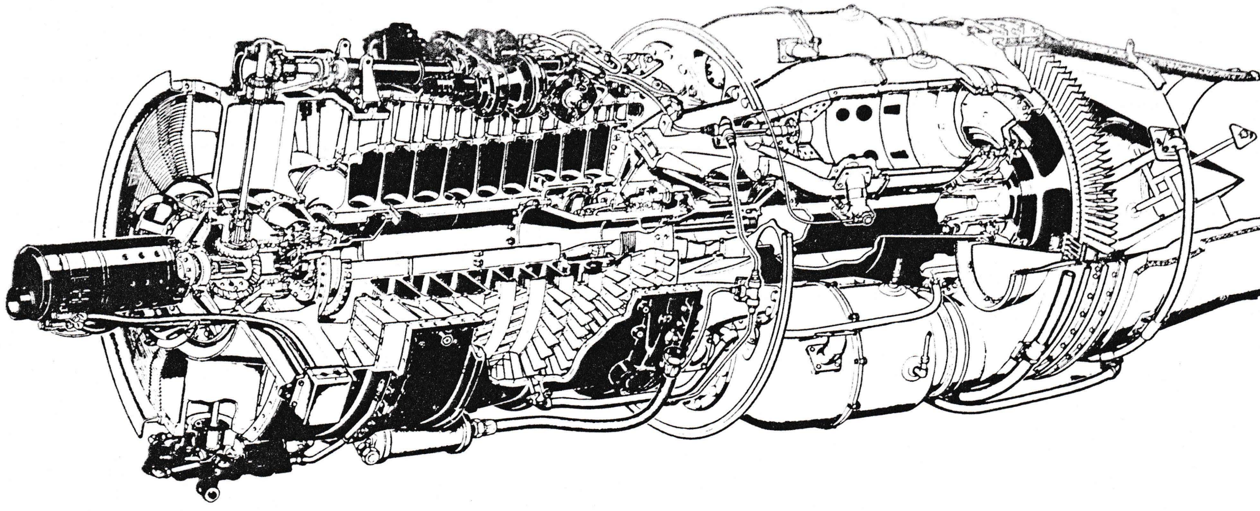

FIG. 1: CUTAWAY OF ORENDA 10

The Orenda and the Future

By B. A. AVERY

The following article was originally presented as a paper at the first joint meeting of the Canadian Aeronautical Institute and the Institute of the Aeronautical Sciences, held last October in Montreal. The author, B. A. Avery, is Chief Design Engineer for Orenda Engines Limited.

NO ONE could hope to discuss all the mechanical design of a turbojet engine in the comparatively small space allotted for this article. Instead I would like to outline briefly the role of the mechanical designer in the aircraft engine business; to use portions of the Orenda engine to indicate how the problems originally encountered were met; where the theories broke down and were corrected; and finally, to mention some of the design problems that will be encountered in the near future.

The design of the Orenda was commenced over eight years ago and it is now in full scale production as the Orenda 9 for the Avro CF-100 all-weather fighter, and as the Orenda 10 for the Canadair Sabre 5. An uprated version incorporating a two-stage turbine has entered production in two similar versions as the Orenda 11 for the CF-100 and the Orenda 14 for the Sabre.

Complication: The turbojet engine began its existence as quite a simple piece of equipment but through the years it has evolved into a more and more complex machine. Part of this, I will agree, is due to the fact that the functional requirements have become more and more stringent; power requirements for a given size and weight have increased, and the envelope of operational conditions has grown even broader. But there is another reason for this increase in turbojet complexity, and it is the direct responsibility of the mechanical designers.

Aircraft engine design—and for that matter, the design of any piece of machinery—is a program of studying performance and functional requirements, manufacturing techniques, material properties, past experience, making layouts and choosing the best of these for transportation on to engineering working drawings. The basic difference between the design of aircraft components and those of other industries, is that aircraft parts require more control of materials and processes to guarantee reliability under severe operating conditions of stress and temperature necessitated by the use of low design safety factors for minimum weight.

Proprietary Items: Design also includes the careful study of proprietary items and usually close liaison with the designers of these components, leading to the completion of control drawings and specifications and the final inclusion of the best units into the prototype engines. Now if the designer does not have a complete knowledge of the manufacturing facilities, the guaranteed minimum properties of all the available materials, the past experiences of his own company and of others, the performance and functional requirements, and if he draws only one or two layouts of a particular section of the engine and his superiors take just fleeting glances at the designs before approving one for detailing, then that design will have an excellent chance of being overly complex for the duties which it must perform.

However, if the designer has kept himself well informed of these important data, makes several sketches and layouts in striving for the utmost in simplicity, performance and ability to function, discusses the design quite thoroughly with his superiors, the stress engineers, the materials engineers, the planners and tool designers, then the chosen design will quite possibly be functionally a much better design. It will be more easily manufactured and serviced, and it will have fewer parts, which usually means that it will be of lighter weight and should consume less of the operators' dollars during a longer, useful lifetime. If the designer is sufficiently aware of the results that will be experienced if his numerous estimations and assumptions are incor-

