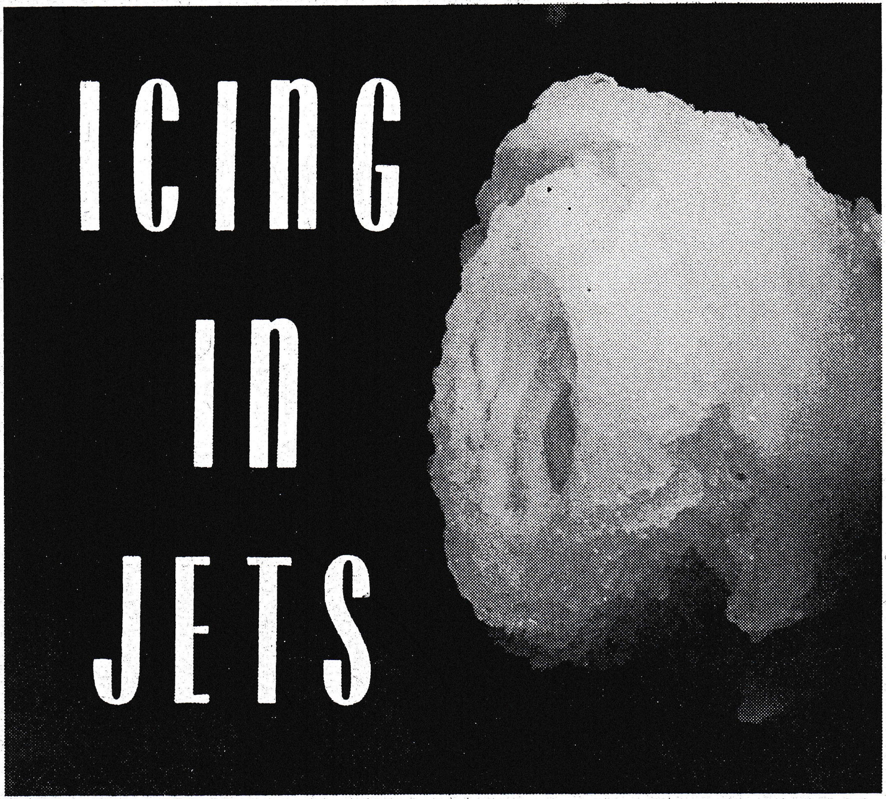
# ICING IN JETS



LEFT:: Side view of the ice "rose" removed from jet engine after icing run.

**White Menace of Aviation, Ice is Being Studied In Jet Engine Tests by Our National Research Council. Preliminary Report on the Experiments**

SOME of the effects of icing in gas turbine engines are described in the report of a preliminary investigation by the National Research Council at Ottawa. Using a German axial-flow jet engine in a special test stand with water spray equipment to induce artificial icing, the Council conducted a series of 39 icing runs during the late winter of 1947.

The experiments are now being resumed. Objectives of future studies are to relate the results obtained from these tests to the icing of jet units in flight, to learn more concerning the physical factors governing ice formation and to investigate means for ice prevention.

Because the tests were started late in the winter of 1947, the experiments were intended more to provide leads and information that would be helpful in planning turbine icing investigation for the winter of 1947-8 than as a study of icing of gas turbine units. Nevertheless, certain conclusions have been drawn. Considerable information has been obtained as to some of the possible ice formations, their effect on the performance of the unit, and the effect of ice entering the compressor.

Under the conditions of test in these stationary runs, ice formed on two main components of the unit: the starter fairing and the guide vanes. Ice on the guide vanes was observed to form and blow off in most of the runs without any apparent damage to the compressor.

In other runs, however, guide-vane icing very rapidly reduced the performance of the unit and in one instance led to the destruction of the compressor.

Two general types of ice build-up were obtained on the starter fairing: the "coronet" type when the normal cowling was used, and the "rose" type when an attempt was made to stimulate more nearly flight conditions by using a straightening entry.

