FULL-SCALE ENGINE RESEARCH

Part I - Research Techniques and Facilities

by E. W. Conrad and Martin J. Saari, Jr.

During your visit here today you will see several examples of our research efforts aimed at the improvement of components for jet engines. Closely related to this component research is our work with the full-scale engine which is necessary because of the many problems that occur when all of these components are assembled into a complete engine. I would, therefore, like to discuss some of the objectives, techniques employed and facilities used in our full-scale engine research. (CS-8900)

To better appreciate some of these problems, let us focus our attention on this cutaway turbojet engine (right of stage). We see that the engine is composed of many components, the principal among which are the compressor, combustor, turbine and exhaust nozzle. It should also be realized that when the engine is installed in an airplane, a duct with an air inlet is attached to the front end of the engine. Now, though each of these components may be designed and developed to operate perfectly as individual units, we find that they may not operate satisfactorily in the environment and conditions created by the neighboring components. For example, the flow leaving the compressor may be so distorted or uneven as to materially reduce the efficiency of the combustor or to create localized hot regions that may destroy the turbine blades. Similarly, the inlet duct may influence the operation of the compressor in such a way as to cause it to stall or surge, resulting in blade failures or loss of power output. Other typical research problems involving the full-scale engine are combustor blow-out at high altitude, overheating of the critical parts of the engine, or unstable action of the automatic control system.

To discover and solve these many problems in the laboratory before an engine reaches the production stage obviously saves an enormous amount of time and effort. It further serves to guide and establish realistic research objectives for our future work on advanced components.

To carry out this research with full-scale engines requires some large facilities and several different techniques are used, each applicable to a particular type of problem. These techniques are listed in this next slide (CS-8898). They are:

1. Direct-connect
2. Free-jet
3. Supersonic wind tunnels
4. Flight tests

The direct-connect technique is the simplest and most direct method and is used to study the internal performance of the engine. As shown

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in the next slide (CS-8903), the engine, in this case a ram-jet engine, is mounted inside a test chamber on a thrust stand with the air duct connected directly to the engine. The pressure and temperature of the air in this duct are maintained at the same values as exist in actual high speed flight. The pressure of the test chamber is maintained at the desired altitude pressure. Thus the engine performs as if it were operating at high altitude.

While this method permits study of problems related to the engine itself, it does not simulate the conditions existing in the complete air inlet system. To study these effects introduced by the air inlet, the free-jet technique shown in the next slide (CS-8904) is used. This method is similar to the direct-connect method except that the inlet duct is replaced by a nozzle which produces a supersonic jet of air. Thus the air inlet of the engine is completely submerged within a stream of air that simulates supersonic flight at high altitude. This free-jet technique is being used at the present time in a study of two "research versions" of ram-jet engines in these two test chambers (open lids on test cells to left and right of audience).

The installation on your left is illustrated schematically in this slide (CS-8904). Such an engine, with a straight symmetrical inlet duct, will be used on a missile of this type (Spot model, off stage, left center). The installation on your right is illustrated by this next slide (CS-8902). In this case the engine inlet is semi-circular in shape and consequently the supersonic nozzle is also of semi-circular cross section. Such an inlet, with its curved air duct, would be used in a missile like this (spot model, off stage, right center) where the engine is buried in the fuselage. From this brief description it is seen that the free-jet technique is a refinement of the direct-connect method in that it permits the study of the internal performance of the complete power plant system, including the air inlet duct.

The newest and largest facility in which these two techniques are used is the Propulsion Systems Laboratory in which you are now seated. This facility is illustrated by this construction model (spot model, upper left center). The two test chambers, in which our ram-jet engines are installed, are located here. All of this remaining equipment is used to provide the proper environment for the test engines. The air is delivered at high pressure by several compressors located in this Equipment Building. Also located in this building are air driers, refrigeration turbine and air heaters. The low pressure in the test chamber required for altitude simulation is provided by several large suction pumps or exhausters in this building. The extremely hot exhaust gases from the engine are cooled by these large coolers before passing into the exhausters.