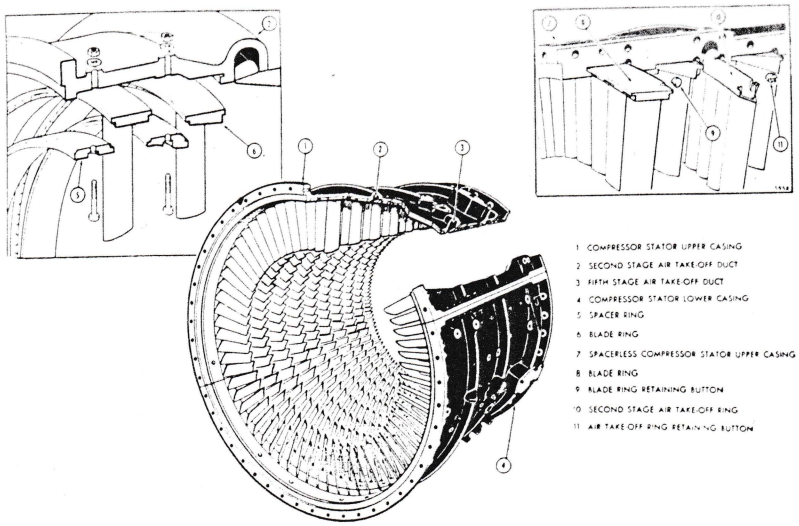

FIG. 2: COMPRESSOR STATOR CASING

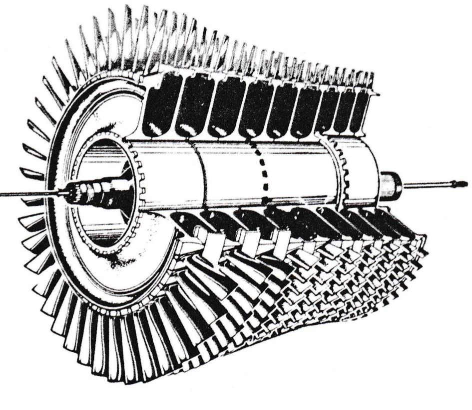

FIG. 3: COMPRESSOR ROTOR

rect, and if he realizes that engines are not frozen for production but are modified steadily for improved performance, his design configurations will be such as to allow these future changes to be made with a minimum of major modifications.

Essential Changes Only: Provided the basic concept of an engine is correct, only the few parts that do not function properly are modified during the development period, with the remainder going into service as originally designed. History has shown that engine designs do not become more simple or of lighter weight during the development period, but tend towards increased complexity since in this business time is at a premium and the "fix it but don't change it" technique is all too often chosen.

The actual prototype mechanical design period is comparatively short. Of the total period of from six to seven years in which a repetitive pattern is followed in the design, development and production proving of a turbojet engine, approximately fifteen months is available between the drawing of the first line on paper and the running of the first experimental engine. Now, you can well understand that an engine is not completely designed within this short period of time. In reality, during the interim between the actual design periods, the design staff, in addition to performing the duties of redesign as development experience dictates, is busy keeping up to date with materials progress, engine development, service experience, manufacturing methods developments, and modifying its design thinking accordingly. It is also gleaning what information it can concerning other power plants, since good designers do not hesitate to use the ideas of others if they are definitely advantageous.

The design staff, in effect, is planning from day to day how to design the next engine or modify the existing ones when the opportunites present themselves. Intimate contact with the test and development engineers and the aerodynamicists and thermodynamicists provides an engineering department that can turn out good initial designs, make efficient use of engine development running time, correct aerodynamic and mechanical problems quickly and provide proper technical service and control to the production program.

Pre-Production Mods: The usual result of all this, is that long before an engine reaches production, several design improvements have been evolved and if these are of sufficient advantage they may be included as modifications. Once the production program is reached however, the difficulty of their inclusion increases, but the situation sometimes arises in the production program where the procurement, manufacturing and delivery status is such that a worthy modification may be included with a minimum of effort.

More often, however, the inclusion of performance improvements into the production line provides the opportunity of incorporating mechanical improvements. Then if these have been proven sufficiently by development engine running, have been type tested, and, of course, if the customer approves, the changes may be incorporated. There are also many excellent design changes that cannot be fitted into

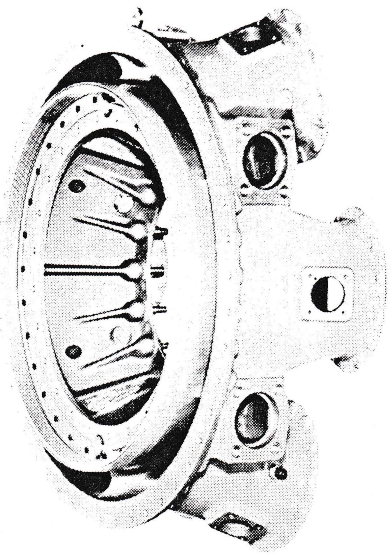

FIG. 4: CENTRE FRAME

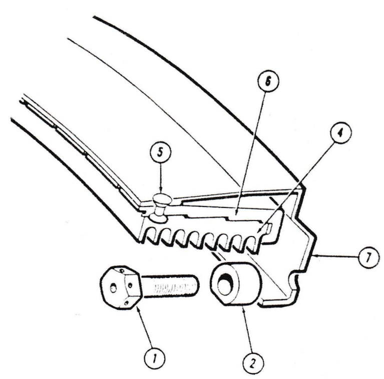

FIG 5A: OLD PERIPHERAL SEAL

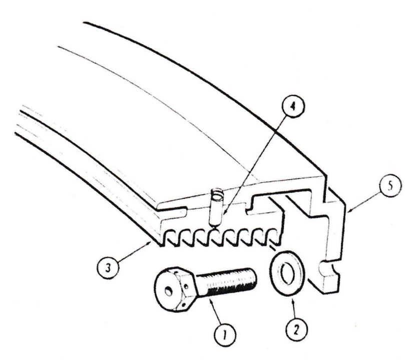

FIG. 5B: NEW PERIPHERAL SEAL

the production program even though they have been proven successful in experimental engines and others that do not get to the experimental manufacture stage. These unused designs are filed for possible future reference.

equal or better

THE ORENDA was designed quite conservatively for its time since the future of the Canadian-designed aircraft engine depended upon its running well the first time. It was designed to be equal to or better than the performance of the largest engines then on the drawing boards and to engine and aircraft accessories and supports the compressor inlet vanes and, in the case of the Orenda 10, a starter-generator.