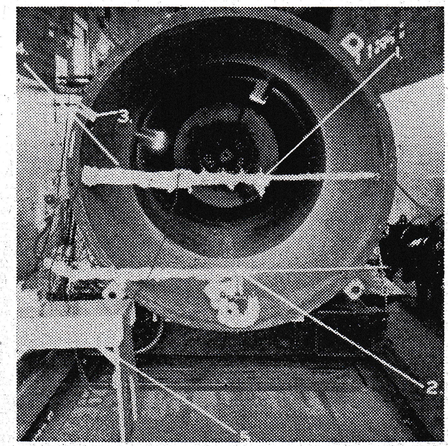
Besides these, under certain not-definitely-established conditions, jagged secondary formations or sometimes a secondary ring formed on the starter fairing behind the coronet. These secondary formations were considered particularly dangerous as they tended to break off and enter the compressor.

The rose type formation, which was obtained with the straightening entry, affected the performance of the unit less than did the coronet type. It is not permissible to conclude from this, however, that the type of ice formation that would occur in flight would behave likewise because in flight, with the approaching stream lines parallel or slightly diverging, a greater water droplet concentration might be expected at the guide vanes and serious icing of the guide vanes might well occur with consequent rapid loss of performance and possible destruction of the compressor.

A total of 39 icing runs were made, mostly under simulated icing conditions rather than under natural icing conditions, by spraying water into the inlet air at low outside temperatures.

The jet unit was run at a constant predetermined speed and readings were taken, usually at five-minute intervals, to record the influence of ice formed on the performance. The runs were continued until shutting down was deemed necessary because of the unsymmetrical ice or ice of unstable appearance, or because the tail pipe temperature exceeded the allowable maximum, usually after about 30 minutes.

Immediately after shutting down, photographs of the ice formation were taken and the ice caught on the starter fairing was weighed. Later, to study the progress of ice formation,



Front view of inlet duct showing spray installation. (1) Four nozzles; (2) Three air spray nozzles; (3) Inlet air thermometer; (4) Remote control camera; (5) Observer's station.

a remote-controlled camera was mounted on the side of the duct 10 feet from the compressor inlet, and pictures were taken progressively during the run. An observer also was stationed in the test cell to watch development of the icing.

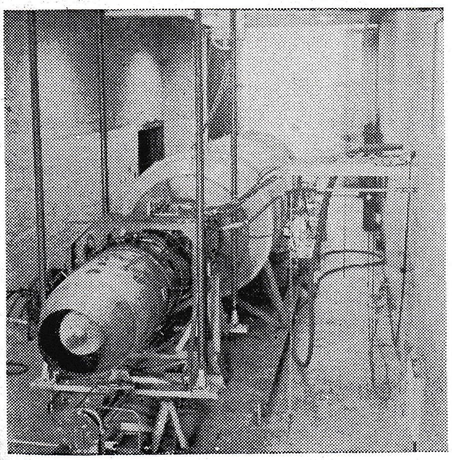
On certain occasions the jet was not shut down in time and the compressor was either demolished or damaged. Altogether, the complete unit was replaced because of compressor demolition and once the compressor section only was changed when one blade was bent.

Two tests were made under natural icing conditions in the form of heavy snow storms. The jet was run 30 and 42 minutes respectively and the snow was drawn into the compressor by normal aspiration. No drop in performance was observed. Very little icing was evident in either case, some forming on the starter fairing and a little on the guide vanes.

