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Fluid Machines—Expanding the Limits—Past and Future

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SUMMARY

During the 40-yr period from 1940 to 1980, the capabilities and operating limits of fluid machines have been greatly extended. This has been due to a vigorous research program, much of which was carried out or sponsored by NACA and NASA to meet the needs of aerospace programs. Some of the events which initiated and drove the research programs are reviewed. Overall advancements of all machinery components are discussed first followed by a more detailed examination of technology advancements in axial compressors and pumps. Limited comments on possible future technology needs are made.

INTRODUCTION

Observing the advancement of fluid machinery for some 40 yr from the vantage point of the Lewis Research Center of NACA and NASA has been a unique and rewarding experience. Over that time span, there has been a very extensive advancement in the capabilities of fans, compressors, pumps, and turbines, as well as a substantial increase in the range and condition at which effective operation could be obtained. At times the improvements or advancements have seemed to be evolutionary in nature with the major effort being expended to achieve optimization of designs about a given technology base and avoidance of recognized limitations. At other times the activity seemed to have been revolutionary in nature. At these times advancements were made by either circumvention or direct assault on the real or imaginery limiting conditions. These apparent revolutionary advances opened whole new areas of application or advancements in capabilities of fluid machines. It could be expected that this evolutionary-revolutionary type of advancement may be typical of fields involving engineering science or technology. With the frequency of the revolutionary periods driven by the expanding demands and the resources applied to the area. In the case of the fluid machinery of concern to NACA and NASA the continuing need for increased capability has been driven by the nation's aerospace program which has also provided ample resources.

The purpose of this paper is to first examine the overall extent of advancement of aerospace fluid machinery performance that has been achieved from the 1940 to 1980 period. The advance in axial compressor and pump technology will be examined in some detail to determine the manner in which these advances came about and the activities that contributed to expanding the operating limits of fluid machines utilized by the aerospace industry. Limited comments will be included concerning the approaches and areas for continued expanding the limits in the future.

It is somewhat unfortunate that a broader range of experience is not included. However, the perception described is entirely that available from observing the advancements of fluid machinery applicable to aerospace programs. It may also be that the authors wished to again review their exciting experiences. In a few areas the participants in the overall fluid machinery program have been mentioned. There were many more who made extensive contributions who have not been noted and to whom we apologize. It should also be noted that each of us may have observed these 40 yr somewhat differently and thus would have highlighted the events differently than the authors.

INCREASING THE CAPABILITY OF AEROSPACE MACHINERY

It is convenient to consider the overall increased capability of several types of fluid machinery that was achieved from the 1940 to 1980 time period. Table I indicates some of the advancements and the expansion of limits achieved in this time frame. No attempt will be made to detail time phase these advancements. It is not necessary to discuss component efficiency as a major advancement since machines that achieved operational status in the aerospace fields over this time frame were all generally of relatively high efficiency. In fact, systems were and continue to be optimized such that the machinery could be operated at high levels of efficiency. However, major advancements were achieved which extended the regions of high efficiency to higher rotational speeds and/or more severe operating conditions thus allowing for substantial gains in systems performance. The gradual and rather modest improvement in efficiency occurred as a result of improved control of the fluid flow conditions and related areas, such as leakage or tip clearance losses. Generally advances were not considered useful unless machinery efficiency could be maintained or increased.

Centrifugal compressors have been important fluid machines over the entire 40-yr time span. Useful performance levels involved stage pressure ratios of 3:5:1 to 4:1 (table I). Even though higher pressure ratios could be achieved by higher rotational speed, substantial performance losses were experienced because of increased losses associated with high Mach number flow in the diffuser element. At the present time good performance levels at stage pressure ratios approaching 8:1 are considered feasible. (It is noted that even higher pressure ratios may be achieved but some performance penalty may be necessary.) The advancement in this case has been the ability to design rotors with high strength material that are capable of maintaining the clearance and passage shapes with the temperature gradients and stress levels experienced at very high rotational speeds. These advances in materials and structures allow the use of backward curving rotor blading thus achieving high stage pressure ratio with relatively low flow Mach number into the diffuser section. The design concept was well known at the earlier time, but the capability for the structural design at high rotational speed was advanced during the reference period. Expanding these limits provides the opportunity to consider the centrifugal compressor stages for a wide range of aerospace applications not otherwise thought feasible.

Early axial flow compressor rotors were designed to limit the relative flow Mach number to subsonic levels somewhat below the transonic drag rise level observed in representative cascade blading. Rotor airfoils that were in use indicated a considerable increase in loss at flow Mach numbers slightly higher than 0.7. The rotational speeds at which this occurred limited the stage pressure ratios about 1.1:1. But even with this limitation, the ease with which axial compressors could be staged to increase cycle pressures and the improved flow per unit of frontal area resulted in axial flow compressors replacing the centrifugal compressors in turbojet aircraft engines. The development of axial rotor blade shapes capable of moderate loss in the transonic region even while achieving considerable turning immediately resulted in high performance stages with pressure ratios between 1.2:1 and 1.4:1 resulting in a substantial reduction in the number of stages required to achieve a given overall pressure ratio. It was also possible to increase cycle pressure ratios to achieve further system performance gains. Continued improvements in blade shape selection and aerodynamic approaches as blade speeds were increased has made possible much higher stage pressure ratios. In some applications, stage pressure ratios of 1.8 or 2.0:1 are considered feasible.

Turbofan aircraft engines were made possible by these advancements to relatively high rotor blade Mach number. A reasonable compromise between low spool turbines and the fan rotational speed match could be achieved by operating the fan rotor blading at transonic or supersonic flow conditions. Early versions of subsonic aircraft turbofan engines employed by-pass ratios of about 1.0. As bypass ratios were increased to near 7:1 to achieve improved specific fuel consumption and reduced aircraft noise, fan blading was required to operate at relative Mach numbers in the order of 1.8. Fan blade shapes were devised to achieve relatively low losses and thus good efficiency. Besides these advancements to achieve good fan performance with high Mach number flow condition a number of other limitations had to be overcome to make the high by-pass ratio turbofan a viable aircraft engine. To achieve a stable blade structure it was necessary to develop a mid-span, or mid-radius, support for the long fan blades. It also became necessary to provide acoustic treatment in the fan ducts to reduce the external noise generated by the high Mach number fan blading. The success of the high bypass ratio turbofan was made possible by these advances. It will be noted in the following discussion that high work turbines were also necessary to avoid an excessive number of turbine stages.

Over the 40-yr time span being considered the gas temperatures at turbine inlet were increased from about 1400 to over 2500 °F. Over this time frame usable metal temperatures have been increased from about 1400 to nearly 1900 °F. These advances have been made possible by an improvement in the super alloys and material treatments including the concept leading to single crystal turbine blades. The capability to operate at the higher gas temperatures (2500 °F) has been achieved by the application of turbine blade cooling. Turbine cooling was of course not a new concept but it was necessary to develop a body of data and information to identify the aerothermal environment and the heat transfer factors in the rotor to avoid substantial performance losses to the turbine or cycle as a result of the cooling air flow. It must also be recognized that advanced material and structural approaches were necessary to operate the rather thin metal elements with severe thermal gradients and achieve the necessary durability.

Radial turbine configurations like centrifugal compressors have been available for a long time. In aerospace applications they have been utilized in relatively small sizes. Besides the advantage for high stage work, configuration advances can be obtained and several are noted. Small rotor systems are often operated at rotational conditions above one or more resonant speeds. Controlling tip clearance in a radial turbine may be more successful than over a multistage axial flow turbine. Although viable cooling schemes have not yet been devised for radial turbines, the rotor configuration may be more amenable to high temperature material, such as ceramics, than axial turbines. This approach appears to have had some success in the experimental automotive gas turbine area. The radial turbines have not received the long term research and technology efforts applied to large axial turbines.

Pumps with high suction speed capability have been achieved by the application of an inducer element which is capable of operating with some vapor present. These inducers operate in a quasi stable manner raising the pressure level such that the following stages can operate cavitation (vapor) free. Suction specific speeds of 7000 rpm were typically achievable prior to the 1940 time period. As large liquid rocket systems were developed it was necessary to apply inducer sections to achieve suction specific speeds at or above 30 000. Thus an increase in rotational speed made possible the very high pressure pumps used in high impulse rocket engines. The liquid hydrogen pumping system for the Space Shuttle main engine develops pressures in the order of 7000 psi. Inducers and boost pumps have been utilized in other applications, however, the development of cavitating inducers operating at very high suction specific speeds is recognized as a substantial advancement.

As hydrogen pump suction performance was accumulated, a lack of correlation with other fluids became apparent. It was soon realized that hydrogen was being pumped relatively near the critical point and the fluid properties were such that an additional benefit to suction performance was achieved. The concept was further evaluated in cavitating venturis and a few unique tests in hot water. The fluid property effects were such that in certain regions boiling hydrogen could be pumped without degradation in delivery head. The effect was that liquid hydrogen pumps could be designed to much higher effective suction speeds and higher rotational speeds than in other fluids. The net result is that very few stages can be utilized to obtain very high delivery pressure in liquid hydrogen.

This general discussion of the expanding capability of aerospace fluid machines indicates that there have been major advances between 1940 and 1980. Very often these advances have depended on materials or structural advances or the accumulation of aerothermal information that allowed for new designs or new application. Certainly the resources were made available because the new applications resulted in new products or systems advancing aerospace technology. Some of these components will be examined in a greater detail in the following sections to obtain a more detailed view of how the fluid machinery limits were expanded.

AXIAL COMPRESSOR TECHNOLOGY

Subsonic Stages

The first significant impetus to axial compressor research came with the decision that the axial compressor with its high efficiency and low frontal area was best suited for aircraft gas turbine engines. It was also determined that the design of the axial compressor could not be based upon isolated airfoil theory. Subsonic two-dimensional linear cascade tunnels were fabricated and blade row flow and performance measured for a wide range of flow and geometry parameters (ref. 1). These parametric studies formed the broad data base used to design subsonic axial compressors and were the basis for the formulation of several new families of blade shapes (i.e., the 4-digit series, the 65-series, etc.). Characteristically, these blade shapes were composed of a rather blunt leading edge, maximum thickness on the order of 10 percent of the chord and the maximum thickness was located at 30 to 40 percent of the chord length from the leading edge. Designs utilizing these blade shapes were generally limited to a maximum inlet relative Mach number of about 0.7 which, in turn, placed restrictions on the compressor flow and pressure rise across individual stages. Figure 1 is an example of the measured performance of a 10-stage compressor of advanced design under these limitations (refs. 2 and 3). At design speed, this 10-stage compressor produced an overall pressure ratio of 6.5 (average stage pressure ratio of 1.206) at an adiabatic efficiency of about 82 percent (polytropic efficiency of 86 percent) and flow of about 25 $lb/sec/ft^2$ of frontal area.

Low Transonic Stages

Good performance of low transonic stages was first demonstrated at Lewis by the safe and efficient operation of a rotor with a tip relative Mach number of about 1.1 and with mixed supersonic and subsonic flows. Designers had speculated for some time on the high losses and perhaps unstable operation when mixed supersonic and subsonic flows occurred in a blade passage. The tests showed that by careful tailoring of blade shape a continuous spectrum of high efficiency operation from subsonic to supersonic Mach numbers could be achieved. A photograph of this first transonic rotor is shown in figure 2. Note the thin leading and trailing edges, the reduced thickness of the blade, and the location of the maximum thickness near the mid-chord. These are significant features that would be incorporated into most transonic blade shapes. The stage pressure ratio and efficiency values at blade tip speeds from 800 to 1000 ft/sec (design) are shown on figure 3 and indicate the maintenance of a high efficiency (90 percent) from the subsonic to supersonic relative flows during which rotor pressure ratio increased from 1.27 to 1.48 (ref. 4).

Two multistage compressors were used to demonstrate the successful staging of transonic blade rows. An eight-stage compressor (refs. 5 to 9) employed two transonic inlet stages and a five-stage compressor (refs. 10 to 13) utilized all transonic stages. The eight-stage produced an overall pressure ratio of 10.2 (average stage pressure ratio of 1.34) at an adiabatic efficiency of 83 percent (polytropic efficiency of 87.5 percent) and a flow of about 30 $lb/sec/ft^2$ of frontal area. These values represent about an 11 percent increase in average stage pressure ratio and about a 20 percent increase in flow per unit frontal area over those obtained with subsonic stages. The measured performance map for the eight-stage compressor is shown in figure 4.

The five-stage compressor test program was unique in that it was operated as part of a jet engine which somewhat limited the compressor operating range that could be evaluated. At design speed the compressor produced an overall pressure ratio of five (average stage pressure ratio of 1.38) at an air flow of 32 $lb/sec/ft^2$ of frontal area and an adiabatic efficiency of 82 percent. At this speed there was a slight overflow (compared to design) which caused the stages to be mismatched and resulted in a penalty in efficiency. At 95 percent speed the stages operated at design flow and produced a pressure ratio of 4.5 (average stage pressure ratio of 1.35) at an adiabatic efficiency of 86 percent (polytropic efficiency of 88.6 percent). These two multistage compressors illustrate the potential for increasing performance without sacrificing efficiency by employing transonic stages and initiated broad research programs on transonic stages.