The mid frame, which is connected to the front frame by the compressor stator assembly, houses the main rotor thrust bearing, incorporates the main engine support trunnions, and acts as the compressor diffuser and transition from the annular compressor outlet to the six combustion chambers. The rear frame of the engine, which is connected to the mid frame by a central backbone structure, supports the turbine rotor, acts as the transition from the six chambers to the annular tur- blade rings are now mounted directly in T-slots machined in the inner walls of the casings. Three similarly mounted rings form the air take-off manifolds. Simple aluminum buttons inserted at the horizontal flanges prevent the rings from rotating. The elimination of the spacer rings and bolts and the resultant decrease in tolerance build-up allows the inner gas profile to be machined at the same time as the slots are machined in the casings.

Casting tolerances were such that in order to obtain wrench clearances at the casing flanges, both spot facing and end milling operations were re-

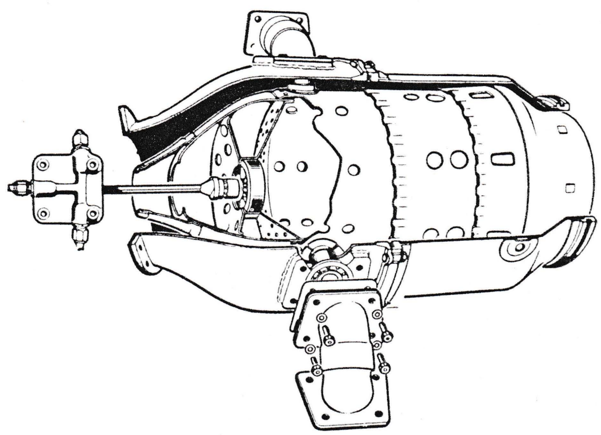

FIG. 6: COMBUSTION CHAMBER

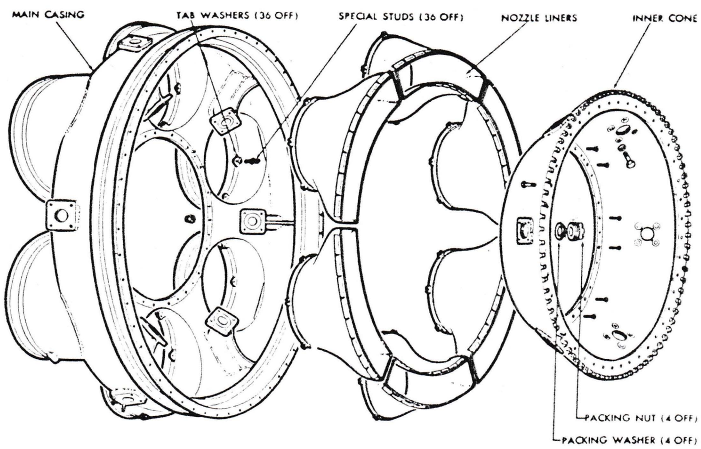

FIG. 7: NOZZLE BOX

accept full fighter manoeuvre conditions up to the speed of sound at sea level. Wherever possible, proven methods of construction were used since our own engine experience and research and development facilities were comparatively meagre. Such features as an annular combustion chamber which might have provided more opportunity for performance improvements, but which would have required these facilities, had to be laid aside in favour of more conservative designs. Even with problems such as this, the Orenda combustion chambers are the largest and most efficient, and the compressor provides the highest pressure ratio and efficiency for the number of stages used, of any similar engine of its generation.

Fig. 1 is a sectional drawing of the Orenda 10 engine. Basically it consists of a 10-stage axial flow compressor, six combustion chambers, a single stage axial flow turbine and an exhaust cone. The forward frame of the compressor supports the forward end of the compressor rotor, houses the power take-off gearbox for driving bine passage, and supports the turbine nozzles. The exhaust cone is connected to the rear frame and acts as the transition from the annular turbine outlet passage to the circular tail pipe section. The various engine accessories are mounted around the compressor casing.

Compressor Casing: The compressor stator casing, Figure 2, consists of two magnesium castings bolted together at horizontal flanges. The original design shown at the top left of Fig. 2 consisted of aluminum half rings, supporting the aluminum alloy blades in broached slots, clamped against the inside of the castings by intermediate aluminum alloy rings and steel bolts. The reasons for this method of construction were the fear of fire as a result of rotor blade rubbing directly on the magnesium casings and the fact that it was a proven design.

However, our own development experience and the service experience of other engines have proven the absence of the fire hazard and the suitability of other construction shown at the top right of Fig. 2. The same aluminum quired, but in this design, the outer diameters of the casings adjacent to the end flanges were decreased without decreasing the metal thicknesses so that simple automatic end milling operations now suffice. Machining and assembly times have been decreased considerably, structural strength and rigidity have been increased and the weight is naturally somewhat less.

Compressor Rotor: The compressor rotor shown on Fig. 3 consists of three aluminum drums, two steel shafts and ten bladed discs shrunk on to the drums with spacer rings between their rims. The three drum construction was used to enable the end discs to overhang the bearing shafts thus decreasing bearing centre distance and providing a more rigid rotor for a given weight. In actual fact this has proven itself to be one of the most stable compressor rotor designs of its generation.