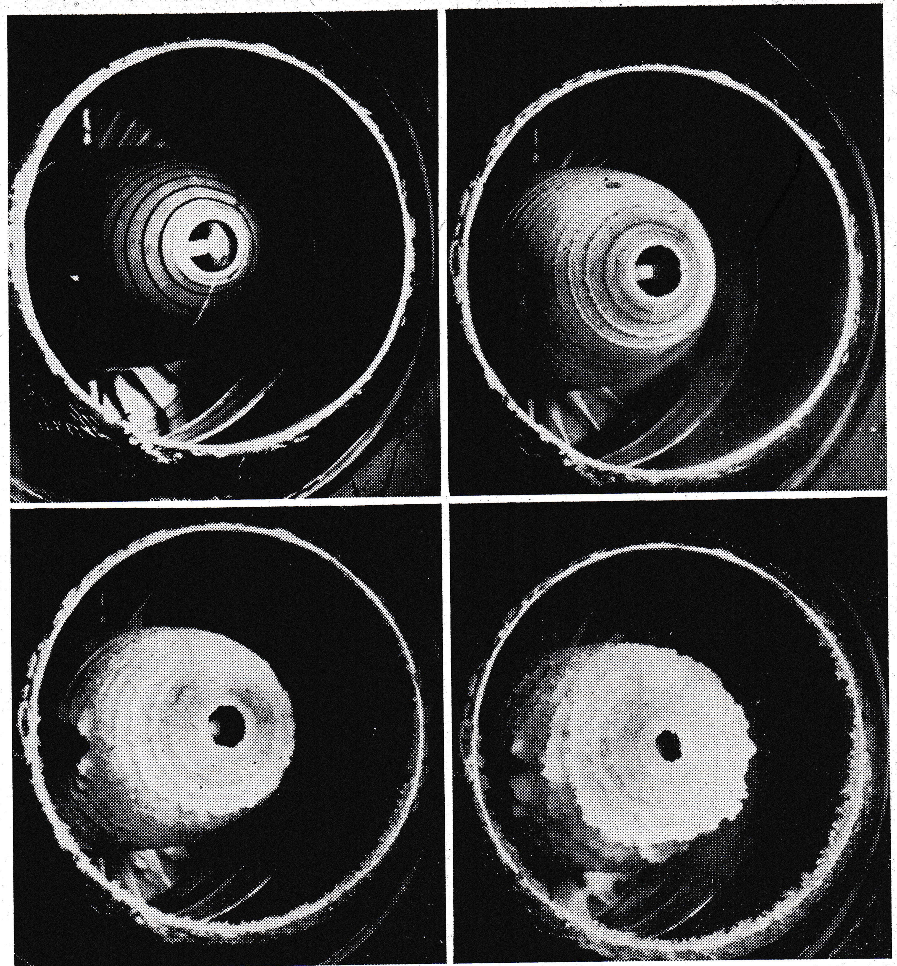
Most of the icing runs were made under simulated conditions, using water spray equipment at low outside air temperatures. The engine operating conditions were standardized at a speed of 7,600 rpm which is in the low cruising range, and with the exhaust bullet disconnected from its driving motor and locked in the open or regular starting position.

A brief preliminary run was made with a wire grid over the compressor inlet. It has been amply demonstrated that such grids ice rapidly and blank off the air supply, however, so no further tests were made with it.

In the first series of experiments, using the regular engine cowling, the ice built up on the front part of the starter fairing in the form of a coronet. In the first phase, the water froze in the form of separate "teeth."



General view of the test stand from the rear of the jet engine with the inlet air duct in position. Most of the experiments involved water spray to induce icing.



The four illustrations above show the progress of icing on the jet starter fairing and guide vanes after 0, 2, 5 and 9 minutes of water spray respectively.

Often they grouped together in the form of separate rings. Then, about three inches from the leading edge, the ice started to grow towards the nose cowling, threatening to block the entire air inlet. The inlet diameter was 18 inches and the larger coronet attained a diameter of 15 inches.

The ice was, in general, in the form of a milky glaze. Its structure was loose or porous, particularly close to the fairing surface. The outside part of the coronet was sometimes a milky glaze and sometimes clear ice.

In order to give a measure of depth to the photographs of sectioned ice formations, rings were painted at one-inch intervals on the starter fairing. It was found, however, that ice built up at these paint rings and that even when these had been sanded almost perfectly smooth, an ice build-up was still induced.