The analysis of transonic flow was considerably more complex than the subsonic flows and there followed a flurry of both analytical and experimental research with the objective of understanding the flow and developing a viable design and analysis system. Specific new analytical advancements included accounting for the meridional streamline curvature effects in the calculation of radial equilibrium (refs. 14 and 15) and Lieblein's formulation of a blade loading criterion named the D-factor (ref. 16). New flow phenomena which had to be addressed included a model to predict losses due to shocks (as reported by Hartmann, Schwenk et al. in ref. 17) and secondary flows in the blade end-wall regions. Notable early efforts to visualize these secondary flows using smoke traces were made by Hansen and Herzig and reported in reference 18. An example of their work is shown in figure 5. Early attempts to calculate these secondary flows were reviewed by Lakshminarayana and Horlock in reference 19. Experimental performance and flow data to support these analytical studies and provide a data base for emerging design and analysis systems were supplied primarily by single stage investigations.

Experimental procedures also were advanced significantly to meet the demands for more detailed flow measurements. Probes were mounted in actuators which utilized stepping motors to move the probes very precisely to desired radial and circumferential locations and automatically align the probe in the flow direction.

First attempts at defining local flow conditions within rotating blade passages using dynamic measurement techniques were also made. Blade-to-blade (tangential) variations of static pressure in the tip region of a rotor were obtained by mounting a row of high response pressure transducers in the outer casing. The static pressure fields generated from these measurements were used to identify shock patterns and blade loadings occurring in the tip flow region. At other spanwise locations, hot wire and hot film probes were used to obtain circumferential variations of temperature and velocity at the exit of a rotor blade row. However, these latter probes are probably better known for their use in identifying a new flow phenomenon, "rotating stall." It was noted from hot wire probes mounted at the rotor inlet or exit that as the overall flow was reduced, local stall (nonflow) regions occurred within the flow, particularly near the blade row tip section. It was speculated that a local stall zone was initiated by some small local perturbation in the flow or blade row geometry. However, once formed, the stall zone disturbed the flow entering the adjacent passage in such a way that the stalled zone moved circumferentially about the rotor in a direction opposite to rotor rotation. By mounting two or more probes at different circumferential positions the number of stall zones and their rotational speed can be deduced. Figures 6 and 7 and Huppert, Graham et al. in references 20 to 22 describe in more detail some of the analytical and experimental efforts to understand and predict rotating stall. It was also observed that increases in blade stress usually accompanied rotating stall, hence the occurrence of rotating stall was used as a limit to the stable operating range of the compressor.

High Bypass Ratio Fans

High bypass ratio fans impacted several of the gas turbine engines continuing goals (1) improved thermodynamic efficiency, and (2) reduced the high engine exit jet noise by mixing the cool bypass air stream with the hot turbine discharge air stream. Figure 8 shows a cross section of a high bypass ratio engine.

Characteristically, the fan rotor outer sections operated at high Mach numbers with light to moderate blade loading while the inner sections operated with moderate flow Mach number but with very high blade loadings. To allow some reductions of the loadings in the fan rotor hub, fractional-span boost stages were mounted just downstream of the fan. Schematics of several such arrangements are shown in figure 9.

To accommodate the high Mach number flows, several new blade shapes (e.g., multiple circular arc, arbitrary, polynomial), were evolved. Improved shock loss models to more accurately predict loss were developed. This was accomplished by accounting for the meridional (hub-to-shroud) curvature of streamlines on flow Mach number and shock strength. Two-dimensional inviscid transonic flow analytical methods were applied to calculate flow velocities and define shock patterns throughout the blade passages.

Significant efforts to experimentally define the passage shock patterns were also made. Dynamic static pressures over the rotor tip continued to be studied to deduce shock patterns in the blade tip region. To observe shocks at all spanwise locations, several visualization techniques were studied. Holographic techniques which would produce the full three-dimensional shock patterns were applied but it was extremely difficult to interpret the recorded test data. Some of these experiences are reported by Benser et al. in reference 23. A laser-fluorescing gas technique was developed by Epstein at MIT. In this procedure, laser light is reflected from a stream of seeded particles unto very sensitive photographic paper. The amount of light captured is then related to density changes in the flow, in particular the density changes across shocks. This procedure is reported in more detail in reference 24.

The high flow Mach numbers and relatively thin blade sections presented some new aeromechanical problems. Part span shrouds, or dampers, were required to keep blade vibrational stresses within safe limits. Also, operating regions where the blades could be excited to a flutter mode were identified. This flow phenomenon can seriously reduce the stable operating range of the fan. Some analytical and experimental studies of flutter are reported in references 25 to 28. One intriguing idea for delaying or eliminating flutter is "mistuning" a blade row. This concept promotes methods for breaking up the traveling wave patterns so that adjacent blades in a blade row are not collectively excited to a resonant mode. Structural means attempt this by varying the resonant frequency of adjacent blades. Aerodynamic means attempt this by varying the flow (forces on blades) in adjacent passages. Experimental tests to prove these concepts and quantify the benefits are in progress.

As the rotor tip region flow Mach numbers were increased, the stall free operating margin (SM) was generally reduced. While experimenting with methods to energize the end-wall flows, it was noted that certain types of open volume in the casing over the rotor blade tip resulted in improvements to the stage stall margin without an undue decrease in operating efficiency. Although the physics of this flow phenomenon are still not well understood, the SM gains achieved with various forms of this aptly named "casing treatment" are well documented. Some examples of "casing treatment" are shown in figures 10 and 11 and these and other forms reported in references 29 to 32. For some configurations the stalling weight flow with casing treatment was reduced 15 percent over that with a solid outer wall.

As noted earlier, the cool bypass air mixing with the hot turbine discharge air greatly attenuated the jet noise at the engine exit. However, the fan stage now became the prime source for generating noise which was radiated out through the inlet. Significant research to identify and eliminate or minimize noise sources in the fan were conducted in order to meet the new reduced noise levels required by law. Three basic types of noise are associated with fans: (1) discrete blade passing frequency noise, (2) broadband noise, and (3) supersonic fan noise (sometimes referred to as multiple pure tones or buzz saw). Some noise reduction concepts studied included choked inlets, reduced shock strength, reduced blade loading levels, optimum ratio of the number of stator to rotor blades, increased axial spacing of blade rows, blade leading edge sweep, blade tangential lean, and acoustic liners (ref. 33). Ultimately, most of the reductions in fan noise were realized from the remarkably good results obtained from very simple single layer acoustic liners. Other noise reduction features that have been incorporated into fan designs include the selection of the optimum ratio of rotor and stator blades, elimination of inlet guide vanes, and a large axial gap between fan rotors and stator blades (see fig. 12).

Energy Efficient Engines

Sharp increases in fuel costs sparked a demand for a new generation of fuel efficient engines. Applying this goal over the life of the engine requires consideration of improved performance retention, lower maintenance costs, fewer parts to fabricate and maintain, and decreased development times as well as the more obvious goals of increased efficiency and lower weight. The NASA Engine Component Improvement Project studied means for improving the performance of components utilized on current engines. The NASA Energy Efficient Engine (E^3) Project defined advanced engine configurations that depended upon technology advances in all components of the engine.

For the fan component these engine goals translate into increased bypass ratio, higher efficiencies, improved performance retention, and low noise. A few significant innovations used to meet these fan objectives will be noted. The higher efficiencies were achieved from improved aerodynamic blade shapes, lower aspect ratio blading, and reduced clearances between the blade tips and outer casing. One advanced feature studied was the use of shroudless fan blades (part span damper removed). These unique blades contained hollow sections in the outer portions of the blade which significantly reduced weight but required a very sophisticated design system to meet both aerodynamic and aeroelastic structural requirements. New advanced fabrication processes also had to be developed. To reduce noise, wide axial spacing between the blades and vanes was used. This wide spacing permitted the integration of the outlet guide vanes and structural struts (that support the fan case) which helps reduce the number of airfoils required which, in turn, reduces engine weight and cost. Additional savings in engine weight were realized by fabricating selected portions of the casing from composite materials.

For the core compressor component, the above engine goals translated into higher pressure ratio per stage, higher efficiencies, improved performance retention, and lower maintenance costs. The higher pressure ratio per stage keeps the compressor as short and compact as possible helping to reduce weight, reduce costs due to fewer airfoils required, and improve performance retention due to greater engine stiffness.

Higher efficiencies were achieved from advanced airfoil shapes, low aspect ratio blading, and carefully controlling tight tip clearances between the blades and the compressor outer casing. The latter is achieved by (1) a thermal matching of the materials used in this rotor and case, and (2) an active clearance control which controlled cooling of the outer case during engine transient operation to help the case expand and shrink at rates similar to those of the rotor. The outer casing also had shallow grooves (trenches) over the rotor blade tips to minimize aerodynamic losses. Advanced airfoil shapes, including the so-called "controlled diffusion" (CD) airfoil were used to minimize profile losses. The CD shape incorporates a relatively thick leading edge which makes the blade more resistant to foreign object damage and erosion. Lower aspect ratio blades permitted higher loadings per blade and significantly reduced the number of stages and number of airfoils required for these core compressors. It is likely that any new and advanced engines in the foreseeable future will be built around the core compressors developed in this technology period.

Schematic diagrams of the energy efficient engines designed by GE and P&W are shown in figures 13 and 14, respectively, indicating many of the advanced features employed. In the fan region note the acoustic lining, the partial span booster stages, the wide axial spacing between the fan rotor and stator blades, and the large air bypass ratio. The GE core compressor had a design pressure ratio of 23 to 1 to be produced in 10 stages or an average stage pressure ratio of 1.37. The adiabatic efficiency goal for the compressor was 88.7 percent which converts to an polytropic efficiency of about 92 percent. Comparing these performance values with the pressure ratio of 6.5 and polytropic efficiency of 86 percent achieved by the 10-stage subsonic compressor indicates the significant advances made by compressor research. Similar advancements have, of course, been necessary in all components to make it possible to realize these advanced engines (ref. 34).

Flow Analysis Techniques

It is highly significant that these advanced turbomachinery designs were successfully carried out the same time that analytical codes and new flow measurement techniques for analyzing the flow through the fan and compressor blade rows were beginning to be used routinely in research programs. Promising results were quickly integrated into design and analysis systems.

Inviscid flow analysis codes (both two- and three-dimensional) were used interactively with boundary layer growth predictive codes to analyze the internal flow through new blade row designs both rotating and stationary. The analytical codes provide much improved procedures for estimating the internal shock patterns, blade row loading levels (blade surface velocity diffusion), and surface boundary layer growth (a measure of viscous losses). They were particularly useful for optimizing blade shape for a particular application. For example, these codes were used extensively to optimize the CD blade shapes used in the P&W core compressor. At least a partial testimony to the value of these analytical procedures is that with all the new technology introduced into the energy efficient fans and compressors described above, they all performed very close to the design intent with essentially the first build.

One experimental technique that reached maturity at this time was the rather routine use of laser anemometry techniques for measuring velocity components throughout the passages of both rotating and stationary blade rows. This flow detail is needed to promote understanding of the internal flows, to verify the accuracy of analytical codes, and to suggest new flow models for accurately calculating certain complex flows. The enormous number of data points recorded can be sorted and processed in many ways to provide either average axisymmetric values or local time dependent values. The laser anemometry techniques have been used to describe passage flows within high speed rotating rotor blade passages (including location of shock waves), to define the boundary layer velocity distributions on surfaces of blades in cascade, and to measure the separation bubble and shear layers velocities during boundary layer separation and reattachment. References 35 to 37 describe these laser anemometer measurements in more detail.

Future Technology Drivers

The immediate advances in axial compressor technology will probably depend upon how vigorously and expertly we exploit the two complementary analytical and experimental techniques noted above. The maturing of these technologies is expected to sharply improve our understanding of the complex flows through turbomachinery. This improved understanding must then be translated through more accurate and reliable design and analysis systems into improved performance of the compression system. In particular, significant new insights into unsteady flow effects such as occur from the impingement of upstream blade wakes and are observed during rotating stall are appearing.

The design of relatively small size engines will receive increased attention. Many of these engines utilize regenerative cycles which require added ducting of the air to take advantage of the benefits of preheating and precooling the air flow. This is an added component part to analyze and optimize. Research obtained with larger size components should be generally applicable provided the effects due to Reynolds number, scaling laws, and the certain fabrication limitations are known.

New complex missions will consider a combination of operating conditions ranging from vertical take-off and landing to supersonic cruise. Variable cycle engines to optimize performance over this wide range of operating conditions are under study. The turbomachinery designer must provide a fan and core compressor that will operate efficiently over a broad range of flows and rotative speeds. Both the fan and compressor will utilize variable geometry to modulate flow (thrust), to block flow through portions of the fan during some operation, and to maintain a stable and efficient compression system throughout the mission. Obviously, the radial matching of blade sections comprising the fan as well as the matching of all the compression system components over a wide range of operating conditions present very formidable problems.