Originally it was felt that the disc hubs which are shrunk on to the drums had to be accurately positioned axially to prevent dishing of the highly stressed webs. Several shims were used to allow for tolerance build-up, with the result that a substantial part of the assembly time was used in the determination of shim thicknesses. Engine running proved that as long as assembly web dishing was not severe, the hubs would find their own positions during operation, since the initial high interference fit is greatly decreased by centrifugal force during operation. By the simple redimensioning of the drums, discs and spacer rings, the shims have been eliminated, thus decreasing assembly time considerably.

The flanges of the drums and shafts began life as the reverse spot-faced buttress type to decrease the probability of stress concentrations during periods of high shaft bending stresses in flight. Laboratory testing proved that, when properly designed, turned flanges would suffice and the reverse spot facing operations no longer are required. The bolt holes of the mating flanges were previously line reamed on assembly and the bolts were selectively chosen for a snug fit. By closely controlling the hole sizes and positions, and the bolt diameters, complete interchangeability has been achieved and the assembly reaming operations eliminated.

Hand Fitted: Each compressor blade of the early engine was hand fitted in its dovetail support slot by removing material from the bottom of the dovetail and checking the tip movement. Experimental testing proved that the fit tolerances could be increased sufficiently so that proper dimensional control of blade roots and disc slots would eliminate the hand fitting. Blades are now taken from stores and assembled directly and at random into the discs and stator rings, for a considerable decrease in man-hours per assembly.

The centre frame, Fig. 4, is an aluminum alloy casing and has changed very little physically during its history. The backbone support bosses and gussets were enlarged to accept, without yielding, the very high manoeuvre bending forces and the axial gas load of the combustion chambers. Originally, the combustion chambers were each fastened to this frame by fourteen bolts to provide sufficient flange pressure for sealing air using a standard gasket. The development of an elastomer able to withstand the temperature in the form of "O" rings at this position has provided a sealing means using only two bolts per flange, for an increase in sealing efficiency, and a considerable decrease in assembly and combustion chamber liner inspection times. The successful development of a magnesium alloy of slightly better properties at operating temperature than aluminum alloys available, has provided a slightly stronger structure and with a weight saving of approximately 40 lbs.

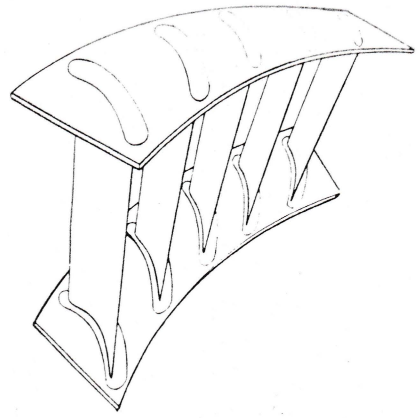

FIG. 8: BRAZED TURBINE NOZZLE SEGMENT.

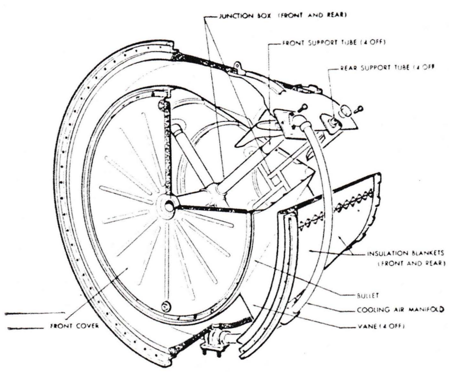

FIG. 9A: OLD EXHAUST CONE.

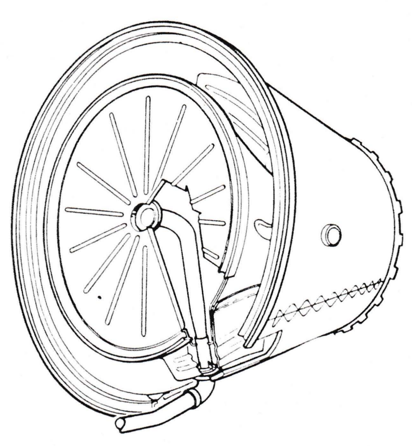

FIG. 9B: NEW EXHAUST CONE.

The labyrinth seal which can be fastened to the front face of the centre frame minimizes the loss of compressor delivery air and lowers the pressure behind the compressor rotor in order to decrease main bearing thrust loads. The disc rim rotates inside of the seal within a radial clearance of about .015 inches. In order to overcome the considerable thermal expansion differential, the seal assembly consisted of three main parts as shown on Fig. 5a. The steel mounting ring was slotted at the flange adjacent to the aluminum structure to allow for thermal expansion differential. Being very thin, it was difficult to machine and quite unstable. The ring riveted to it was also of steel and the theory was that the average deflection of this ring and the aluminum gland ring fitted inside of it would be very nearly the same as the sum of the thermal and centrifugal expansion of the disc. This proved to be correct but the aluminum yielded in compression when heated during operation and became loose upon shut-down. On succeeding runs, rubbing would occur as a result of this yielding and eccentricities allowed by the unstable support ring. Clearance increases caused by the wearing of the seals during rubbing resulted in uncontrolled air leakage.

Redesign: The redesigned seal assembly shown on Fig. 5b, consists of a rigid, easily machined, aluminum alloy mounting ring which expands directly with the aluminum or magnesium mid frames. Fastened to it by radial pins is a mild steel gland ring which is free to expand only thermally and thus to a slightly lesser degree than the disc. Minimum clearance is therefore realized during engine running where it is required while providing reasonable build clearance with less chance of assembly damage. The assembly is quite rigid; concentricity can be maintained; it is more easily manufactured, and air leakage control is much more definite.

This may sound like a great amount of effort to improve a seemingly unimportant part, but when one realizes that the prime purpose of a turbojet engine is to pump air, it becomes obvious that air leakage is an enormously important problem and well worth careful design. A one percent loss of this compressor delivery air can mean as much as a two percent decrease in overall engine efficiency.