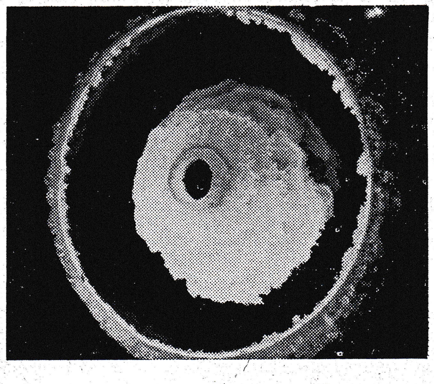
The ice adhered strongly to the surface of the fairing but occasionally pieces from the coronet broke off and entered the compressor. This was heard as a sudden disquieting roar of the jet. These roars were usually more frequent toward the end of the experiment when the large coronet had attained a fair size and, along with the increase of the exhaust temperature, were used as a signal to stop further injection of water.

Besides these intermittent roars there was a continuous deep throbbing roar which would be first noticed after about 20 minutes of water addition, becoming progressively louder until the unit was shut down.

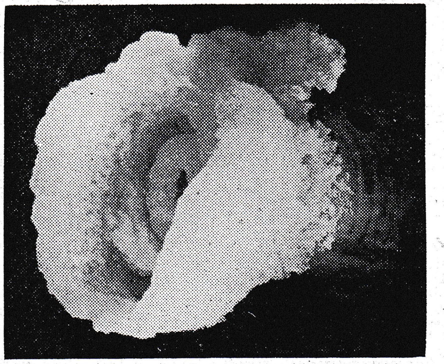
Ice did not build up on the inside surface of the nose cowling, probably because the direction of flow deflected the water droplets from this surface towards the starter fairing. Only when the coronet grew so that only a narrow passage was left between it and the nose cowling did a light white hoar form on the inside of the cowling.

A little ice only built up on the outside of the nose cowling in the form of separate teeth. This might be expected as there was very little air flow in this region. No particular attention was paid to the ice formed there as this ice did not affect the engine operation.

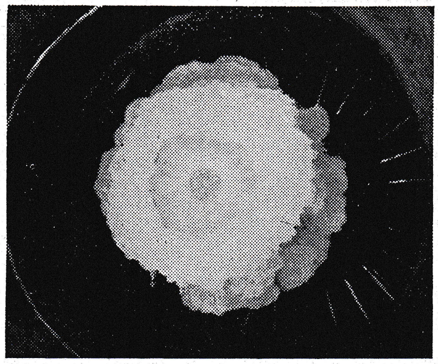
An entirely different formation would be expected in flight where



Ice "coronet" weighing 7.5 lb.



Ice "tulip" formed on jet starter fairing.



Ice "rose" formed as jet ran at 8,420 rpm.

there would be a high air velocity over this surface. The leading edge of the cowling was usually free from ice. Sometimes a fringe of ice would form here, marking the break-away of air flow from the edge.

In this series of tests, no great difference was noted in the ice formation obtained with different spray nozzles at the various distances. With the nozzles at a distance of six feet, the ice coronet was unsymmetrical. For further tests, a distance of 18 feet was chosen and most of the tests were made with four NRC nozzles giving a rate of water spray of about 1.2 lb./min.

The nozzles were arranged in line on the horizontal diameter of the duct and discharged spray upwards, perpendicular to the air flow. This arrangement was found to result in a more symmetrical ice build-up than other configurations of the nozzles which were tried.

During this first series of experiments, it was found that the ice grew radially across the compressor entry, more or less perpendicular to the axis. It was realized that the conditions of air flow at the entry must influence the type of ice formation. In the stationary test, where the air is drawn into the compressor entry from the ambient atmosphere or from the large duct, the stream lines converge towards the entry and there is considerable break-away from the inner edge of the cowling.