Advanced aeronautical technology studies are considering vehicles with supersonic and hypersonic flight speeds. The propulsive systems for such vehicles are not well-defined, but fans and compressors will be considered for the atmospheric flight parts of the missions. One interesting concept that will no doubt be studied is a fan that will accept supersonic axial inflow velocities. These supersonic velocities could be maintained throughout the fan or some degree of diffusion considered. The obvious advantage of such a fan is the reduction of the inlet diffuser length with some savings in weight and flow losses. Whether these savings will be lost in flow through the supersonic fan and downstream diffuser will have to be answered by experimental investigations supplemented by analysis. Advanced studies of this concept have indicated sufficient potential gains that more detailed design and proof-of-concept tests will have to be made to answer questions of efficiency, off-design performance, stability, starting problems, etc. It is anticipated that these supersonic through-flow fans could operate up to flight Mach numbers of about 3.5. Fan blades exposed to Mach numbers any higher may have to consider cooling of the blades. This requirement would complicate blade design severely.

PUMP TECHNOLOGY

Cavitating Inducers

Cavitation, the formation of vapor when the local static pressure of a flowing liquid drops below the vapor pressure of the flowing liquid, is a source of noise, deteriorates pump performance, can result in material damage, and may be a source of flow instabilities. The turbopumps of liquid rocket feed systems are particularly subject to cavitation since they operate at high rotative speeds in order to minimize weight. In order to reduce or prevent cavitation in the high pressure pumps, an inducer pump was placed at the inlet to the main pump. The objective of the inducer was to accept a cavitating inflow and gradually raise the pressure of the liquid to suppress the inducer cavitation and assure a cavitation-free flow through the main pump. The need to assure a constant flow of liquid fuels and oxident at high pressure (constant thrust) to the rocket combustion chamber resulted in a broad research program to better understand the flow in cavitating inducers and to develop design and analysis systems to accurately predict performance. Particular emphasis was directed toward the pumping of the high energy cryogenic fluids (i.e., liquid hydrogen, liquid oxygen, liquid fluorine) being considered for large new booster rocket systems.

Basic cavjtation studies utilizing visualization techniques and detailed performance measurements were conducted in water tunnels. Figure 15 is a schematic of the water tunnel used at Lewis. The inducer configurations tested herein characteristically have a small number of blades (1 to 4). Long narrow passages provide the time and space for the collapse of the cavitation bubbles and the gradual addition of energy. The major characteristic features of the inducer are low flow coefficient (axial velocity normalized by blade speed), large stagger angle, and high solidity (few blades with long chord length). Experimental evidence indicated that a very simple, but effective, inducer configuration was composed of helical blades (constant lead) wrapped around a cylindrical or conical hub. Figure 16 shows a typical helical inducer which sustained some cavitation damage to the blade material. These inducer configurations were tested over a range of inlet pressures related to operation from noncavitating flow through various degrees of cavitating flow and any deterioration of head rise due to cavitation noted. Figure 17 relates the visualization of cavitation to its effect on head rise as inlet pressure is reduced.

Additional inducer configurations tested included helical blades with a variable lead, a tandem-bladed inducer, and a cambered inducer. These experimental studies indicated that in water a net positive suction head (NPSH = inlet pressure above fluid vapor pressure) consistent with a suction specific speed of about 25 000 could be achieved. The experimental data from these water tunnel tests provided much of the data base for inducer design. During this same period test facilities to accommodate inducer tests in cryogenic fluids were constructed at a remote location. A liquid hydrogen (see fig. 18), a liquid oxygen, and a liquid fluorine facility was operated. In general, test times were limited so care was exercised in setting test conditions and the rapid recording of the results. One notable result from these tests was that the performance decay due to cavitation differed considerably from that observed in water tests (see fig. 19). This difference was associated with the different physical properties of the fluids and the research focused toward quantifying the effect will be discussed in the next section.

The experimental studies noted above provided a data base to build an acceptable design system. However, a longer term dedicated research program was needed to understand and quantify the flow physics occurring in the flow within the inducer passages. This type of study was carried out at Penn State University under grant to Lewis over an extended period of time. The strong real three-dimensional flow and local secondary flow effects were recognized and the basis for new and more meaningful flow models for use in design methods and analytical codes reported. A detailed review of this extensive research (guided by Wislicenus and Lakshminarayana) is given in reference 38.

Thermodynamic Effects on Cavitation

It was recognized by researchers that the inducer performance under cavitating flow conditions varied considerably with different test fluids. For example, these differences were dramatic when the same inducer was pumping liquid hydrogen as compared to pumping water. Extensive research on the physical effects in cavitating flows, those microscopic aspects that allow cavitation to occur, and the need for the existence of nuclei in the liquid was ongoing. However, preliminary attempts were made to relate these differences to the physical properties of the fluids, e.g., Stephanoff's B-factor (ref. 39).

One of the more successful studies to quantify these so-called "thermodynamic effects" and formulate a model for predicting the required inlet pressure, or NPSH, needed to operate in different fluids and fluid temperatures was carried out using similar venturis and four fluids with widely varying physical properties (water, Freon, liquid nitrogen, and liquid hydrogen). Details of these studies are reviewed by Ruggeri in reference 40. The model developed combines the effects of fluid properties, flow conditions, and heat transfer - termed thermodynamic effects of cavitation - to predict the inlet flow pressure, or NPSH, required to obtain geometrically similar cavities.

Generally based upon the venturi model, a method for predicting pump cavitation performance with varying liquids, liquid temperatures, and rotative speeds was formulated. Comparison of computed and test results indicated very good agreement for several different inducers and liquids. Details are provided by Moore in reference 41.

To support research on scaling due to the physical properties of liquids, a variable temperature water pump test facility was built at Lewis. The test fluid temperature could be varied from 80 °F (where the fluid properties are those of cold water) to 450 °F (where the fluid properties are similar to those of liquid hydrogen). Visualization techniques and both steady and unsteady measurement systems were utilized. Limited tests conducted in this test facility tended to confirm the models formulated in the venturi and pump tests noted above. However, the facility was never operated to its full capability.

High Pressure Pumps

The pumping of the cryogenic liquids to very high pressure posed a new set of problems to the pump designer. The effects of the extremely low temperature of this liquid on the physical properties of all the various metals used throughout the pumping system including the corrosive effects were not well known. These liquids were all high energy fluids, some with high explosive potential, so that special care was paid to eliminating rubbing of moving parts and contamination of the test fluid. This led to the use of generous tip clearances over the rotating blades. The cooling and lubricating of the bearings was done with the test fluids to eliminate contamination. The pump feed systems were required to produce very large pressures increases - up to 6000 psi on some engines. This results in unusually high thrust loads on the bearings and led to the development of stable and sophisticated thrust balance systems. Rapid startup and shut down subjected the system to unusually large flow transients. Significant performance variations were required of the pumping system, for example (1) "pump out" capability, the ability to continue to deliver full engine flow after a failure of one of two parallel turbopumps, requires a flow rate variation of 2:1, and (2) some throttleable systems require a delivered pressure variation of 10:1. Overall there is the desire for high efficiency of the pumping system. Because of the wide range of design requirements and fluid properties, scaling of performance or mechanical designs from proven configuration was discouraged. Most new pump programs passed through the entire sequence of conceptual design, development, and qualification prior to use.

The natural choice of a pump configuration to produce the pressure rises demanded by rocket systems was the centrifugal type pump. The relative simplicity and high reliability of this type of pump was generally recognized and its performance features have been well documented from experience in the commercial pump industry. In particular, Aerojet General Corporation has greatly advanced the development of this type pump for application to aerospace engines (see ref. 40).

At Lewis small size centrifugal pumps were successfully used to pump liquid hydrogen and liquid fluorine at Lewis' Plum Brook Facility - a remote site dedicated to testing of cryogenic liquids. While these tests demonstrated the capability for pumping these cryogenic fluids, the measurements of performance were rather limited so that it was very difficult to analyze flow details. For more detailed flow measurements together with some visualizations of the flow a centrifugal impeller was tested in water. Flow visualization was obtained by injecting dye into the water and by mounting tufts on the flow surfaces and photographing with a high speed camera. Figures 20 to 22 show the impeller with tufts mounted and some examples of photographs of the flowing fluid. Detailed measurements and visualization results are reported by Soltis and Miller in references 42 and 43. Of particular interest in this study were comparisons of measured and visual results with analytical calculations based on the streamline curvature methods reported in reference 44. Surface flow velocities including the location of reverse flow regions were calculated. The code proved very useful for locating splitter blades within the main flow channels.

One intriguing pursuit of pump research was to apply Lewis' background in axial compressor research to the design of axial type pumps. Rocketdyne Corporation was actively engaged in developing a liquid hydrogen multistage axial pump with some success. The potential of axial stages to provide improved efficiency (advanced specific impulse cycles require highly efficient pumping systems) and a more-controlled design system seemed to warrant additional studies. Twelve axial rotor configurations were tested in the Lewis Water Tunnel covering a range of design parameters such as blade loading, flow coefficient, radius ratio, tip clearance, and radial energy addition distribution. All but one of the rotors used a double circular arc (DCA) blade shape. Another characteristic of this group of rotors was the high inlet relative flow angles (measure of blade stagger). These parametric studies provided a data base for the design of pump stages (and other axial compressor stage applications utilizing low Mach number, high hub-tip ratio, and relatively high stagger). Performance data from all 12 axial rotors were compiled by Serovy et al. at Iowa State University in reference 45. This pump rotor data was supplemented by similar measurements in a water cascade investigation carried out at UTRC. DCA blade sections with inlet flow angle from 50° to 70° and covering a range of blade loading and solidity were tested and the results reported by Taylor et al. in reference 46.

In general the axial rotors did operate efficiently (90 percent) with a reasonably broad stable operating range even at high blade loadings (D ~0.66). As might be expected, it was noted that the three-dimensional correction factors applied to minimum-loss incidence angle and deviation angle for the pump configurations differed from those recommended for compressor rotors based on compressor single stage test results.

System Dynamics

One very serious dynamic problem experienced by rocket systems was longitudinal oscillation of the entire vehicle as observed during flight test of several missiles and vehicles. This phenomenon, called POGO, was traced to an unstable closed-loop coupling of the vehicle structure and the vehicle propulsion system. The frequency of these oscillations generally fell in the range of 5 to 25 Hz. The oscillations usually occurred near the end of the boost phase of flight where the system resonant frequencies were in this range.

The unstable loop coupling the vehicle structure and propulsion systems is self-sustaining. The structural longitudinal oscillations cause variations in the pressures and flows in the propellant fed into the pumps; this results in a variation in the pressures and flow of propellants delivered to the engines combustion chamber and, hence, a variation in engine thrust. The variation in engine thrust produces a longitudinal structural oscillation which completes the unstable loop.

A combined analytical and experimental research effort was initiated to determine an accurate mathematical transfer function for the performance characteristics of the turbopumps when there is a variation in their inlet pressures and flows. At Lewis a unique pump dynamics research test facility was constructed which would allow detailed measurements of the fluctuations of pressure and flow at the inlet and exit of the pump under both noncavitating and cavitating conditions. A schematic diagram of the pump perturbation test facility showing the significant components is shown in figure 23 and the details of many of the unique components described in detail by Stevans and Blade in reference 47. The facility received limited use but the limited dynamics data obtained indicated that the components of this facility operated according to the design intent. The need to continue this research effort was diminished when it was demonstrated that the POGO problem could be largely eliminated by the judicious use of capacitors in the propellant flow lines.

It was observed during visual studies of cavitation in the Lewis' water tunnel that under certain combinations of flow and inlet pressure (notably the low flow rates and low inlet pressures) cavitation has an unsteady nature. In general, this unsteady cavitation seemed to occur when the cavity closure point (on the inducer blade surface) extended just inside the passage formed with an adjacent blade. Significant pressure oscillations were measured within the system under these operating conditions and probably impose a limit on the useful operating range of an inducer. Figure 24 shows a film strip illustrating the movement of cavitation in and out of the passage. (Note the appearance and disappearance of cavitation in the same channel on successive frames.)

A rotation of cavitation zones around the rotors - analogous to rotating stall patterns in air compressor rotors - has also been observed in inducers. During operation of a rotor with short chord double circular arc blades the rotating cavitating zones moved out ahead of the rotors. Attempts were made to integrate these observed results into the pump off-design performance prediction methods.

Liquid Metal Pumps

Closed-loop power generation systems for use in space may utilize high temperature liquid metals either as the working fluid or as a heat-transfer medium. In the vapor loop the working fluid experiences a change of phase, hence the liquid metal must be pumped at or near boiling conditions. These systems must operate unattended for long periods of time. The pumps used in this application must be highly reliable, efficient, and light weight.