With this facility, and our direct-connect and free-jet techniques, we can, you will recall, study the internal performance of complete engines and their associated inlets. A limitation of the free-jet technique is, of course, that the supersonic stream is only a little larger than the air inlet of the engine itself and thus does not allow the study of problems associated with the external flow over the complete engine installation. Therefore, the effect of spillage of air around the inlet or of external flow on the performance of the engine exhaust nozzle cannot be evaluated by this technique.

To study these and other similar problems, supersonic wind tunnels are used. In the wind tunnel shown in this slide (CS-8905) the supersonic stream fills the entire test section and is, therefore, much larger than the engine installed, which permits study of the external aerodynamics.

In our 8- by 6-foot supersonic tunnel shown by this construction model (spot model, extreme upper left of stage), the test section is located at this point. Air at supersonic speeds is forced through the 8- by 6-foot test section by this 87,000 horsepower compressor. The velocity of the air in the test section can be varied from 1½ to 2 times the speed of sound by adjustment of the flexible walls of the test section. The air entering the tunnel is dried by adsorption in this huge building to insure proper flow conditions in the test section. During operation of the tunnel, as much as 1 ton of water is removed from the air each minute.

To accommodate larger engines at still higher air speeds, a new facility depicted by this model (spot model, lower left of stage), is now under construction. This facility is a part of our nation's Unitary Tunnels Program. The test section of this tunnel is 10 by 10 feet and is located in this building. The air is forced through the test section at speeds between 2 and 3½ times the speed of sound by these two large axial-flow compressors which have a total power absorption of 250,000 horsepower. It will be noted that because of the larger test section and the higher air speeds, the power consumption of this tunnel is approximately three times that required by the 8- by 6-foot supersonic tunnel. The unique thing about this tunnel is that it can be operated either as a closed-circuit tunnel or as an open-circuit tunnel. For propulsion research where fuel is burned in the test engine, the tunnel will be operated as an open-circuit tunnel. In this case the air would be drawn into the tunnel circuit through this large air drier, through this first compressor, through the test section, and then through the second compressor, after which the air is ejected into the atmosphere through this large exhaust stack. For research problems where fuel is not burned in the test engine, the tunnel may be converted into a closed-circuit tunnel by the operation of this large valve and, therefore, the air would follow a closed path around the tunnel. With this mode of operation, somewhat larger ranges of altitude conditions could be obtained in the test section.

Just as the components of an engine must finally be proven in the engine itself, so must the complete engine be proven in flight. You will recall that the fourth method of full-scale engine research was that of flight testing. The next speaker will discuss some of the general aspects of our full-scale flight research work.

Part II - Flight Tests of Full-Scale Ram-Jet Engines

by John H. Disher and Leonard Rabb

As the previous speaker pointed out, in order to obtain a complete performance evaluation of an engine, actual flight tests are required in addition to tests under simulated conditions. Conditions which are encountered in flight and which cannot readily be simulated include high acceleration, with rapidly changing altitude and Mach number.

In order to obtain these flight data on one important type of engine, the ram jet, the NACA has flown a series of ram-jet propelled, pilotless models similar to these on the stage (left). Now, before going on to discuss these flight tests, let us consider the characteristics of a ram-jet engine. A schematic diagram of a supersonic ram jet is shown here (overhead, center).

The ram-jet engine, in contrast with the turbojet engine, has no moving air compressor and depends on forward velocity to compress or "ram" air into the engine. The air is slowed down in the engine diffuser with a resulting increase in pressure. Heat is added to the compressed air in a combustion chamber, and the heated air discharges from an exit nozzle in a steady stream at a high velocity, giving a thrust force. It is apparent that at zero speed, the engine has zero thrust and some means must be provided for obtaining the initial speed required for operation. Launching the model from the ground with booster rockets, or launching from an airplane are two methods that may be used to obtain this initial velocity.

The NACA has used both of these methods for launching ram-jet engines. Typical altitude time histories for both the air-launched and ground-launched models are shown in this slide (CS-890D). The air-launched models start off at high altitude and low Mach number and reach maximum speed near sea level. The ground-launched models, on the other hand, accelerate upward and reach maximum speed at high altitude.