In flight, the stream lines will differ because of the aircraft's speed. For an aircraft speed equal to the velocity in the entry, the stream lines will be parallel, slightly converging for lower and diverging for higher aircraft speeds.

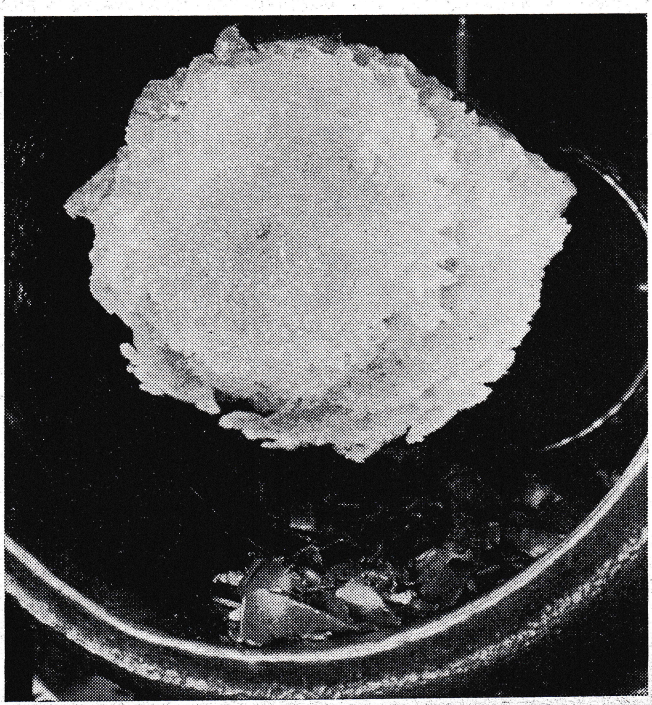
To obtain the desired shape of the stream lines, a high air velocity around the jet must be induced or the air flow forcibly straightened at the entry. This second method, being the quicker, was chosen for the preliminary study and the so-called bell-mouth straightening entry was fitted in front of the compressor entry.

The flow conditions at the entry to the unit with the regular cowlings and with straightening entry were studied, using a smoke-generating apparatus. It was seen from observation of the flow patterns that with the normal entry at static conditions there is a pronounced break-away from the inside surface of the nose cowling and sharp curvature of the stream lines which result in most of the water droplets impinging on the nose bullet.

**Flight Conditions Not Attained**

With the bell-mouth straightening entry, it was noticed that the flow converged toward the bell-mouth, then flowed parallel to the walls in the straightening section and that the break-away at the nose cowling entry was avoided.

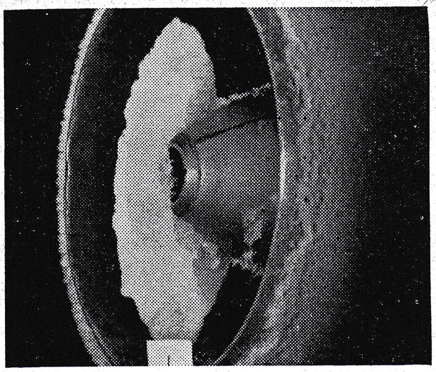
However, the curvature of the stream lines at the bell-mouth, although less than with normal cowling, still caused a concentration of water droplets near the centre of the air stream and, consequently, an increase in the number impinging on the starter fairing and a reduction in those striking the guide vanes. Therefore, while conditions were improved with the bell-mouth entry, flight conditions were not attained.



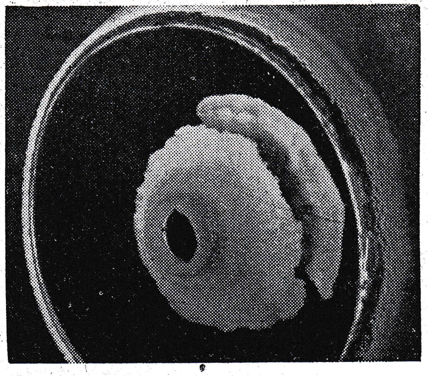
Ice "coronet" remaining after failure. Part of ice formation had broken off and demolished the compressor. Note broken blades in foreground. Weight of remaining ice was 4.7 lb.

