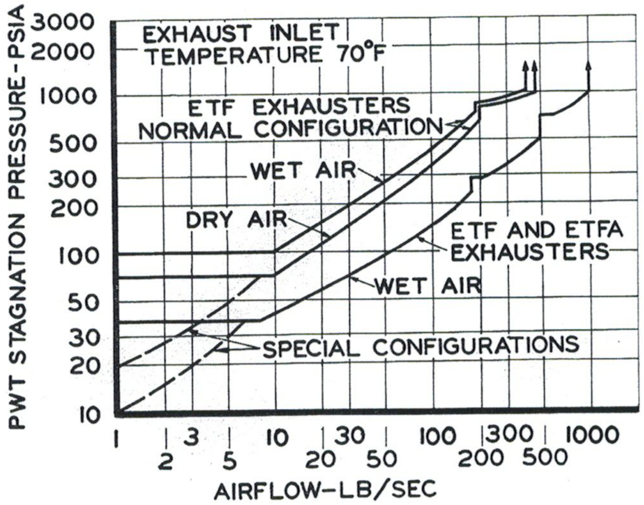

Fig. 9. Scavenging capacity as a function of tunnel stagnation pressure.

Cooling

Some analytical studies were made initially of cooling methods. Assuming that the scoop diffuser material could withstand the high temperature, it was found that only a relatively small drop in the gas temperature would occur (5° to 6°F. per foot of duct) from combined convection and radiation. In addition, because of the high initial temperatures and restricted space and mechanical considerations, "dry cooling" by some type of shell and tube heat exchanger within the scoop diffuser was not feasible.

Other methods considered were external duct surface cooling by water, internal surface water-film cooling, water-jacketing, and direct water spray cooling of the hot gases. It was determined that spray cooling was the most advantageous method and that scavenged gases should be spray cooled to near saturation as soon as possible. In order not to induce choking within the duct, spraying should not begin until the gases have been diffused to a moderate Mach Number ($M = 0.6$ to 0.75).

As noted previously, test results indicated the great importance of adequately cooling the lips of the scoop inlet. However, because of its limited entrance size and the high velocity of the entering gases, water-jacketing and spray cooling were not feasible. The inlet portion of the scoop was therefore designed as a replaceable section of stainless steel, approximately three inlet diameters long, without water cooling. This arrangement also permitted the use of different sizes and shapes of that part of the installation. The walls of the scoop diffuser between the replaceable tip section and the saturation sprays were protected by water-jacketing for the Transonic Circuit, and by film cooling for the Supersonic Circuit.

Water Requirements

A special study of spray cooling, undertaken at the University of Minnesota, gave information from which the quantities of cooling water and spray bank arrangements could be determined. It was assumed that the hot gases would be spray cooled down to a point near saturation, about 200°F., which would give a specific humidity of roughly one pound of water per pound of dry air. The actual distance required for the spray to cool to 200°F. was determined to be quite small so that a relatively short length of duct was needed following the saturation sprays to permit the water to evaporate and the flow to stabilize before making the turn into the duct leading out of the tunnel. It was not necessary to cool the scavenge duct downstream of the saturation sprays because the gas temperature would be low enough for the structural steel to withstand.

Based on some proposed propulsion units expected to be tested, the amount of water required for spray cooling to 200°F. was calculated at about 2,000 gal. per min. The condition of engine "flame-out" or "cold-flow," as well as the need for fire protection, dictated the use of the maximum amount of 4,000 gal. per min. cooling water flow.

The excess free water must be removed from the scavenge system to protect valves and turning vanes in the ducting from damage and also to minimize any hazard of "water hammer." In addition, some provision for water separation must be made to safeguard the blading of the exhauster machines. Water drains were located at several elevations above grade in the scavenge system and empty into a barometric well