We have a brief movie showing the two methods of launching. First a ground launch firing will be shown. The model you will see is similar to this one on the stage. The model is a twin engine ram-jet propelled vehicle. The two engines are mounted to the tail surfaces of the vehicle and are about 7 inches in diameter. (Movie) Here the model is shown as it is brought to the launching ramp, and here it is on the ramp ready for firing. The booster rocket is in tandem with the model. The booster will accelerate the model to a Mach number of about 2.2 after which the booster separates and ram jets take over. The model reaches an altitude of over 100,000 feet during the flight. (End movie.)

The air-launched engines have been either 16 inches in diameter, as this one (standing off-stage right) or 10 inches in diameter as the smaller one (on stage, extreme right). The larger engines have been used for gasoline fuel tests while the smaller engines are used for experimental fuels of limited availability.

In the next film sequence, air launching of engines similar to these is shown. (Movie) Here the plane is shown in flight with a 16-inch engine under the wing. The engine is ignited on the airplane and released after satisfactory operation is observed. Now we see one of the smaller engines on the launching plane. The engine is again ignited and observed before release. Launching occurs at about 35,000 feet altitude and the models reach sea level about 40 seconds after release from the carrier plane. (Movie off.)

Now there is little point in flying these pilotless models unless we can know accurately how the engine is performing throughout the flight. (Pick up telemeter unit from shelf at right). To do this we use equipment called a telemeter, which is contained in the forward part of the engine island, or centerbody, of the air-launched models or in the fuselage of the ground-launched vehicles. A telemeter unit is simply a small, highly refined radio transmitter which is designed to transmit data rather than voice or music. The radio signal transmitted changes systematically with variations in the quantities measured. It is possible to transmit virtually any measured quantity by this means with an accuracy comparable to that obtained with conventional instrumentation. This particular telemeter is equipped to transmit eight pressure and acceleration measurements. The telemeter is on the air right now and the transmitted signal for one of the pressure measurements is being picked up by a receiver behind the stage and fed into this oscilloscope (right center). Watch the signal change as I change the pressure. Although here the signal is only transmitted a few feet, and the transmitter is stationary, accurate results have been obtained while the models are travelling through space at a velocity of over 4000 miles per hour. The data are recorded at ground receiving stations on rolls of photographic paper like this (hold up section of chart record). Here is an excerpt from a typical record. A one-second time interval has been indicated. Each measurement is represented by a separate line. The change in conditions here (point to right end of chart) were, in this particular case, caused by the model running out of fuel and starting to slow down.

During the past several years that these flight tests have been in progress, we have demonstrated the value of full scale engine tests by the free flight technique. Significant increases in fuel economy, Mach number, and range have been observed. One of the interesting phases of our ram-jet research has been the control problem. This subject will be discussed by the next speaker, Mr. _________.

Part III - Ram Jet Controls

by Seymour C. Himmel and Fred A. Wilcox

The purpose of this phase of our discussion of full-scale engine research is to acquaint you with some of theproblems associated with the control of supersonic engines. To help us in this discussion we have a number of visual aids up here on the platform. In addition to the model of the ram-jet engine (overhead) there are several gages (left center) to indicate the operating conditions of the engine, and over here (right center), a throttle which enables me to change the operating point of the engine.

Mr. ________ briefly described the operation of the engine and I would like to discuss the operation of the air intake system a little more deeply. The inlet of the ram jet is the compressor for the engine and as Mr. _______ noted, it has no moving parts and compresses the air by slowing it down. You can bring this to mind perhaps by recalling what you feel when you put your hand out the window of a moving automobile. You feel a force acting on your hand because your hand is slowing down an air stream which results in an increase in the pressure of the air and thus the air pushes on your hand. The same sort of thing happens in the inlet of a ram jet and as long as we are flying at subsonic speeds the transition from velocity to pressure occurs gradually and smoothly along the length of the diffuser. Once we attain supersonic flight speeds an entirely new phenomenon arises -- this is the phenomenon of shock waves. A shock wave is a very abrupt transition from velocity to pressure and it occurs in an extremely short distance.