Both electromagnetic and mechanical pumps have been considered. At Lewis some analytical studies of electromagnetic pumps were conducted (e.g., see ref. 48) but emphasis was placed on studying mechanical pumps. Two test loops were built, a low pressure loop (see fig. 25) to study inducer-type stages with cavitation and a high pressure loop to study the complete pumping system. Both systems were operated with liquid sodium at temperature up to 1500 °F for various operating periods up to approximately 40 hr. Operating times were limited by seal and bearing failures.

The special problem for these pumps is damage to the structural metal parts, especially with cavitation present. Also, high temperature liquid metals are very corrosive. Hence special attention was paid to those design features, e.g. low speed, shaping the leading edge region, shrouding, materials, etc. and to system features, e.g., use of radiators for sub-cooling fluid, use of jet pump, etc. that would tend to inhibit cavitation and associated material damage. Although this research at Lewis was terminated before long range studies could be completed, sponsored research in the basics of cavitation damage, particularly in liquid metals, was completed, especially by Hammitt, et al. at the University of Michigan.

The possible application of the jet pump to liquid metal pumping systems stimulated an experimental study of low-area-ratio water jet pumps at Lewis (see fig. 26). (Low-area-ratio jet pumps are required to match with a high pressure pumping system.) Both noncavitating and cavitating performance were studied. Noncavitating experimental results were compared to an existing one-dimensional theoretical prediction method. Several related cavitation prediction parameters were developed and compared to experimental data. The results are detailed by Sanger in reference 49. The results from this study has since been computerized into a rapid design system for low-area-ratio jet pumps.

Future Technology Needs

The design of pump systems currently in use have been based largely upon experience together with a broad experimental data base. It is expected that two- and three-dimensional analytical codes for calculating the internal flows through pump systems together with improved flow measurement techniques will greatly expand our knowledge of the real flows through pump systems and provide the nucleus for developing a more accurate and reliable analysis and design methodology. This, in turn, should lead to pump systems with improved performance and capable of operating over a broader range of conditions. For example, it is envisioned that inducer flow passages would be tailored to minimize the cavitation formed on the blade surfaces and significantly reduce the strong frictional and secondary flow losses observed in typical high solidity helical type inducers. The main pressure producing pumps (either axial or centrifugal or both) would have blade passages tailored to keep surface velocity diffusions levels at appropriate limits. From a similar evolvement, improved analysis systems would become available to accurately predict the flows and performance at off-design operating conditions. It is recognized that the occurrence of cavitation with the associated effects due to two-phase flow, thermodynamic effects of the liquid, the presence of voids, nuclei, etc. in the liquid, and the possible occurrence of shock-like effects in two-phase flow make numerical flow modeling a formidable challenge. Many of these above effects, together with certain three-dimensional viscous flow effects, will probably have to be accounted for to some extent through empirical models.

Present trends for space operations seem to lean toward craft that can fly from earth-to-orbit and return, vehicles that can change orbit, reusable craft, etc. Besides the continuing propulsion system goals for higher efficiency, lighter weight, and larger pressure rise, the above trends would place additional demands on the throttleability, reliability, durability, and restart capability (in zero gravity) of the engines. Pump systems to provide off-design operation that is efficient, safe, and reliable will be required. These requirements encompass both steady-state operation at varied thrust levels and transient operation experienced during thrust excursions as well as rapid start-up and shut-down procedures.

This overview has briefly surveyed some trends for a new generation of pumping systems for space propulsive systems. Parallel advances in the technologies of materials, structural design, fabrication methods, and new engine monitoring systems would be expected to be available to ease many of the hydrodynamic concerns.

REMARKS

From an overall standpoint, 40 yr of technology efforts have greatly extended the capability in fluid machinery. The major extension has come in the range of conditions over which suitably high component efficiencies could be achieved. Substantial increases in cycle pressure and temperatures have been achieved along with substantial reduction in weight and increased operating range. Machinery has been evolved for a wide range of fluids such as liquid hydrogen. A continuing program to expand the limits of aerospace fluid machines has been in place.

A rather extensive review of the activities in specific areas of the technology program reveals a number of important aspects.

(1) Fluid machinery flows are extremely complex. These flows may be compressible or incompressible and multiphase. Subsonic, transonic, or supersonic flow regions may all exist in the same passages. Laminar, transitional, and turbulent flows may exist along with large separated regions. Highly three-dimensional, rotational, unsteady, nonuniform flows are encountered with a wide variety of working fluids. Noise and other environmental effects must be accommodated. Modeling and understanding limiting conditions in high performance fluid machines is a major challenge.

(2) Expanding the limits of fluid machinery has required a continuously increasing dependence on a wide variety of disciplines. These include hydrodynamics, aerodynamics, thermodynamics, aeroelastics, aeroacoustics, rotor dynamics, materials, structures, computer sciences and manufacturing methods. It has been and will continue to be the steady advancement in capabilities in all of these disciplines that are necessary to expand the limits of fluid machinery.

(3) In a general sense concepts which lead to more realistic simulation of the flow conditions have lead to major advancements in capability. Axial compressors have successively been modeled as isolated airfoils, two-dimensional cascades, and quasi three-dimensional blade rows. Some progress has been made in three-dimensional viscous and inviscid numerical simulation of blade row flows. In each case as the modeling was advanced experimental facilities and measurement techniques were adjusted or advanced to provide the necessary empirical information or verification.

(4) Perhaps not so evident from the detail discussion but very necessary to the advancement of the technology has been the need for new marketable

aircraft or a national goal requiring, or substantially benefiting from, fluid machinery with broader capability.

As aerospace systems continue to advance, more complex fluid machinery requirements will be demanded. Performance and installation requirements for vertical take-off and landing together with supersonic cruise, supersonic and hypersonic flights place particularly severe increases in operational ranges of the machinery. Continued extensions of operations in space will also need machinery with greater capability. These aerospace applications will require that the fluid machinery technologist work at or beyond his present level of knowledge.

In conclusion, the ingredients for a continued expansion of the limits of fluid machines are available. The numerical simulation of three-dimensional flows and the nonintrusive flow measuring systems are becoming available. Using these new analysis approaches, technologists will be able to understand and adjust fluid machine geometries to remove limiting flow phenomena from the desired broader operating ranges. Coupling these with new materials, structural and manufacturing technologies will provide continued expansion of the limits over which future fluid machines will be operated.

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TABLE I. - EXPANDED CAPABILITY OF AEROSPACE FLUID MACHINES

Machine type	Early experience	Present capability
Centrifugal compressor		
Blading	Radial	Swept back
Pressure ratio	3.5:1	8.0:1
Axial compressor (multistage)		
Stage pressure ratio	1.1:1	2.0:1
Spool pressure ratio	4.0:1	23.0:1
Fans	Subsonic	Supersonic
Relative Mach number	0.75	1.9
Stage pressure ratio	1.1:1	2.0:1
Turbines	Uncooled	Cooled
Stage work factor	Low	High
Inlet fluid temperature	1400 °F	2500 °F
Blade metal temperature	1400 °F	1900 °F
Pump		
Suction specific speed	7000 rpm	30 000 rpm
Delivery pressure (hydrogen)	400 psi	7000 psi
Jet pump		
Secondary/primary ratio	3.0:1	5.0:1

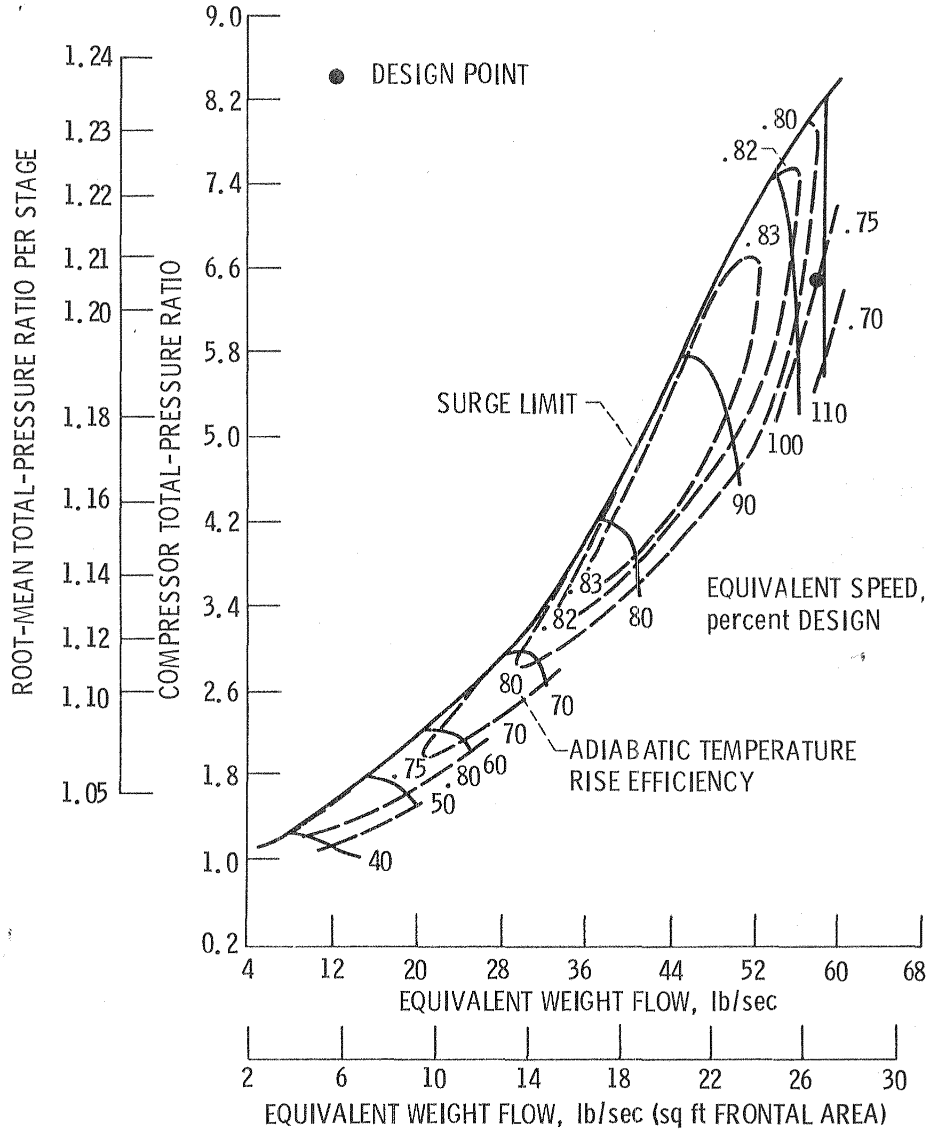


Figure 1. - Overall performance of 10-stage, axial-flow research compressor.