When the unit was run with the bell-mouth straightening entry at "standardized" conditions with the selected spray equipment, four NRC nozzles at 18 feet, it was found that ice still formed on the starter fairing but that the shape was different. It no longer grew radially across the entry but more or less axially toward the front, producing what is referred to as a "rose" formation. The structure of the ice was similar to that of the coronet, porous near the surface of the fairing and milky glaze ice toward the outside.

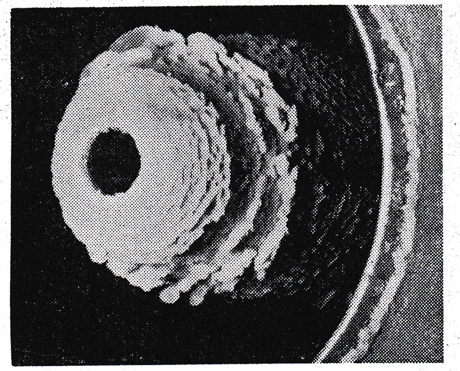
As this formation had less effect on the performance of the unit and the



Sectioned ice "coronet" shows construction.



Ice "coronet" with secondary ring. Missing part broke compressor blade.



Ice "teeth formation. Separate teeth broke continuously and flew into compressor.

exhaust temperature did not rise excessively after 30 minutes, its development with further running was investigated. Water was injected during a one-hour run. The usual rose formed at the beginning, then its outside "petals" started to grow axially and parallel to the straightening section, eventually attaining a length of six inches from the fairing tip and 11 inches in diameter.

It has been shown by the runs described that the form of ice build-up depended on the direction of the air stream. However, it is realized that after the initial period the conditions imposed by the straightening entry again become artificial. In flight, the ice formed would deflect the air stream and with it the direction of ice build-up. The straightening entry forced the air constantly to flow parallel to its wall, including direct impingment of droplets and axial ice build-up.

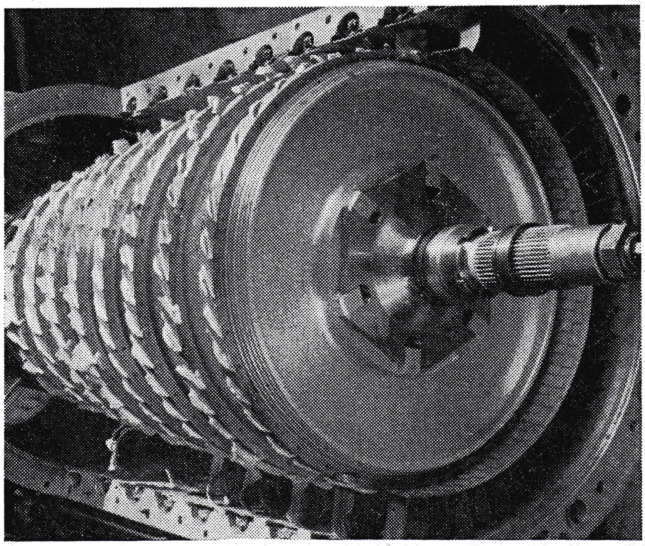
During the early runs, some icing was observed on the stator vanes. This ice usually melted off before pictures could be taken and it does not appear in the photographs.

Later when an observer was stationed in the test cell, it was noticed that when the unit was run at 7,600 rpm, ice formed on the guide vanes immediately after the injection of water and grew slowly to a thickness of about half an inch. Soon after this it started to break away and usually very little of it would remain at the end of the test.