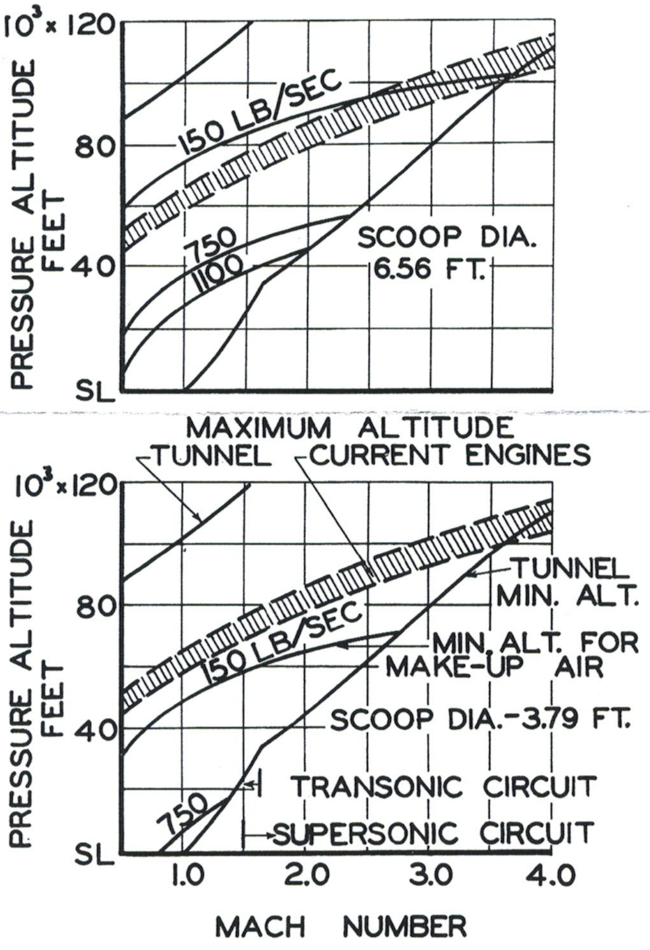

Fig. 10. Make-up air capacity effect on PWT performance for two scavenge scoop sizes.

which maintains a water leg seal of the ducting. A separator of the "Centifix" type is located near the inlet to the exhausters to further assure adequate removal of any excess water.

Exhauster and Make-Up Air

Exhaust System

The scavenging system, as pointed out previously, will capture the supersonic jet gases and some tunnel air, and diffuse the mixture to subsonic speeds. These gases will then be cooled and exhausted to atmosphere by means of the exhaust compressors associated with the existing AEDC Engine Test Facility and Engine Test Facility Addition (ETF and ETFA). Estimated capacities of the ETF and ETFA exhauster system from some recently published data[1] are shown in Fig. 9 as a function of the PWT stagnation pressure. The ETF exhaust system is now available for exhausting and tunnel pressure level control, and the additional increment in the ETF exhaust system will soon be available.

The minimum allowable scoop inlet size would be selected for a given engine nozzle exit and, depending upon the jet spreading expected, would be located for interference-free conditions. The scoop inlet size then fixes the scavenging and make-up air requirements, which thus determine the available operating range for the given engine in the PWT.

Make-Up Air System

In order to maintain desired tunnel mass flow conditions, make-up air equal to that scavenged must be re-injected into the tunnel circuit at a sufficient dryness to prevent condensation of moisture particles in the air. The air supply system of the ETF-ETFA test facilities already available was therefore selected as the main source of continuous-flow make-up air for both the Transonic and Supersonic Circuits of the PWT. This air supply system includes both heating and cooling equipment so that tunnel requirements can be met within certain limits.

The make-up air temperature must be maintained at the temperature of the tunnel main stream so as not to affect the compressor performance. Although the temperature in the stagnation chamber of the Supersonic Circuit will reach a maximum of 650°F., the airflow will be cooled prior to re-entering the compressor by (a) the pressure drop across the nozzle, (b) the make-up air which will not exceed 175°F., and (c) a cooler (by-pass) just downstream of the test section.

Since the only parameters requiring close matching to the tunnel main stream are the temperature and weight flow of the circuit, the injection pressure of the make-up air can be held equal to or greater than the total pressure at the injection location. Control of the pressure will be used to energize the wake from the trailing edge of the scavenge scoop support strut for the Transonic Circuit as indicated in Fig. 6, and to improve the diffuser recovery in the Supersonic Circuit (Fig. 7).

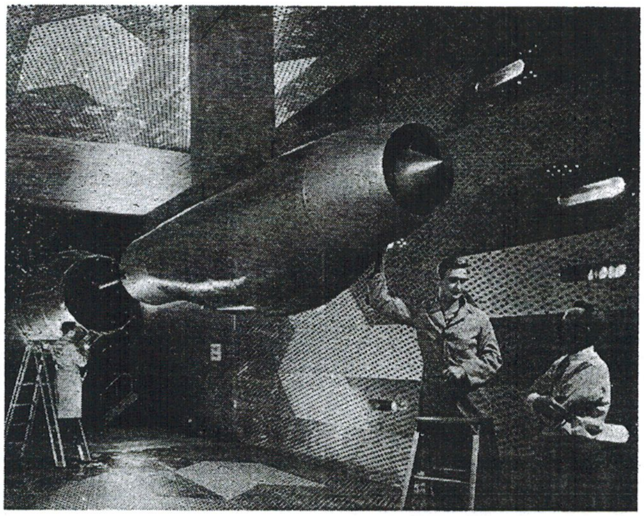
Fig. 11. Full-scale propulsion unit set up for test in the transonic test section.