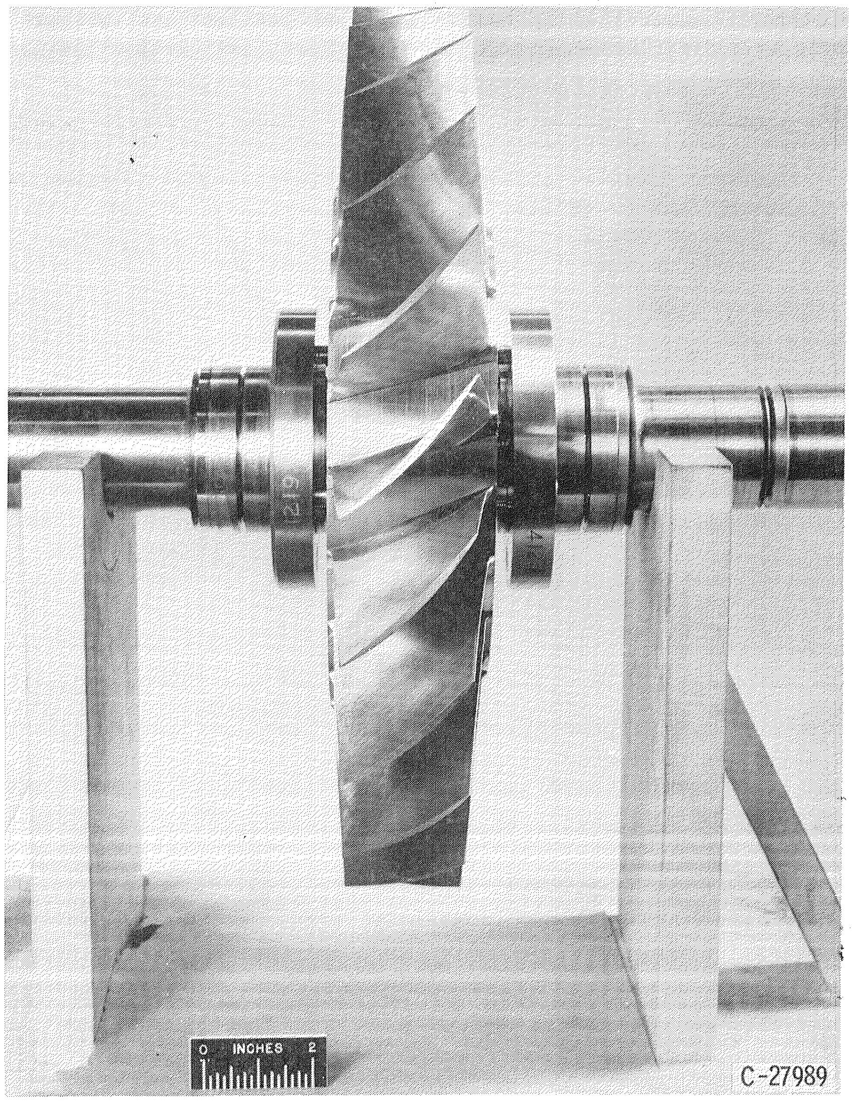
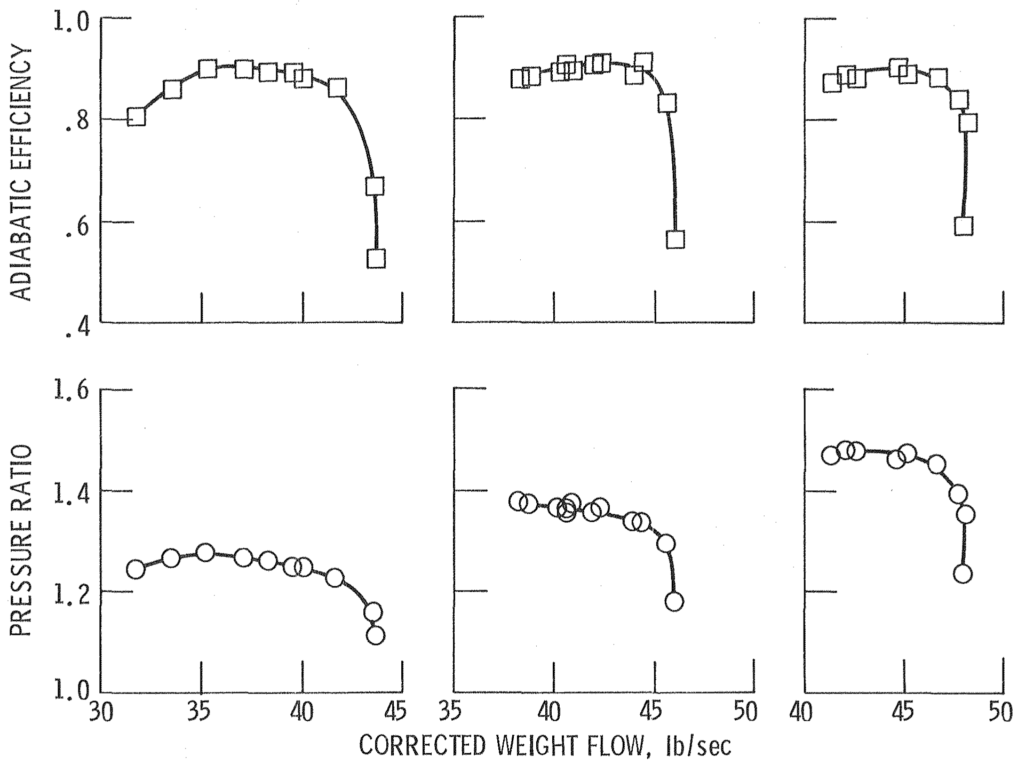


Figure 2. - Transonic compressor rotor.



(a) Corrected tip speed, 800 ft/sec.

(b) Corrected tip speed, 900 ft/sec.

(c) Corrected tip speed, 1000 ft/sec.

Figure 3. - Over-all performance of transonic inlet stage.

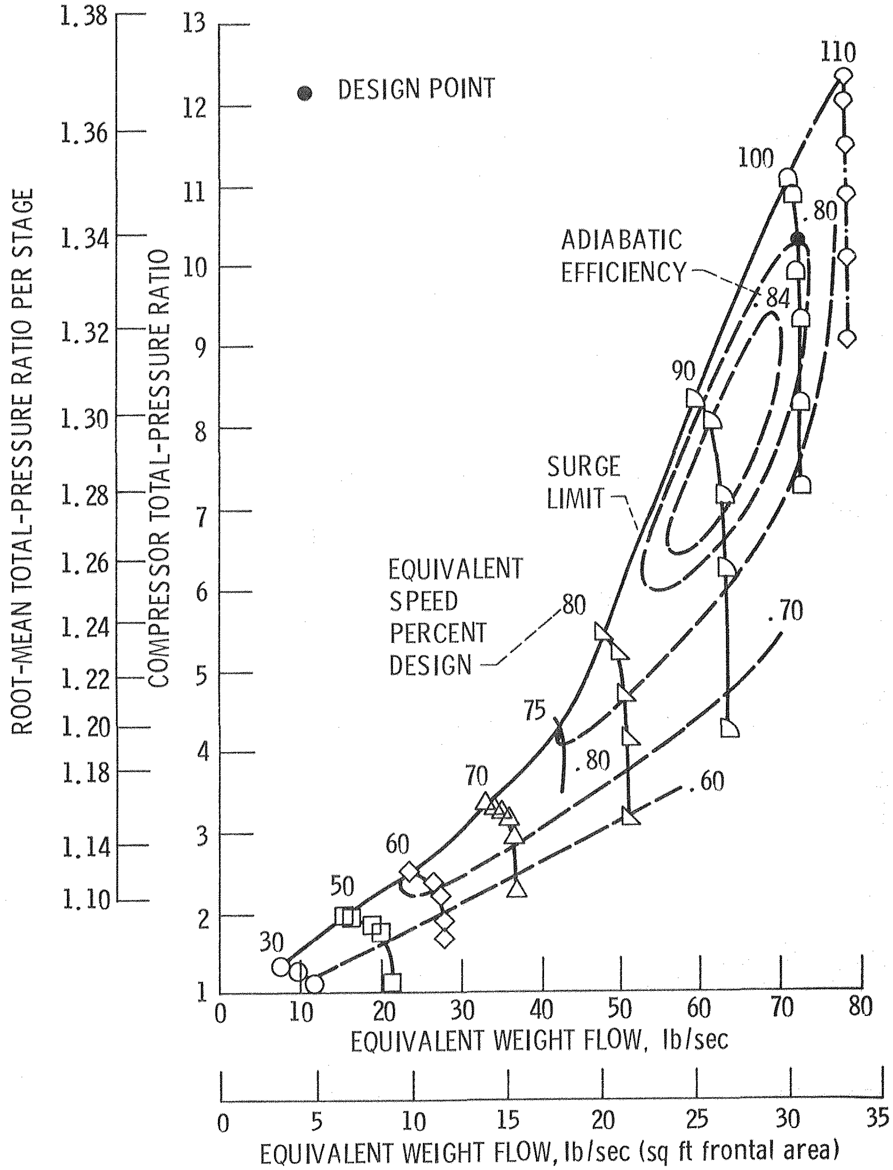


Figure 4. - Overall performance of modified 8-stage, axial-flow research compressor.

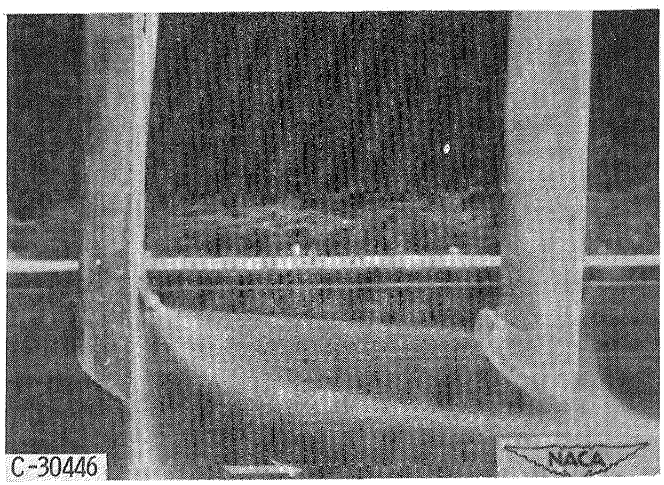


Figure 5. - Streamline patterns showing scraping effect of blade; suction surface leading.

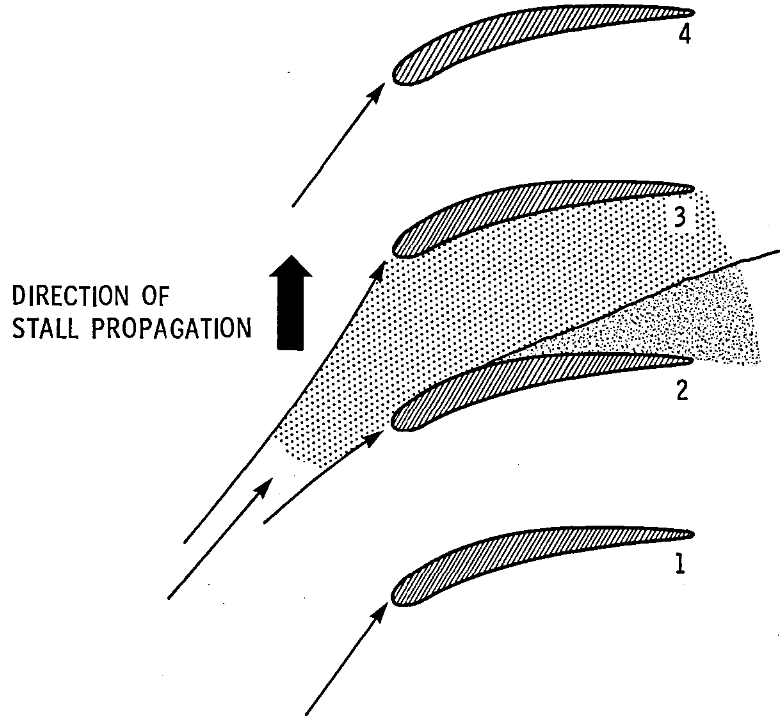
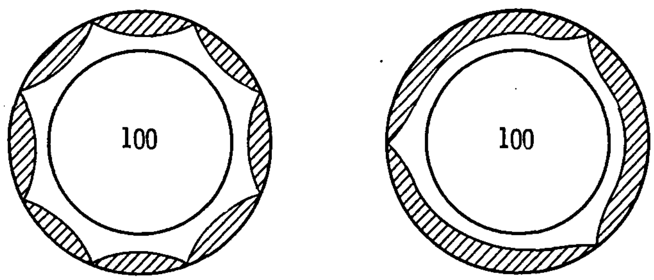
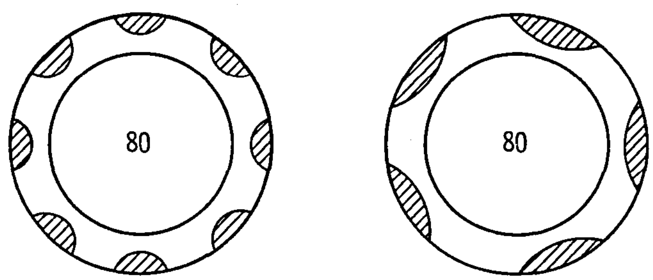


Figure 6. - Stall propagation in cascade.