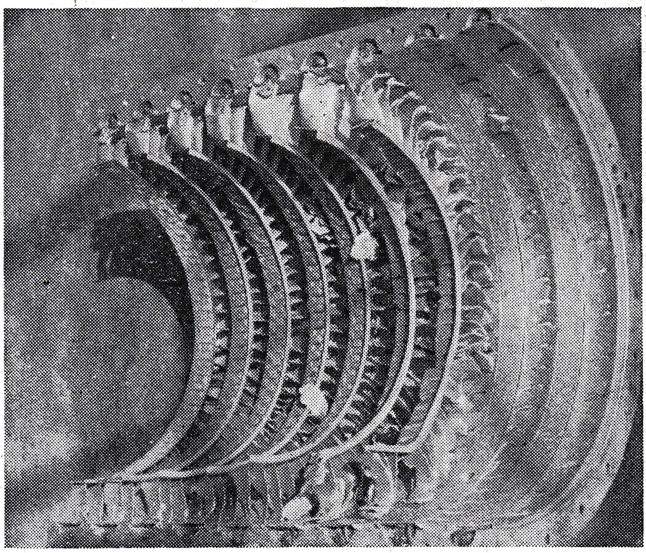
When icing runs were made at 6,000 rpm, the ice was observed to build up very quickly on the guide vanes and in 10 minutes to bridge from one vane to another. The ice was in the form of thin leaf-shaped blades of solid glaze ice which had built up circumferentially at right angles to the air stream.

This formation was particularly interesting because it built up very quickly and had a pronounced adverse effect on the performance of the unit.

Ice breaking off the starter fairing and passing through the engine stripped all the blades from the compressor rotor as shown at right.



Damage to the compressor stator, right, during the same run in which the compressor rotor was stripped. The piece of ice responsible was estimated at three to six pounds in weight.



Very heavy icing of the guide vanes with the engine running at 7,600 rpm, was noted in one run. In this instance, water was sprayed at the high rate of 3.64 lb./min. After 10 minutes' running, the compressor failed. In this time, only 4.5 lb. froze on the starter fairing.

**Effect of Icing on Jet Engine Performance**—Generally it may be said that icing resulted in a drop in thrust and compressor performance and an increase of exhaust gas temperatures and fuel consumption. The rate of change in performance with time was different for the various ice formations. The rise inexhaust gas tem-

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just outside of Toronto. This company took over National Research Council activities and continued the operation of the Cold Weather Test Station, while at the same time recruiting, organizing and training staff to engage in the larger activities of engine design and development.

Though considered a long-term project, and not intended as part of the war effort, except for the operation of the Cold Test Station, nevertheless, it was found possible gradually to recruit personnel. Engineers and draftsmen were hired and a number were sent for training in the United Kingdom. The RCAF also sent a number of officers and NCO's to take courses of instruction in the U. K. and many of these later took up employment with Turbo Research upon their release from the service.

At the end of the war, the Canadian Government, consistent with its policy of disposing of Crown companies, decided to discontinue the operation of Turbo Research. At this point, A. V. Roe Canada Limited, engaged as it was on the design and manufacture of jet-powered aircraft, realized the importance of the jet engine in its own program, and desirous of carrying on the work in Canada, took over Turbo Research facilities in 1946, and transferred these, together with the staff to Malton.

The acquisition of this staff brought to Malton the majority of those men who had been working in the new field in Canada. At the same time, National Research Council undertook to carry on the necessary allied fundamental research work.

While the life of Turbo Research Ltd. was a short one, nevertheless it provided a vital working basis for the gas turbine organization at Avro Canada.

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## Icing in Jets

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perature is directly induced by the increase of fuel flow which results from the governor trying to maintain the set engine speed in spite of decreasing compressor performance.

The runs were usually continued until such time as the exhaust gas temperature exceeded the maximum permissible value of 700 deg. C or the ice formation was considered dangerous. The drop in thrust which is important for aircraft operation was not the limiting factor in the bench tests.