Axial thrust is the major factor af-

(Continued on page 62)

LETTERS TO THE EDITOR

Canadians All

Sir:

Your recent February issue of *Aircraft* contained a fine article by J. T. Dyment, called "An Air Line's Viewpoint of the Turbine Era". He mentions some of the worlds' outstanding personalities in aviation, but did not give mention to any of our Canadians who influenced the birth of commercial aviation in the early twenties. These men have seen it develop through phases of novelty, prejudice, trial, acceptance, and finally necessity, in order to reach the ledge of silvery stardom which it now proudly occupies in the aviation world. Yes, it took men like the undermentioned to put it across. Roy Maxwell, Doc. Oakes, Mr. Quigley, A. T. Cowley, J. A. Wilson, Bill Williams, Harry Wiltshire, Tommy Thompson, Tommy Siers, Billy Hill, Elmer Fullerton, Wop May, Matt Berry, Leigh Brintnell, Al. Cheesman, Jack Cauldwell, Nobby Clarke, Joe Finnigan, Romeo Vachon, Duke Shiller, Jack Hyde, Bert McClatchie, Pat Reid, Rod Ross, Walter Gilbert, Terry Tully, Ted Stull, both Roy Browns, Stan Macmillan, Sam McCauley, Bill Gorman, Roy Tandy, and others who were in the industry at that time.

During the thirties TCA's W. English, CPA's Grant McConachie, who, through their devotion to aviation, have produced two air lines second to none.

Benefactors like James A. Richardson, J. E. Hammell, Col. R. McAlpine, they surely deserve honourable mention. No, we don't have to be modest as to our position in world aviation. "Let another man praise thee and not thine own mouth. A stranger and not thine own lips." (Proverb: Chapter 27). The names mentioned should be praised for their great efforts and achievements.

No offence Mr. Dyment, I like your article, but it is my private opinion that our pioneers did equal share to produce aviation as it is today in the world.

S. A. (SAMMY) TOMLINSON.
Calgary, Alberta.

ED. Replying to Mr. Tomlinson, Mr. Dyment had this to says "All the names you mentioned are household words in aviation. Unfortunately, in spite of their terrific contributions to aviation at large, this country has never gone in for worldwide publicity and, hence, few of them are well-known outside of Canada. Other countries likewise undoubtedly have pioneers to whom aviation owes at lot, but we in Canada are not familiar with them. My paper was prepared for the SAE meeting in Detroit so I purposely only included names well known to our United States friends; names that have received wide publicity in American newspapers and popular magazines . . . I think it would be very appropriate for 'Aircraft' to quote your letter because the names your mentioned should periodically be brought to the attention of our younger generation in aviation in Canada so that they will be proud of the achievements of their predecessors."

LAMINAR FLOW

(Continued from page 31)

the laminar airplane ought to have air-ejection spoilers . . . and so it goes on from pro to con!

Conclusion

THE WRITER feels that the proponents of laminar control of the boundary layer, and in particular Dr. Lachmann, have made a strong case for its use in air transport. Because of the very limited military possibilities, it will probably be difficult to get the funds for the engineering research—particularly into surface materials and structure which alone can lift laminarization from the laboratory into practical usage. But the last word is with Dr. Lachmann.

"There is too much tendency nowadays to transfer the speed fixation of the military into the realms of civil aviation."

"Fundamentally there is no improvement of flight economy at supersonic speed, on the contrary the increase of drag due to shock waves is barely compensated by the improvements of efficiency of propulsion in comparison with flight at subsonic Mach numbers. The civil operator is attracted by the prospect of better utilization of aircraft due to reduction of flying time. But the prospect for the aircraft constructor is to enter a rapidly shrinking market and to face ever-increasing and harder competition if this outlook should materialize."

ORENDA

(Continued from page 41)

fecting the life of the main rotor bearing. This force is the net sum of gas loads of very large proportions which are balanced against each other. Thus, the pressure behind the compressor rotor acting on the large area of the last disc, if not controlled very closely, will cause bearing thrust to increase and hence life to decrease considerably. The bearing thrust load varies with operating conditions from approximately 500 lbs. to 12,000 lbs. and an increase in average seal clearance of .010 inch could increase the load by about 2,000 lbs., thus severely decreasing bearing life.

Combustion Cans: Each of the six combustion chambers, Fig. 6, originally consisted of a nickel alloy inner liner or flame tube, a cast aluminum alloy front casing and an aluminized mild steel rear casing. The small machined ring at the front or snout of the liner was proven of no use and eliminated. The hand polishing operation on the edges of the parts, including the holes, for crack prevention, has been replaced by simple deburring with no increase in cracking. Since these liners are subjected to severe operating conditions, a considerable amount of development has taken place to increase the operational life and this combined with the manufacturing simplifications provided a considerably less expensive unit per hour of life.

The forward casing is now fabricated of mild steel to match the rear casing since fabrication is quite in order for this structure. Fewer rejections are experienced, because welds can be reworked if not pressure tight, whereas the aluminum casings were rejected. The machined pilot diameters originally used at the centre joint have been eliminated since the bolts connecting the two sections together provide sufficient alignment accuracy. The sprayed aluminum coating on the mild steel rear casing has been replaced by a silicone paint protective finish which provides more effective corrosion protection for both the front and rear casings, is applied more easily and is less costly.

The nozzle box, Fig. 7, has undergone some change but several tested design improvements

COMING EVENTS

April 25-26—AITA Semi-Annual Meeting, Empress Hotel, Victoria, B.C.

April 26—Annual General Meeting, Automotive & Aircraft Parts Mfrs. Assoc. (Canada), Royal York Hotel, Toronto.