STALL ZONES, 8
TIP CIRCUMFERENCE OCCUPIED,
100 percent

STALL ZONES, 3
TIP CIRCUMFERENCE OCCUPIED
100 percent

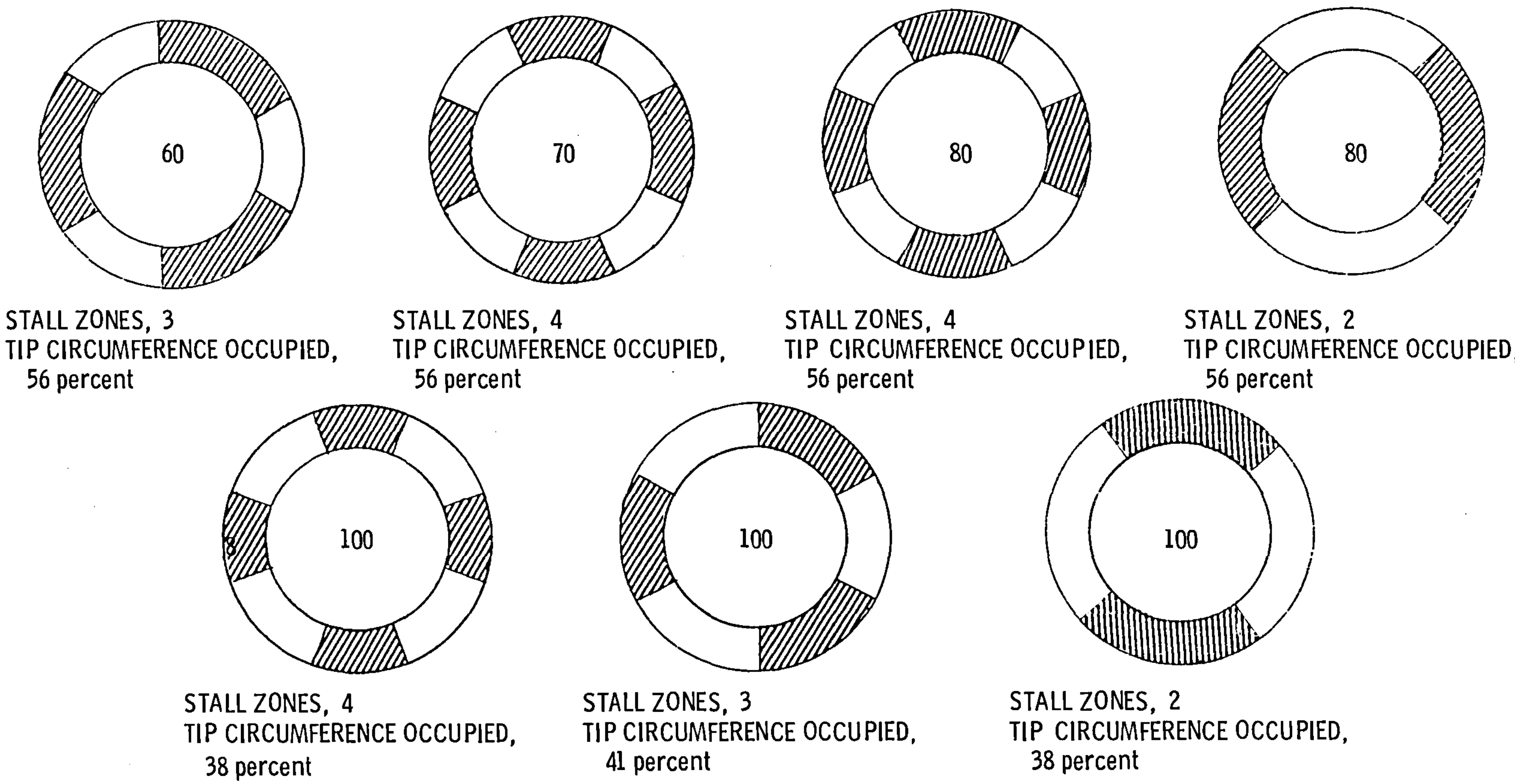


STALL ZONES, 8
TIP CIRCUMFERENCE OCCUPIED,
44 percent

STALL ZONES, 5
TIP CIRCUMFERENCE OCCUPIED,
37 percent

(a) Partial-span rotating stall.

Figure 7. - Circumferential extent of stall zones. Figures in centers represent percentage of design speed.



(b) Total-span rotating stall.

Figure 7. - Concluded.

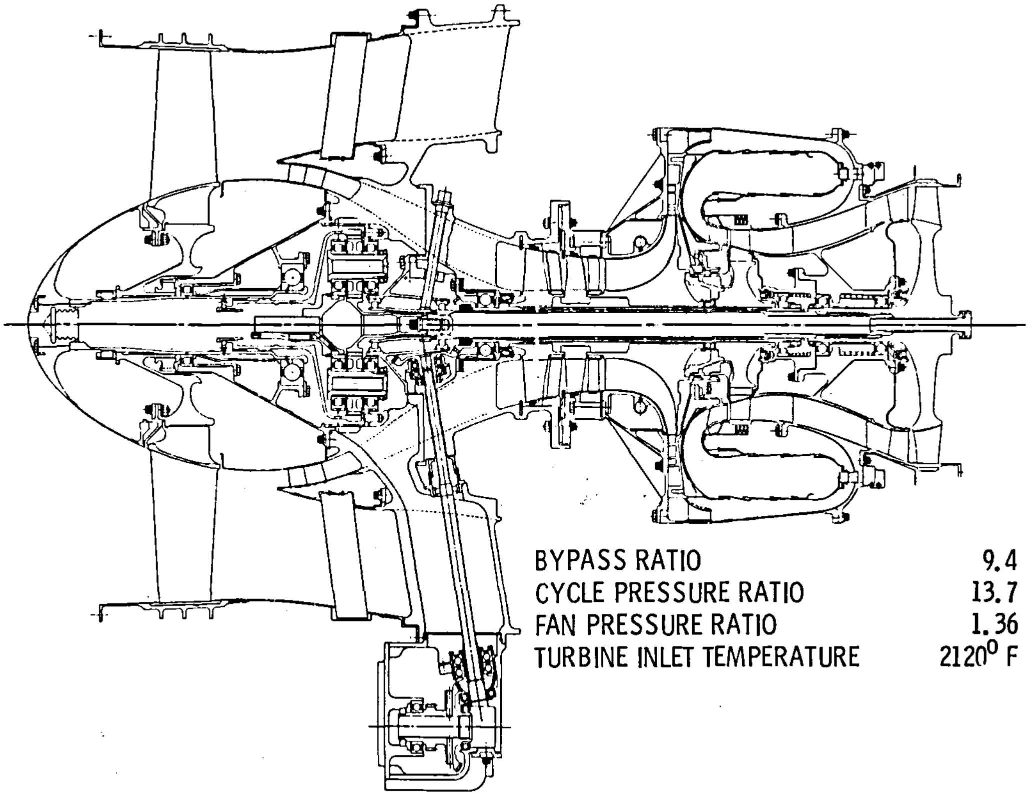
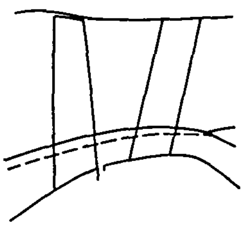
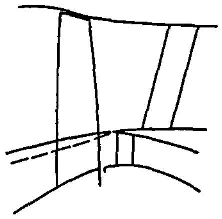


Figure 8. - NASA QCGAT cross section-AVCO Lycoming.

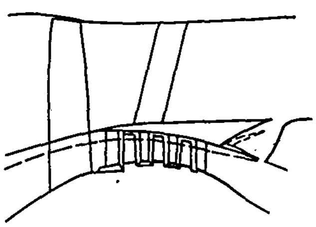
——— SPLITTER STREAMLINE, NORMAL OPERATION
------ SPLITTER STREAMLINE, OFF-DESIGN OPERATION



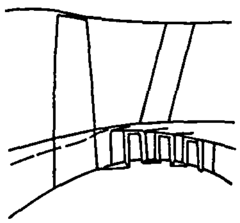
(a) Fan with remote splitter.



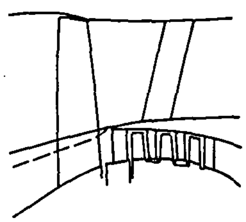
(b) Fan with split stator.



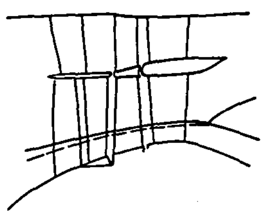
(c) Fan with core boost stages; off-design matching with bypass valve.



(d) Fan with core boost stages; off-design matching with variable stators.



(e) Fan with core boost stages; off-design matching with third spool.



(f) Fractional-span fan with remote splitter; short-span stage ahead of main rotor.

Figure 9. - High bypass ratio fan arrangements.

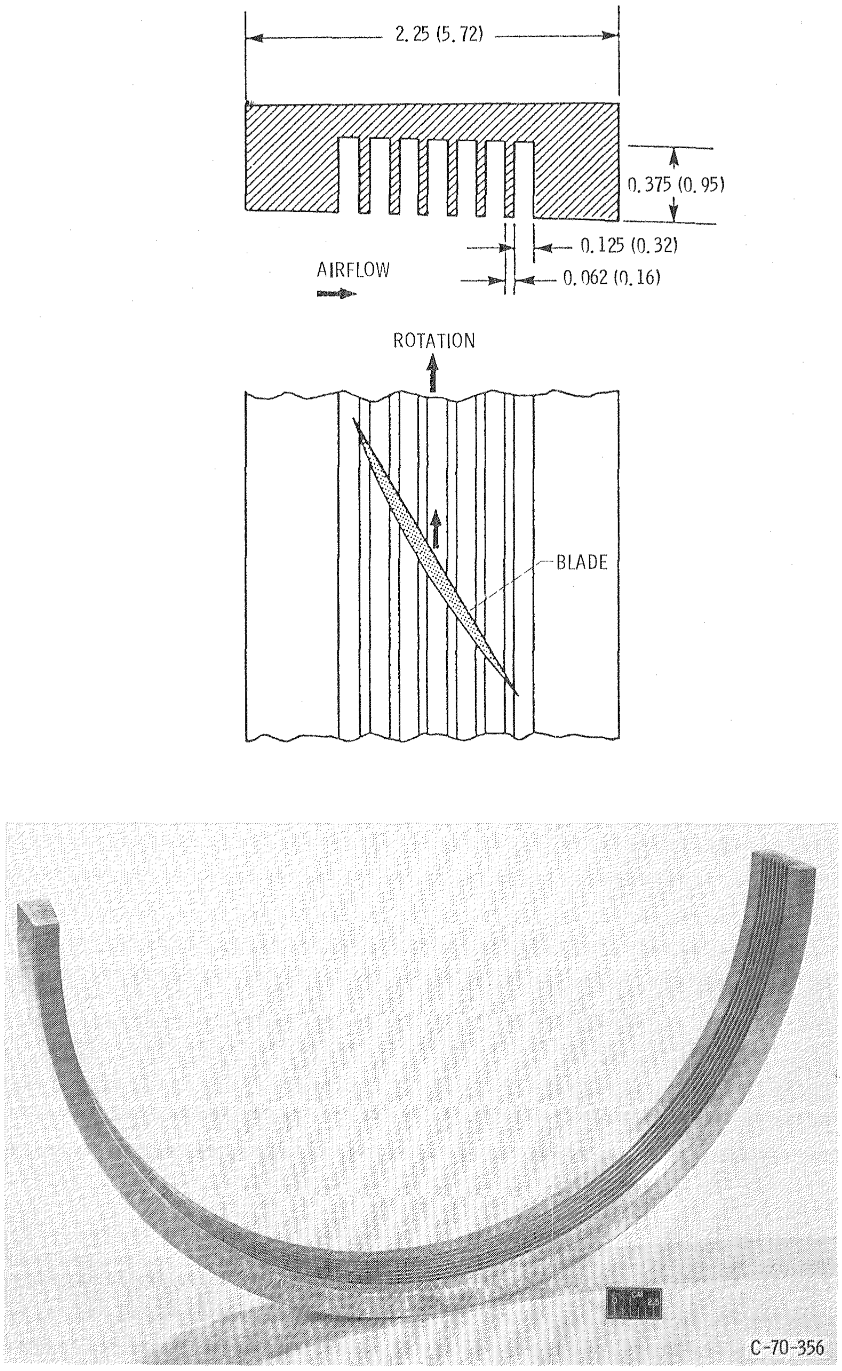


Figure 10. - Circumferentially groove insert. (Dimensions are in inches (cm).)

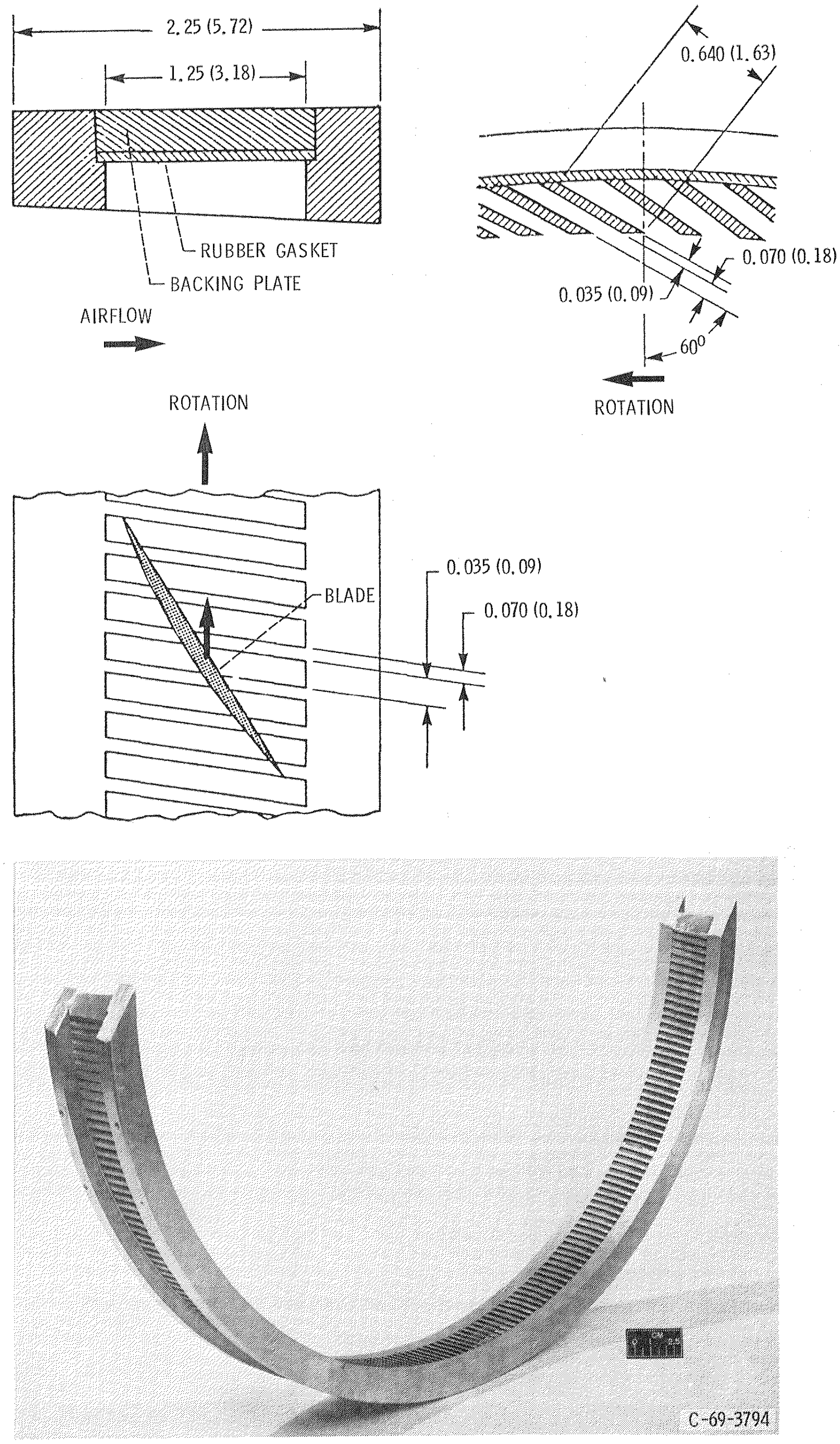


Figure 11. - Skewed slot insert. (Dimensions are in inches (cm).)