In the inlet of a ram-jet engine there are two such shock waves. The first of these originates at the tip of the inlet cone or spike and is oblique to the air stream. The second is located within the diffuser and is at right angles or normal to the air stream. The over-all compression provided by the diffuser depends on the location of the normal shock wave and this in turn depends only on the rate at which we are burning fuel in the combustion chamber. As we increase the fuel flow, the intensity of the combustion process increases and the normal shock moves forward, providing the increased pressure required to force the now further expanded products of combustion out the exhaust nozzle. At the same time you may have noticed that the thrust of the engine increased. This process continues as I continue to increase the fuel flow to the engine until such a point that the normal shock is at the cowl lip. At this condition the diffuser is producing the maximum pressure which it is capable of providing, and any further increase in fuel flow cannot provide the increase of pressure needed to push the gases out the nozzle. The only thing that can happen is for the engine to use less air. It does this, as I increase the fuel flow, by expelling the normal shock and spilling the excess air about the cowl.

Under these conditions, the flow entering the engine frequently becomes unstable and the expelled normal shock oscillates as you can see. Further increase of fuel flow merely pushes the normal shock further forward and in an actual engine the oscillations become more severe. These oscillations can become sufficiently bad that it either blows out the flames in the combustion chamber, or, worse yet, can structurally damage the engine.

You perhaps noticed that as I increased the fuel flow beyond that required to place the shock at the cowl lip the thrust no longer increased. Observe now, as I decrease the fuel flow, that the thrust does not start to change its value until the shock reaches the cowl lip. Therefore, at this condition, we have a maximum thrust at the least expenditure of fuel flow for this thrust and hence the most efficient operating point for the engine, and one which would provide a missile with maximum range.

We do not expect to have a pilot to operate the fuel throttle on a flying ram-jet engine and therefore we must provide an automatic control system to obtain the desired engine operation. To do this we can use the position of the normal shock within the inlet to provide an indication of the performance of the engine.

(Drop movie screen to expose animated automatic control.) We have here a schematic representation of a control system based on the shock positioning principle. Because we want to have the most efficient operation of the engine, we desire to position the shock at the cowl lip. To determine when the normal shock is at the cowl lip we measure a pressure at this point (on conical spike of engine overhead). This pressure is transmitted to the interior of this bellows and the value of the pressure is indicated on the pressure gage to your left.

When the shock is within the diffuser, the pressure at the cowl lip is low, because as you will recall, there is a pressure rise across the normal shock and we are measuring the pressure in front of the shock now. This low pressure causes the bellows to collapse, which closes an electrical circuit to an automatic throttle valve, calling for an increase in the fuel rate to the engine because we want the shock to move forward. As the fuel rate is increased,the normal shock is driven forward until it passes the cowl lip. When the shock passes the cowl lip the pressure at the measuring point increases because we are now measuring the pressure behind a normal shock. This higher pressurecauses the bellows to rise, closing another electrical circuit,which calls for a decrease in fuel rate because now the shock is too far forward.

We have arranged to be able to simulate the automatic action of this control system as it would occur in an actual ram-jet engine in flight. The normal shock is now well forward and the measured pressure is high and the control is calling for a decrease in fuel flow.

When we throw the system into automatic simulation, the fuel flow will immediately start to decrease,the the normal shock will move rearward and settle out at the cowl lip after oscillating about this point. Now we will throw the system on "automatic" (operates lower lever, right center). With the shock at the cowl lip we have the desired maximum thrust at minimum fuel flow for this thrust and the control is calling for neither an increase nor a decrease in fuel rate.

This control system and others have been successfully applied to the operation of a full-scale ram-jet engine in the 8- by 6-foot Supersonic Wind Tunnel over a wide range of flight conditions.