May 2-5—Society of Aeronautical Weight Engineers Annual Conference, Hilton Hotel, Fort Worth, Texas.

May 4-6—International Aviation Trade Show, 69th Regiment Armory, New York City.

May 19-20—Canadian Aeronautical Institute Annual Meeting, Royal York Hotel, Toronto.

May 26-27—Electronics Components Conference, Ambassador Hotel, Los Angeles.

May 29-30—B.C. Aviation Council Annual Conference, Empress Hotel, Victoria.

May 30-June 10—Canadian International Trade Fair, CNE, Toronto.

June 4—International Air Show, CNE, Toronto.

June 7-10—Spring Meeting and Welding Show, American Welding Society, City Auditorium, Kansas City, Missouri.

June 21-24—Fifth International Aeronautical Conference, Joint Meeting of the RAeS and the IAS, IAS Bldg., Los Angeles.

June 22-24—Aviation Distributors & Manufacturers Mid-Year Meeting, Breezy Point Lodge, Brainerd, Minnesota.

July 27-29—Rotterdam Helicopter Congress, Rotterdam, The Netherlands.

October 11-15—SAE Golden Anniversary Meeting, Aircraft Production Forum, & Aircraft Engineering Display, Hotel Statler, Los Angeles.

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have not yet been incorporated. The main bodies of the inner and outer casings were originally machined from rough stainless steel castings with a resultant long production flow time and a terrific waste of raw material in the form of swarf. Both of these structures are now fabricated of sheet metal and rolled and butt-welded rings, resulting in a considerable decrease in weight, critical materials and cost, and an increase in rigidity by a simple redesign in the construction of the inner casing.

Current Practice: If this structure were designed today, the inner and outer casings would be integrated into a single welded structure for increased structural rigidity and decreased eccentricity, both of which affect turbine blade tip clearances and hence turbine efficiency. In this case, maximum sea level static thrust can decrease as much as 15 lbs. for each .001 inch increase in average turbine blade tip clearance.

The turbine nozzles are precision castings of a nickel-cobalt alloy and are individually mounted in supporting slots. This alloy can be machined only by grinding of which considerable is required to finish the integral support shrouds within the tolerances necessary. The development of high temperature brazing compounds provides the designer with a much better solution in the design of turbine nozzles and other "hot end" assemblies. Fig. 8 is a sketch of a suggested method of utilizing this brazing procedure. The nozzles are simple castings with little or no machining and are brazed to separate shrouds in groups. The quantity of strategic material is less since the mounting shrouds can be of lower quality stainless steel. Less machining is required on the mating structures since the blades are mounted in groups rather than individually and the shrouds can be overlapped at their ends to decrease the amount of gas leakage around the ends of the nozzles. Although this type of construction can be performed by welding, the brazing operation causes such little distortion that fewer post brazing machining operations are required.

Hot End: The present exhaust cone, Fig. 9a, consists of a fabricated stainless steel outer casing and inner cone or bullet. Both are stiffened with spot welded "Z" stiffeners and the bullet is supported by two sets of four crosstubes. The forward set of crosstubes is connected by external pipes and carries cooling air to the centre of the rear face of the turbine disc. Mounted on the support tubes are four streamlined vanes fabricated of folded skins spot welded to internal formers or ribs.

This construction, which was used almost universally eight years ago and is even appearing on some new engines, is complex and expensive. Cracking and buckling of the sheet metal parts occur, especially in the vicinity of the stiffener spot welds due to thermal shock and vibrational fatigue. Various schemes have been used by the engine companies to increase life; however, most solutions consist of the addition of extra stiffeners, doubler plates and the like to overcome the results rather than the causes.

Careful study of failures suggested that by allowing the material to breathe with temperature variations and by eliminating the spot welds and locally stiffened areas, the life could be greatly increased. When two sheets of metal are spotwelded together they are decreased in thickness considerably at the periphery of the nugget by the welding electrodes. The stresses caused in this area by the differential expansion of the hot skin and the cooler stiffener combined with vibratory stresses finally cause a crack which then progresses until severe failure occurs.

Problem Solved: The solution is the design shown on Fig. 9b, which is much simpler and lighter, and has a test bed running life such that the design is being readied for production of new engines and overhaul replacements. The outer casing "Z" stiffeners have been removed. Four sheet metal pressings (each consisting of one half of two vanes with integral pressed-in stiffening beads or corrugations, and one quarter of the bullet) are fusion welded together to form the complete unit. Internal stiffening plates in the vane root fillet areas were the only additions made during development and were necessary to overcome metal fatigue caused by torsional vibration of the bullet. An end plate on each vane incorporates a support sleeve which engages a hollow radial pin connected to the outer casing via a doubler plate. The bullet is thereby supported rigidly, yet is free to expand radially. One of the support pins is connected to the centre of the bullet diaphragm by a tube for carrying turbine cooling air, thus eliminating the external air manifold.

This exhaust cone design is the result of a thorough study of the failure problems and correct diagnosis of the causes and could not have been evolved without the experience gained on the original unit. It is, I feel, a good example of design simplicity.

This philosophy of design simplicity must be used for future turbojet generations to an even greater degree since performance demands are inceasing at an alarming rate. It took fifty years for aircraft to reach the sonic range and immediately the tonic changes to twice the speed of sound. This trend to higher altitudes and speeds into the supersonic regions at altitude, places the requirement upon the engine companies for military power plants of higher thrusts with minimum increase in frontal area or weight and able to function over an ever increasing range of operational conditions from take-off to transonic speeds at ground level, and to very high altitudes and supersonic speeds, all under temperature conditions varying from tropic summers to Arctic winters.