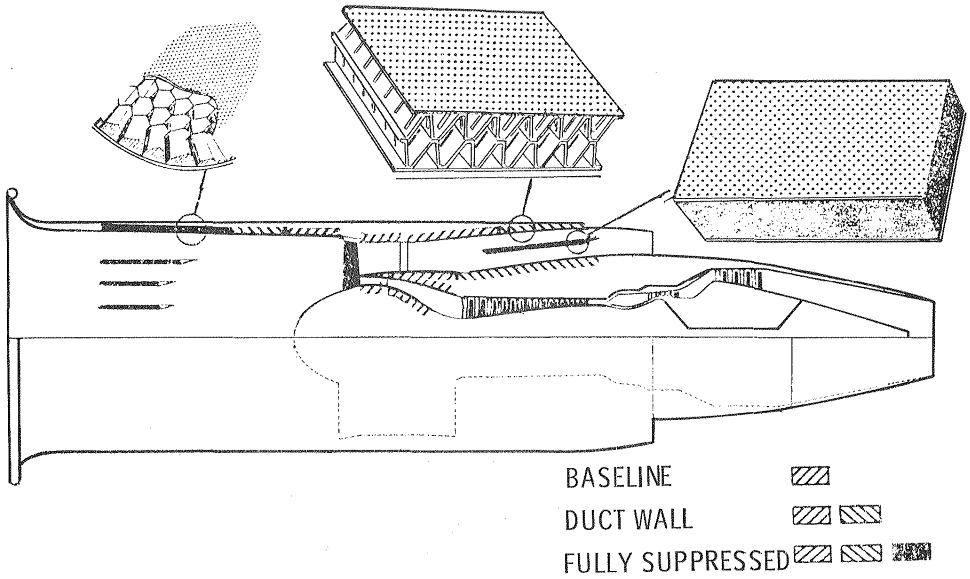
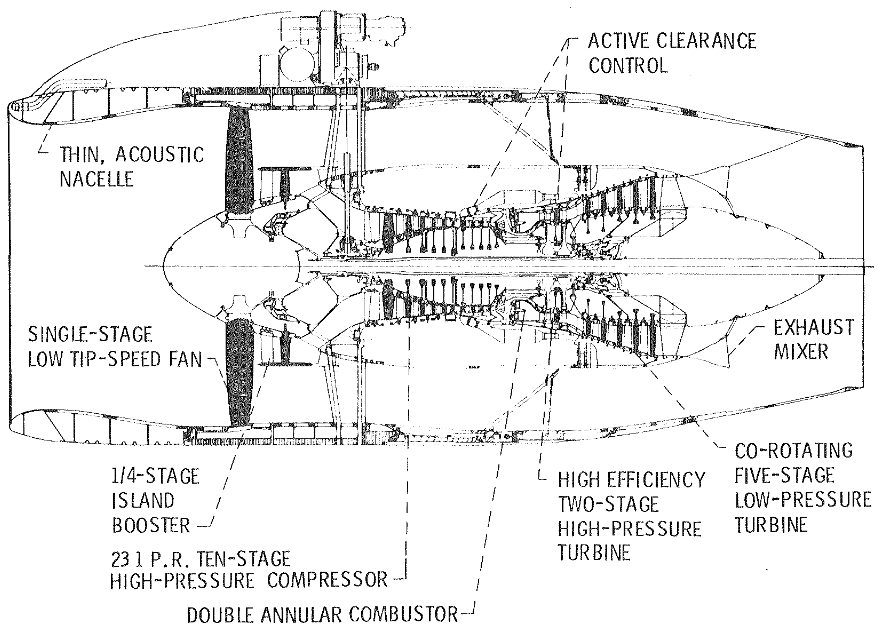
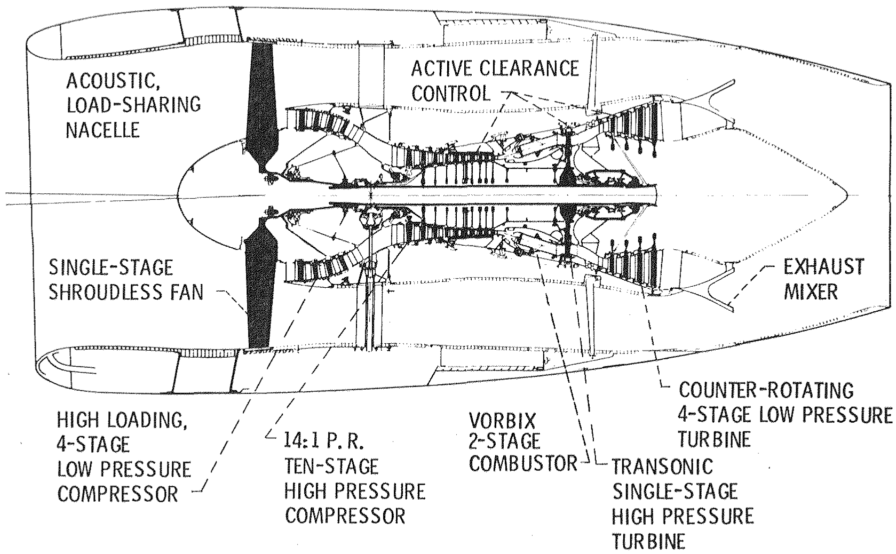


Figure 12. - Low noise design features.



BYPASS RATIO	7.0
CYCLE PRESSURE RATIO	36
FAN PRESSURE RATIO	1.61
TURBINE INLET TEMPERATURE	2440 °F

Figure 13. - GE energy efficient engine.



BYPASS RATIO	6.55
CYCLE PRESSURE RATIO	38.6
FAN PRESSURE RATIO	1.74
TURBINE INLET TEMPERATURE	2450 ^{0}F

Figure 14. - P & W energy efficient engine.

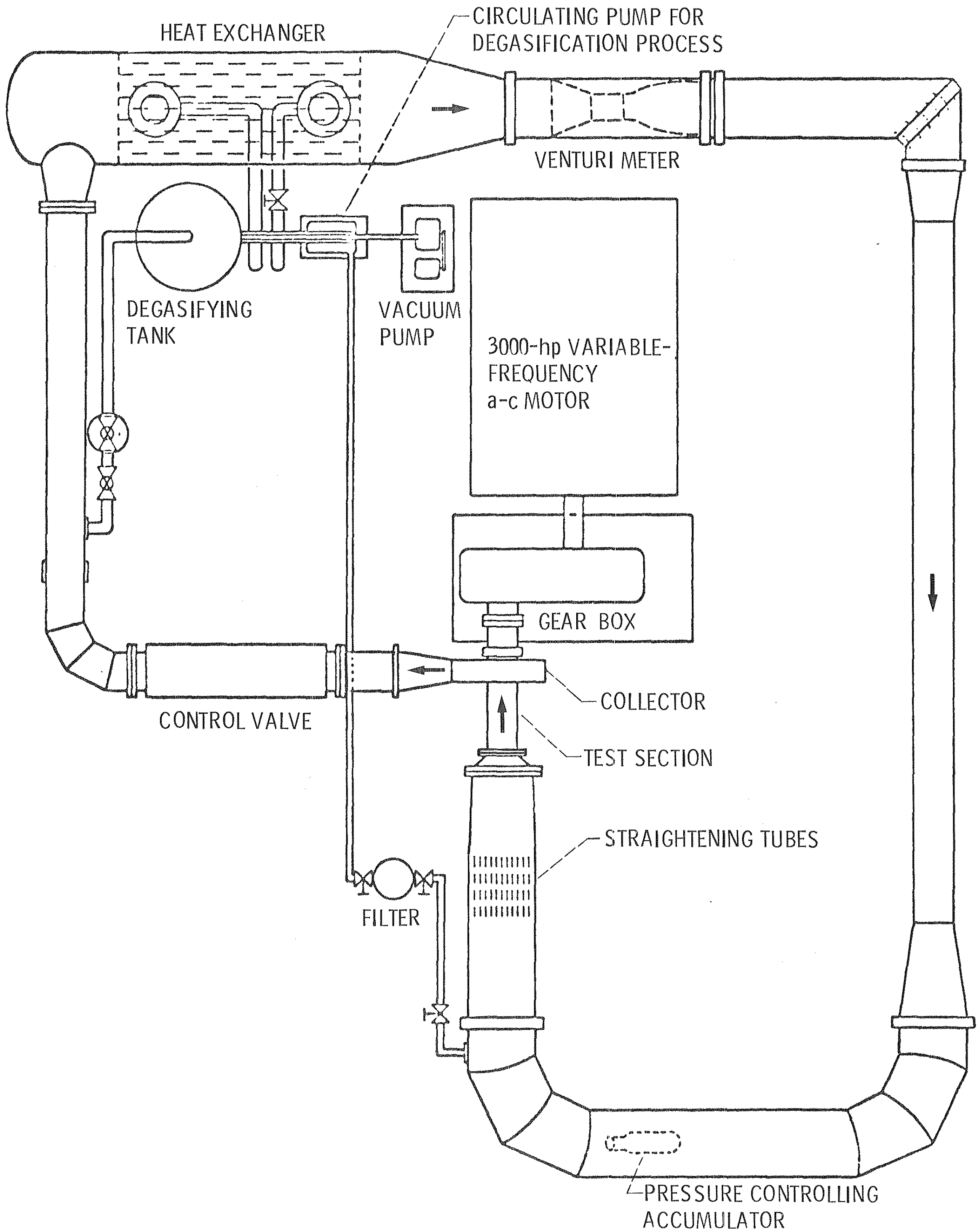


Figure 15. - NASA Lewis water tunnel.

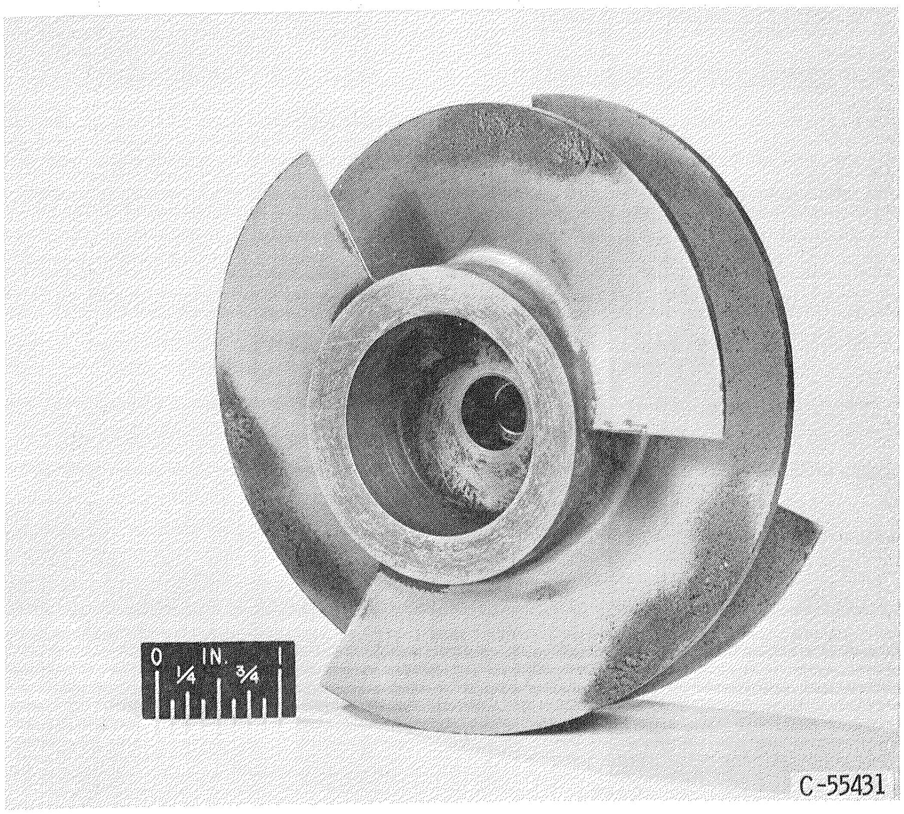


Figure 16. - Helical inducer showing regions with cavitation damage.