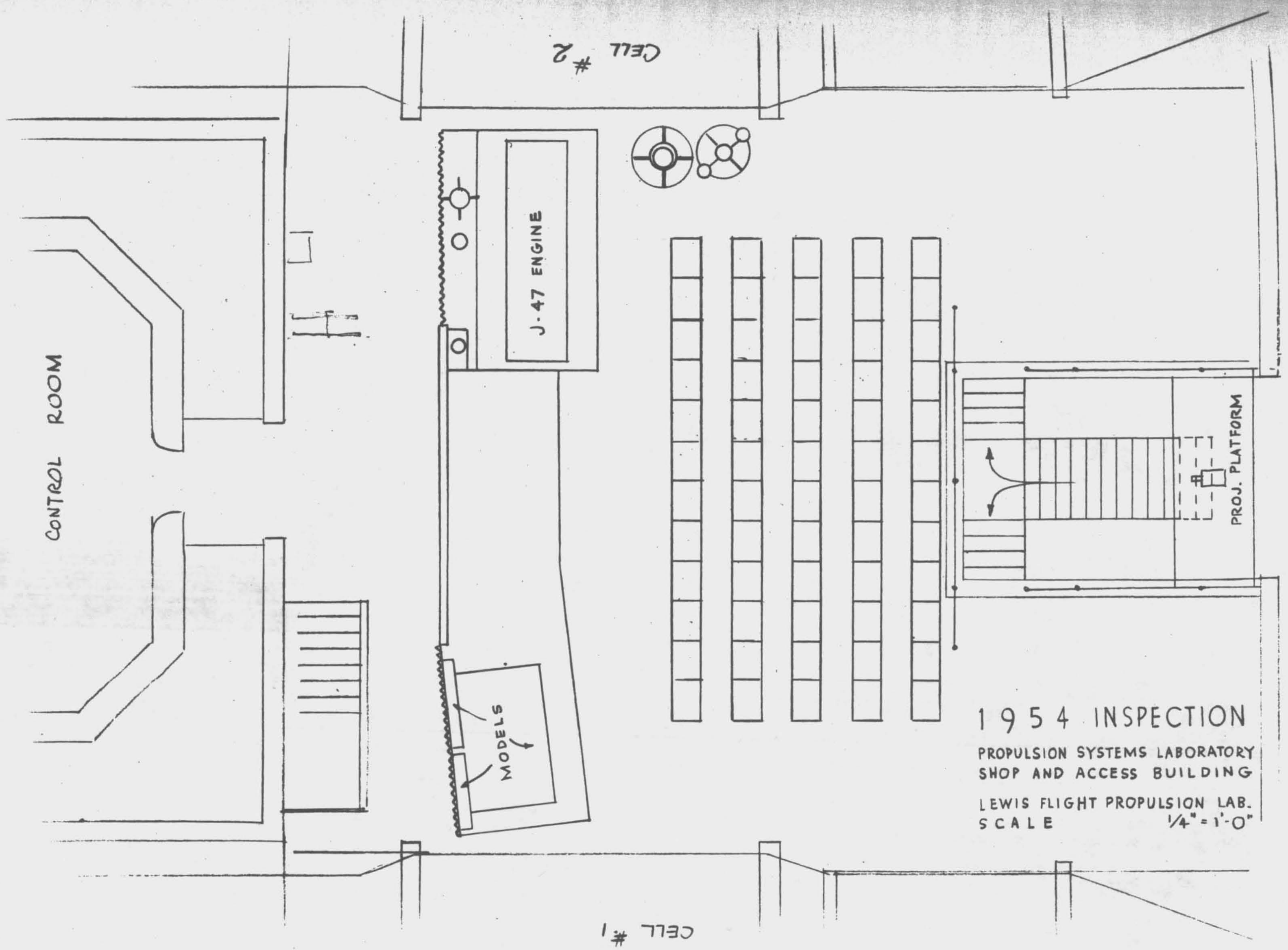
Thus far we have discussed a control for an engine operating at a fixed flight speed; in particular, the design speed of the inlet. This is only a part of the problem because engines will have to fly at speeds other than design, as a matter of fact, over quite a wide range of flight speeds. When an inlet is operating at a speed other than design, it is not very efficient, and to obtain efficient operation over a range of flight speeds, we must provide certain adjustable features in the inlet system. This further complicates an already complex control problem for the inlet control must be linked to an already complicated engine control.

We have here above us (on hoist above backdrop) a turbojet engine installation whose inlet system incorporates some of the adjustable features required for efficient supersonic flight. This is the first complete turbojet installation to operate in an air stream at Mach number 2.0. These tests were recently conducted in the 8- by 6-foot Supersonic Wind Tunnel.

The adjustable features in this inlet are two in number. The first is the inlet cone or spike which is located up forward on the engine, is painted red, and has a couple of white bands encircling it. This spike can move back and forth in an axial direction. In its present position it is set for operation at speeds from take-off to about Mach 1.5. As the flight speed exceeds this value the spike must be continuously moved forward in this manner (spike is moved by remote control) until at Mach 2.0, the maximum speed for this particular installation, it is in its most forward position.