Vibration Factor: The increase in air swallowing capacity required to provide high thrust yet with minimum weight and frontal area will necessitate the use of a very low hub to tip ratio at the inlet of the engine: this will lead to long front compressor blading and a new realm in the vibration problem. The vibrational fatigue of blades in the turbojet engine is a most exasperating phenomenon since the causes can be many and until the engine runs, the troublesome causes are unknown. Test bed engine running does not tell the whole story but actual flight experience usually is required to develop a configuration free from blade fatigue.

A glass-reinforced plastic construction for compressor blading is now in the development stages and has actually been operating in test compressors with excellent results. This material is of about the same density as magnesium and at temperatures up to 250°C. provides comparatively high tensile strengths. Very light rotors, therefore, could be the result, but the main benefit will be gained from the fact that the high internal damping quality of the material provides excellent resistence against vibrational fatigue. Laboratory test machines have proven the material almost incapable of withstanding temperatures up to about 250°C it is reasonable to assume that in the near future 375°C operation will be a reality. This material will suffice for the first few stages of compressor blading and perhaps even the discs and compressor casings which can be molded to sufficient accuracy that only slight finishing should be required.

As aircraft speeds increase into the supersonic region, so the ram temperature rise increases. At twice the speed of sound at 30,000 ft. on a normal day, for instance, the temperature of the air entering the engine is approximately 180°C, a normal oven baking temperature; and this is the coolest natural air available in the aircraft. This increase in temperature will move the magnesium and aluminum alloys farther towards the inlet of the engine and in their places in the rear zones of the compressor, titanium may be used.

Three Forms: Titanium today is available in the engineering forms of sheet, bar, and forgings; as yet it can only be cast in a vacuum and is still very expensive at from $15 to $20 per pound in these forms. The early machining difficulties experienced with titanium have been overcome considerably so that today it can be machined as readily as normal stainless steels. The higher strength alloys that can be used for compressor blading and discs, are not weldable but the lower strength commercially pure titanium and a few alloys can be welded in an inert atmosphere. In the molten state, titanium possesses a severe attraction for nitrogen and oxygen which causes brittle alloys to form. Great care must be taken, therefore, to prevent the metal from coming in contact with air during any process requiring melting.

Even in spite of its great cost and difficulty of handling, titanium will definitely be a major structural material in aircraft engines, and in the very near future, since it has by far the highest stength-to-weight ratio of any engineering material and is high-corrosion resistant up to about 450°C. New methods of refining titanium which will tend to decrease the cost are now in pilot plant production, and as the requirement for the material increases and the quantity of production thus increases, and it will, so the price will decrease still further.

The high-strength-at-medium-temperature aluminum and magnesium alloys are not weldable materials, and therefore exist in engines mainly as castings. As these materials move toward the front of the engine and steel or titanium structures take their places, the structures will be welded or brazed fabrications of sheet, bar, forgings and small castings. Because these materials have higher specific weights than aluminum or magnesium and the modulus of elasticity to weight ratios are nearly the same, thinner sections can be used for the same rigidity. Since these thicknesses can be obtained more readily by rolling than by casting, the sheet metal engine, as it may be called, is definitely the engine of the future.

Hotter and Hotter: One of the main methods of obtaining more thrust for a given size and weight of power plant is to increase the combustion temperature. This will increase the temperatures of the parts operating in or near the gas passage such as discs, blades, nozzles and shrouds and, of course, their supporting structures. New alloys providing better properties at temperature or higher temperatures for given properties than of those in present general use are becoming available and others are in the development stages. Even those will not carry us into the realm of combustion temperatures required for the future turbojet and the air or liquid-cooled turbine blade and nozzle will be seen in engines in the not-too-distant future. Cooling methods for blades have been developed and tested by several of our government research organizations; the problem now is to evolve configurations that can be produced in quantity.

Several companies have developed cemented carbide materials for nozzles and turbine blades. These ceramets provide high strengths at high temperatures but, being quite brittle, require special means of fastening to the discs or shrouds and possess little resistance to vibrational fatigue. When these problems have been overcome the ceramets may well add their part to the construction of future engines.

In most present day turbojets, air is the primary bearing cooling agent, but at supersonic speeds, as has been mentioned previously, the air becomes too hot and the oil or lubricant will have to perform the cooling. This again will require cooling, probably, as at present, by the fuel flowing to the engine through an intercooler. Under some flight conditions however, even the fuel will not be a sufficiently large sink for the heat rejection required and artificial means will be necessary to keep the lubricant within its working temperature limits.

LOW LEVEL: With the latest lightweight Martin-Baker ejection seat, an aircraft crewman can be ejected and parachuted to safety even when the aircraft is on the ground. The photos show an actual ejection from a Meteor on the runway. The airplane was moving at a speed of 120 kts. at the time of ejection. The test was carried out with Martin-Baker's 80-ft.-per-sec. long stroke ejection gun. The new seat weighs approximately 60 lbs. and is shot about 80 ft. above the aircraft on ejection.

Lubricant Limits: Bearing steels have been developed that will stay hard at temperatures up to about 550°C but we still do not have lubricants that will stand these temperatures. The oil and chemical companies have developed synthetic lubricants capable of operation at nearly 200°C but lubricants that will operate at 350°C and higher will be absolute necessities. Lubricants that will not break down at these high temperatures in contact with the oxygen in the air is the requirement and even the synthetic lubricants now in use in some of the synthetic lubricants a tendency towards sludging or break down into a black sticky substance that gradually blocks the flow passages. Lubrication will be a serious problem and could be the limiting factor in the development of supersonic aircraft engines.