It should be noted that most of the icing runs were made with the exhaust bullet locked in the retracted or starting position. In this position, the exhaust gas temperatures are lower than with the bullet in operation. This permitted a larger ice accumulation to be built up without exceeding the allowable tail pipe temperature than would otherwise have been possible.

When an ice formation of the coronet type was building up, the exhaust gas temperature rose slowly at the beginning, then at a rapidly increasing rate. When the coronet attained a diameter of about 15 inches, the increase was about 50 deg.C. per minute and an immediate shut-down was necessary. The drop in thrust was about 350 lb. in this run.

The rose and its advanced stage, the tulip type of ice formation obtained with straightening entry to the compressor, blocked the compressor entry to a lesser extent than did the coronet type. Hence the drop in performance was not so pronounced. In the longest run, when 16.7 lb. of ice built up on the starter fairing in one hour, the exhaust gas temperature rose only about 90 deg. C and the thrust dropped only 150 lb.

One run with straightening entry was performed at a higher engine speed, 8,420 rpm, which is the maxi-

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# Icing in Jets

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mum continuous speed for the Jumo engine. After 25 minutes of water addition, an ice rose weighing 6.6 lb. was formed, the exhaust temperature increased only 30 deg. C, thrust dropped 60 lb. and the conditions seemed to stabilize.

**Effects of Ice on the Compressor—** During the icing runs small pieces of ice were observed to be breaking off frequently and entering the compressor. In one run, for instance, separate ice teeth probably weighing about 1/10th of an ounce broke off continuously. At times, in other runs, larger pieces of ice estimated at about a quarter of a pound went through the compressor without damaging it. These larger pieces on entering the unit would produce a sudden roar clearly distinguishable in the observation room.

In another run, a part of the ice ring estimated at one pound, broke off resulting in one compressor blade in the first stage being bent. In another run, after 31.5 minutes of water addition, using an air spray nozzle at 18 feet, a large piece of ice broke loose and destroyed the compressor. The weight of the broken piece could not be exactly estimated but it is believed to have been between three and six pounds.

As the coronet built up symmetrically, it may be suspected that the structure of the ice was looser under the conditions of this test than in previous runs. All blades were stripped from the compressor rotor and the stator blades were extensively damaged. Although most of the broken blades remained in the unit, some blades and pieces of blades were thrown forward as far as 20 feet.

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# Controllable Propeller

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hand on one side of the bearing only (see fig. 9). Work the grease in until it appears on the other side. Rotate the bearing several times and work in more grease. Apply a small amount of grease to the second side and wipe off any excess grease between the ball and the outer edges of the bearing races.

5. Reassemble the bearing in the reverse order of disassembly. Replace the seals with new seals and check the snap rings for proper seating in the grooves of the outer bearing race.

The propeller **blade bearing** must be repacked with AN-G-4A grease every 500 hours. Cleaning and regreasing is similar to the process used for the actuator bearing.

**Propeller Assembly.** When reassembling the propeller, care should be taken to reinstall all the parts to their original places, and the parts should be free of all dust and dirt. Apply a small amount of AN-G-4 grade A-A grease to all moving parts.

1. Place the drive gear on the sleeve with the bevelled teeth facing away from the sleeve flange and with the plank section of the drive gear located approximately one inch to the left of the attaching point of the pinon gear.

4. Install the gear retaining ring and secure with the screw.

3. Insert the actuator bearing in the sleeve, from the flange side with the ugs fitting the slots in the sleeve. (see fig. 7). Actuate the drive gear so that the actuator bearing assembly will be held securely.

4. Place the pitch control assembly with the arms up, the rear half of the hub with the dust cover down, and the spider with the long end down on the mandrel.

5. Hold the propeller blades and shims in their relative positions on the spider and at the same time tap the lower half of the hub up to its correct position on the spider and blades. (The hub is to be installed on the spider so the serial number of the hub is on the corresponding side as the number "1" on the pivot pin) (see fig. 10.)

**To Be Continued**