The second adjustable feature of this inlet system is a bypass door which is located on top of the inlet just forward of the support strut and is painted red. The purpose of this bypass door is to maintain the normal shock at the cowl lip under all engine and flight conditions, for in this manner the engine produces thrust most efficiently. It does this by opening up to dump overboard air which the engine cannot use.

During the test program on this engine the spike and the bypass door were operated by control systems of the shock positioning type similar to that demonstrated for the ram-jet engine. The only difference was that the controls actuated the mechanisms required to move the bypass door and the spike rather than the fuel throttle.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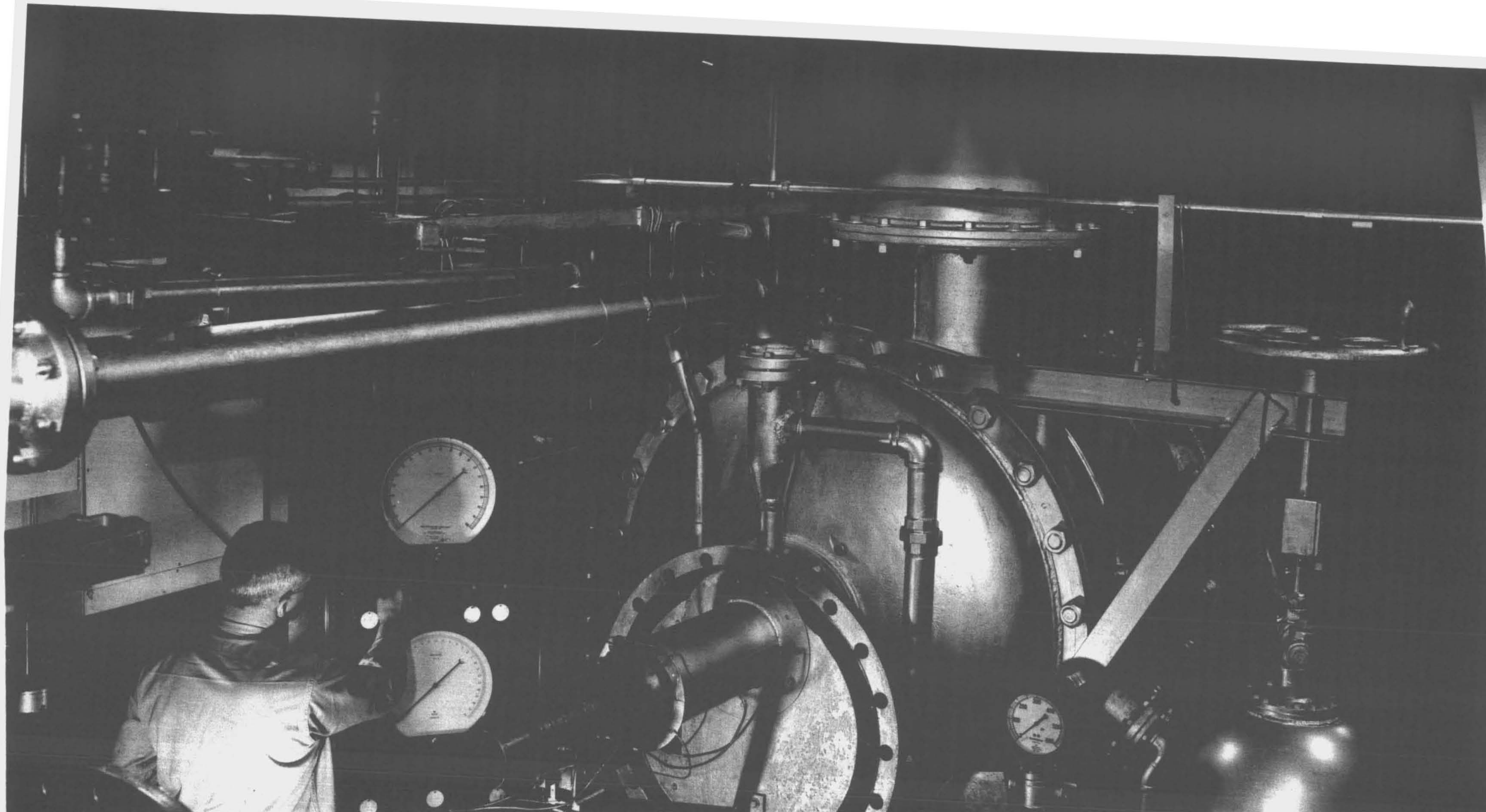
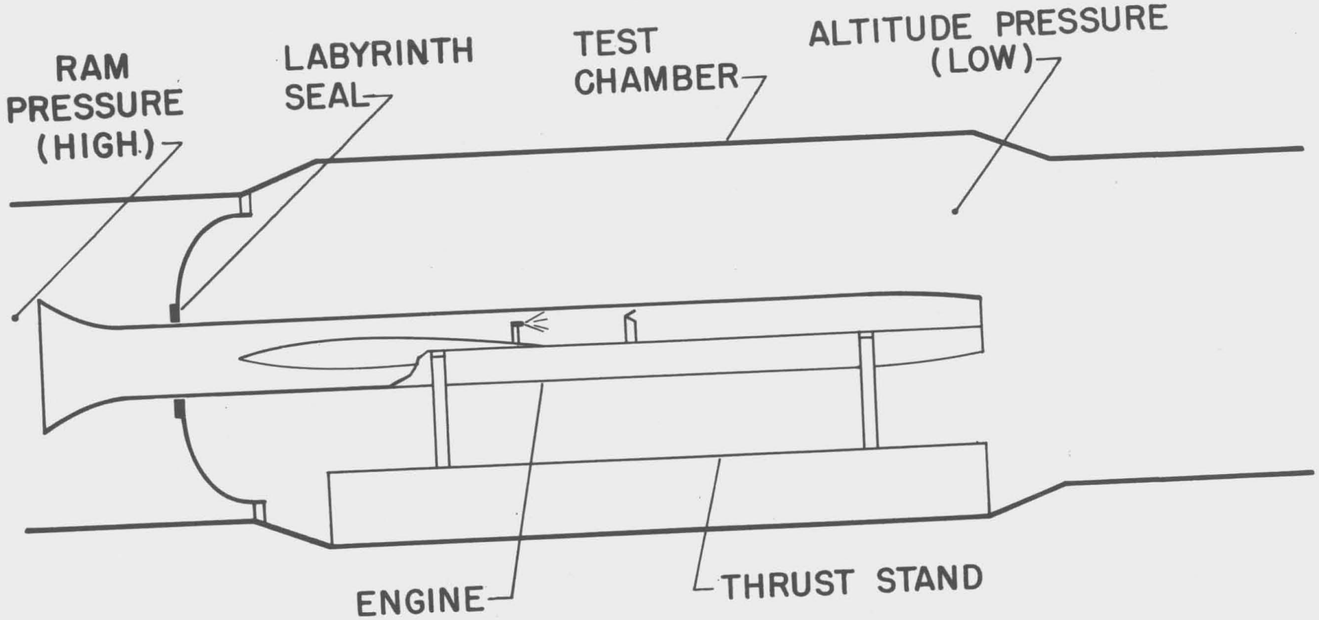
PROPULSION SYSTEMS LABORATORY
SHOP AND ACCESS BUILDING
LEWIS FLIGHT PROPULSION LAB.
SCALE 1/4" = 1'-0"
CELL #2
CELL #1
CONTROL ROOM
J-47 ENGINE
MODELS
PROJ. PLATFORM


FULL SCALE ENGINE RESEARCH
AUTOMATIC CONTROL
FULL SCALE ENGINE RESEARCH FACILITIES



The experimental ram jet model seen here is mounted for testing to simulate high altitude conditions in a test cell at NACA's Lewis Flight Propulsion Laboratory. After the technician completes a final check on the instruments which will record its performance, an enclosure will be placed over the model and it will be tested in a blast of air under actual burning conditions. Data from tests of this kind are hastening development of the ram jet unit which may play a major role in sustained supersonic flight.

DIRECT-CONNECT TECHNIQUE



This discussion of the supersonic control problem has, of necessity, been limited. It does, however, serve to illustrate one range of investigation which, together with those concerning component interaction in turbine engines such as these, and altitude performance, requires NACA research on full-scale engines in altitude test chambers such as those on either side of us, supersonic wind tunnels such as those depicted by these construction models, and on the free flight ranges. Thank you.