The elastomer compounds for O-rings and gaskets, the other main non-metallic substances in the gas turbine engine, are quickly reaching their thermal limits. The present materials such as the silicone rubbers and fluorinated polyethylenes are useful up to about 300°C but materials for 500°C operation will be a definite requirement since the construction of flexible gas and liquid tight joints for use at high temperature is very difficult to effect without them.

In order to pass the high air flow of the future engine, the can type combustion chamber will probably be replaced by the annular type since a larger gas passage is obtainable within a given engine diameter. Considerable combustion development will be required to attain units capable of operating efficiently at combustion temperatures and average gas velocities well above the 1100°K and 80 to 90 feet per second now in general use.

Reheat Required: Until such time as the combustion of the fuel towards the stoichiometric limit is possible in front of the turbine, an afterburner may be used to increase the thrust of the engine during certain combat manoeuvres, acceleration and climb. Means of keeping this unit light, simple to manufacture and service, yet able to burn fuel efficiently at temperatures of 2000°K or more for a reasonable lifetime will be no easy task. It should have a fully modulated adjustable final nozzle for optimum performance and the control and fuel systems could be integrated with those of the main engine to form a single power plant control.

These larger power plants, swallowing great quantities of air, will require high fuel flows and the normal gear or piston types of engine driven fuel pump would be of tremendous proportions to handle these flows. These types could be designed to operate at higher speeds or the air driven centrifugal pump being developed for afterburners might be used. This problem might be made clearer if it was stated that pumping capacities of 30,000 to 60,000 lbs. of fuel per hour will be required. Upon further deduction you will understand why the search continues for fuels possessing greater heating values than the 18,000 BTU per pound of the normal hydrocarbons.

The matching of the operational characteristics of a power plant to the operational characteristics of an aircraft, will require that each engine installation be specially tailored to each individual aircraft. The days

SHADES OF 1930! Developed by "Mechanix Illustrated", the MI Baby Ace is based on the Corben Baby Ace of the early thirties. According to the magazine, the aircraft can be built at home for less than $800. Powered by an unspecified 65 hp engine, the Baby Ace is said to be capable of a top speed of 110 mph, though normal cruise is 95 mph; landing speed is 30 mph. The prototype (shown) has been approved by the CAA.

of the universal power plant are almost behind us and much more effort will be required in the installation of the power plant in the aircraft than has ever been provided before. The matching of the engine inlet and exhaust portions with the aircraft and the cooling of the nacelle will all require special attention for optimum performance over the ever increasing range of operating conditions.

Contol Complexity: The control system of the future aircraft power plant will become more and more complex in its operational requirements. It will have to control the engine fuel flow for the various aircraft speeds, altitudes and temperatures; it will have to guard against engine rotor overspeed, against over-pressurization of the combustion chamber, against over-heating of the turbine and it will have to control the fuel flow to the afterburner. It probably will be integrated with parts of the aircraft control system to control such variables as aircraft speed since the pilot will be too busy flying and navigating to have time for such items.

In the design of such engine accessories, therefore, it becomes increasingly important that the philosophy of design simplicity be applied to the utmost in the execution of each mechanical function to avoid hopeless confusion in the overall result. When you visualize the maze of equipment, practically covering the outside of the average turbojet, including the Orenda, you can well understand that, if simplicity is not the preliminary design keynote, this hopeless confusion could well develop as extra equipment is added—and it usually is—during the lifetime of the power plant. These accessory details such as valves, pipe fittings, filters, solenoids, control levers and other are the very items that keep aircraft grounded, perhaps because they seem relatively unimpotant and generally do not receive the same careful study as the major units such as discs and shafts. These tremendous trifles, as they may be named, must assume the same importance as the so-called major parts since grounded aircraft are very poor weapons of defence or profit-making vehicles.

Material Considerations: You have realized no doubt, that materials will play a very important part in the design of future engines, even more than they did in the past. There are ever increasing numbers, each with its own particular properties, and the designer must familiarize himself with them as they are developed, since materials well utilized in a sound mechanical configuration can make a good aerodynamic design a useful power plant.

The importance of the power plant will increase with aircraft speed since it will become the most profitable place in which to expend our efforts in the search for optimum aircraft performance. Abe Silverstein, Associate Director, Lewis Flight Propulsion Laboratory, NACA, showed recently before the IAS, that the engine and fuel weight increases from 25% of the gross weight of a hypotheical aircraft designed to fly at Mach .5, to 40% at Mach 1, and to over 60% at Mach 1.5. This is by no means the full story, but it indicates a definite trend and emphasizes the need for an increased effort on the part of the mechanical designer in practicing the philosophy of simplicity.

Remember that complexity is the easy solution, and simplicity takes a little longer, but every part eliminated is one that can not cause trouble.

ENGINEERS

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goods industry, on the engineering side, and it becomes apparent that our nucleus of aeronautical engineers can be no small helping on the industrial plate.

To estimate this engineering dilution factor, and thus get to grips with the details of our strategic pool of engineers, by reducing it to numbers and plotting its probable growth through the years as we build up our industrial strength, is a governmental job that must be tackled. Then the design and development of airplanes, engines, and equipment can be fed to the growing infant in the proper proportions to maintain its health, nurse it to maturity, and keep it in full grown fighting trim.

This development and pooling of our engineering brain power is a vital part of what the great strategist Admiral Mahan meant when he said, "It behoves countries whose people, like all free peoples, object to paying for large military establishments, *to see to it that they are at least strong enough to gain the time* to turn the spirit and capacity of their subjects into the new activities which war calls for."

In this age of split second atomic war we must be strong enough to "gain the time." And one of our vital bulwarks in this endeavour will be our reservoir of experienced aeronautical engineering man-power. Let us guard it well. For it may have even a greater part to play "in shaping the destiny and form of this country" in the turbulent days to come.