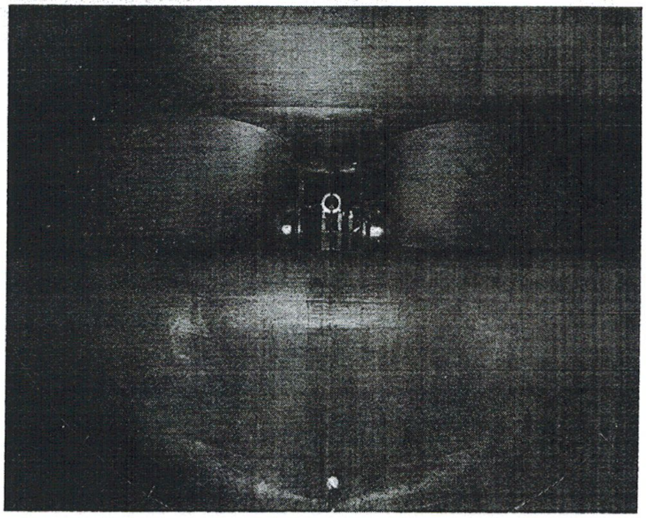
Fig. 12. View of transonic test section from stagnation chamber.

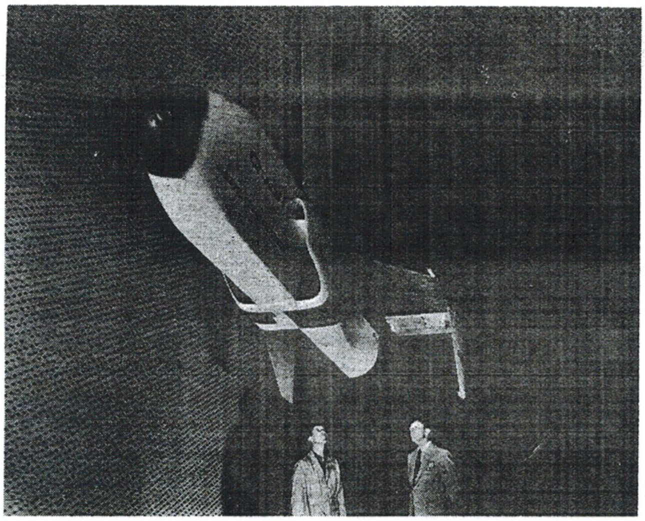
Fig. 13. The Quail (GAM-72) missile installed for test in the transonic test section.

Should the continuous flow make-up air supply system not be capable of replacing all the scavenged air for the PWT, then a penalty of decreased tunnel performance is imposed if constant tunnel flow conditions are to be maintained. In the case of the PWT, where altitude simulation is a basic requirement, this penalty would show up as a limitation on the minimum altitude simulation attainable for any given weight flow of make-up air. Fig. 10 shows the effect of make-up air capacity on PWT performance for two different scoop inlet sizes.[2]

Full-Scale Tests

Experimental

Some tests were recently completed in the PWT Transonic Circuit of a full-scale propulsion unit to evaluate effects of scavenging-scoop proximity, scavenging flow rate, and scoop angle of attack on interference experienced by the test article, on tunnel airstream contamination, and on engine and tunnel operations. The engine-pod installation with supersonic air-inlet configuration and nacelle housing a Westinghouse J-34 turbojet engine is shown set up in the test section in Fig. 11. A view of the empty test section looking downstream from the stagnation chamber is shown in Fig. 12.

These test results indicated[3] that interference-free testing is possible over the complete range of tunnel Mach Number (0.8 to 1.6), altitude (20,000 to 60,000 ft.), and test article angle of attack (−7° to 10°) used in the tests. Scavenging flow rates required to produce interference-free testing were found to fall well within practical modes of tunnel and scavenging system operation. In addition, contamination-free testing was found to be possible for all modes of operation producing interference-free operation.

Complete Missile

An investigation of the full-scale Quail missile (GAM-72), manufactured by McDonnell Aircraft for the U.S. Air Force, was recently conducted in the PWT Transonic Circuit (see Fig. 13). The tests duplicated the Quail flight regime of Mach Numbers and pressure altitudes with the primary object being investigation of the turbojet engine-airframe compatibility. Special emphasis was placed on determination of the engine stall and performance characteristics as integrated with the air-induction system.

A total of 42 hours' engine operation and data recording was obtained during a tunnel usable occupancy time of 80 hours which would have required well over 100 flights and a much longer time to obtain similar data. The operation of the tunnel, scavenge system, and associated equipment bore out to a satisfactory degree the design and development predictions of the facility performance.

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