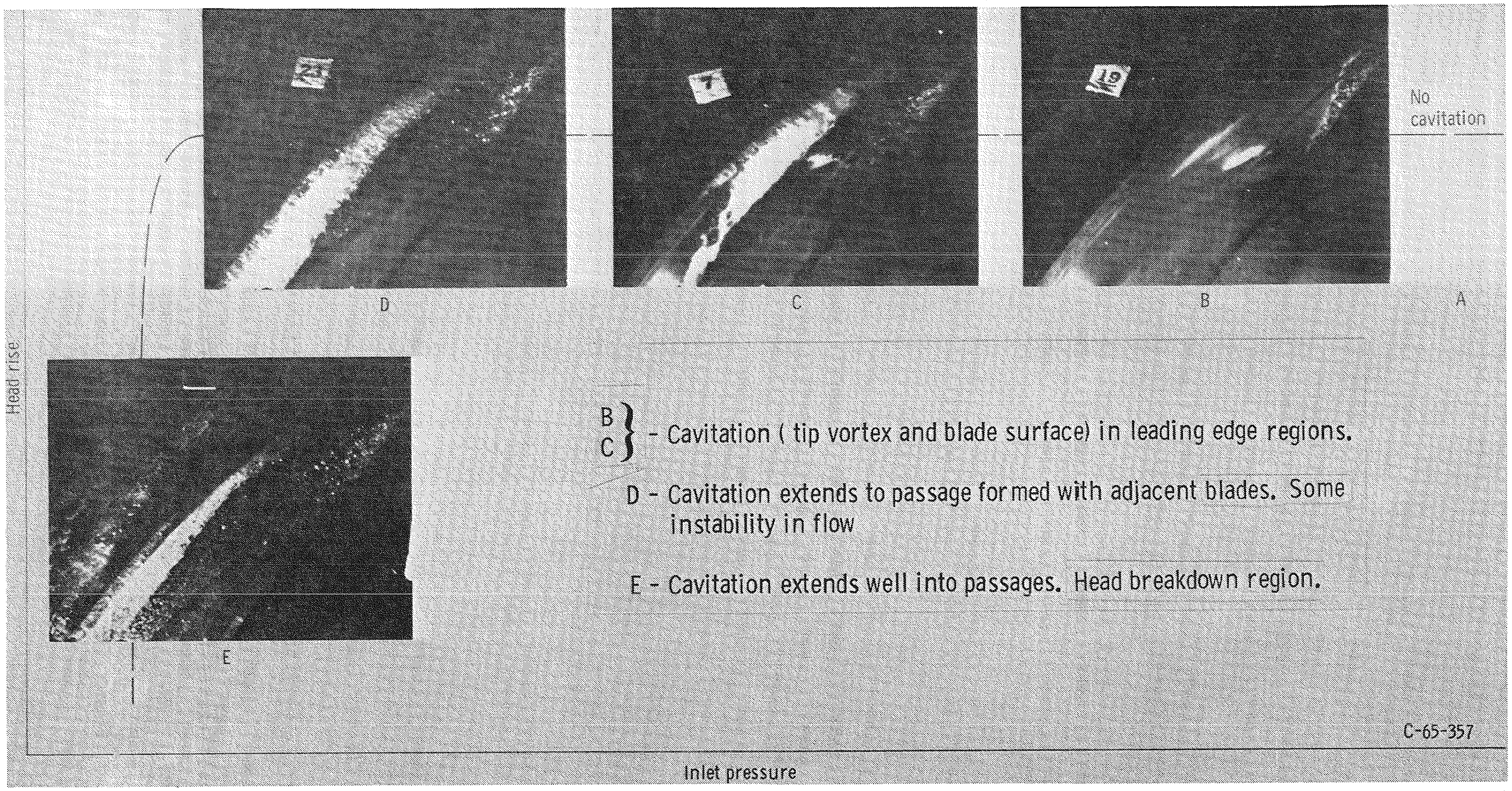


Figure 17. - Photographs of variation of cavitation with inlet pressure at constant flow conditions.

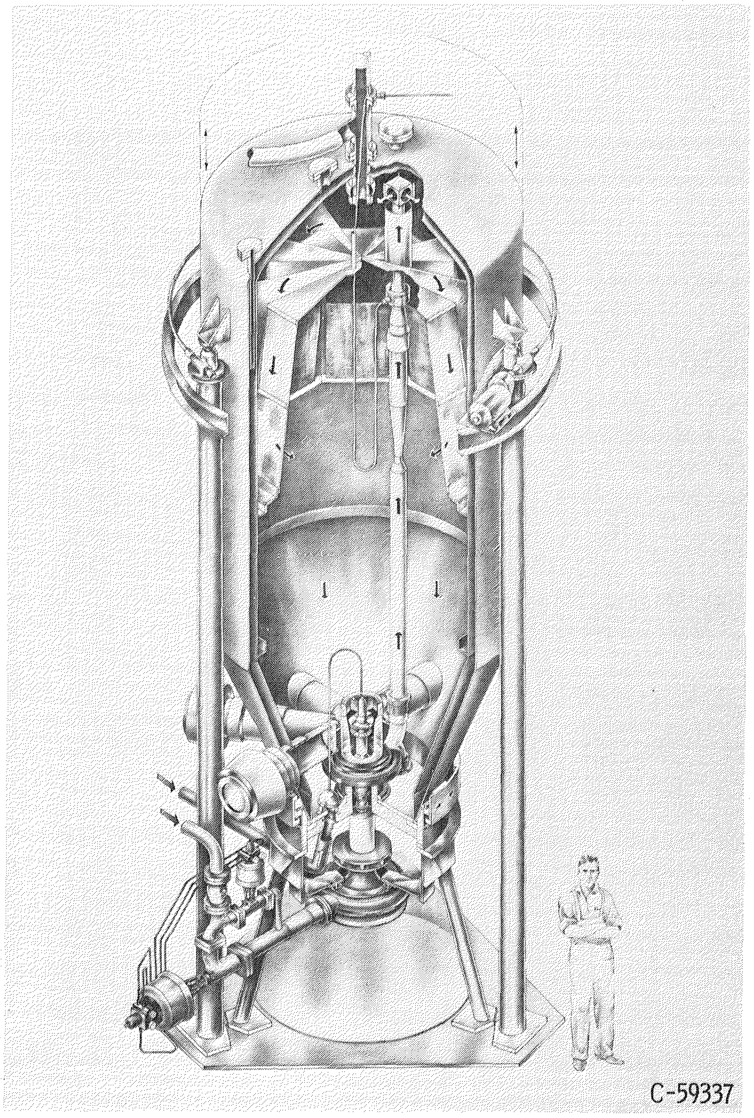


Figure 18. - Boiling-Fluid-Pump test facility.

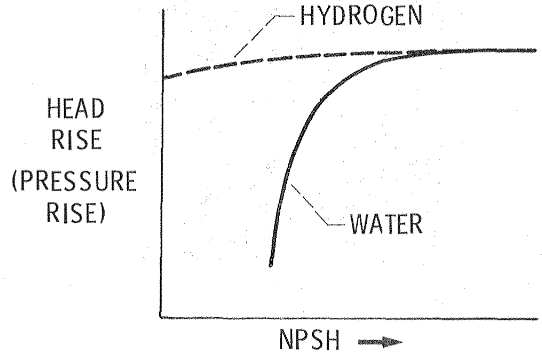


Figure 19. - Cavitation performance of pump inducer in water and in liquid hydrogen.

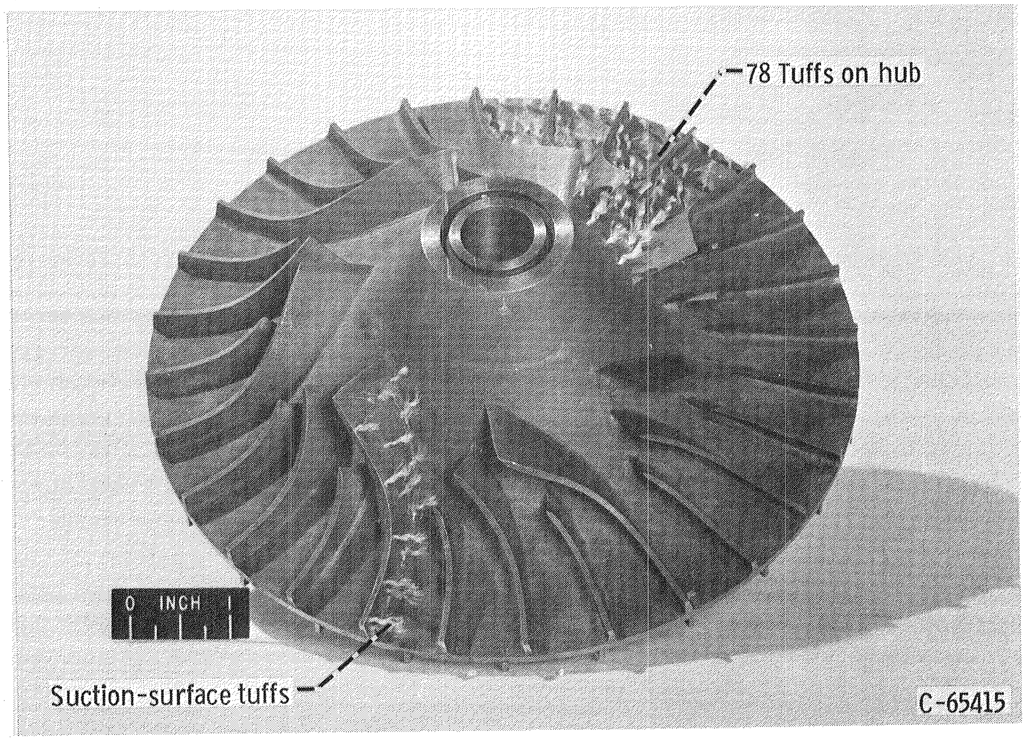


Figure 20. - Impeller with attached tuffs.

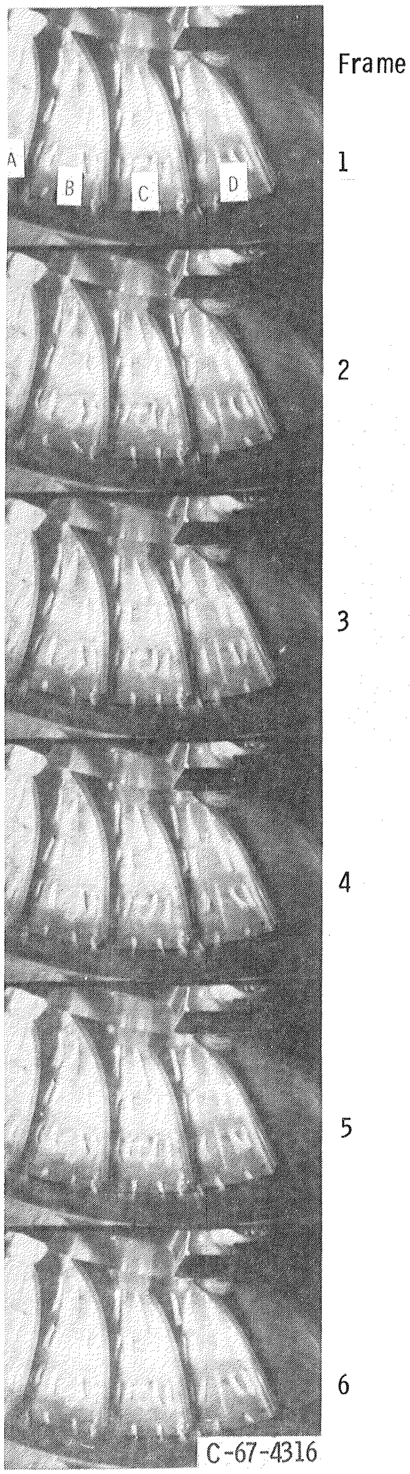


Figure 21. - Film sequence showing positioning of tufts at near-design flow coefficent of 0.368

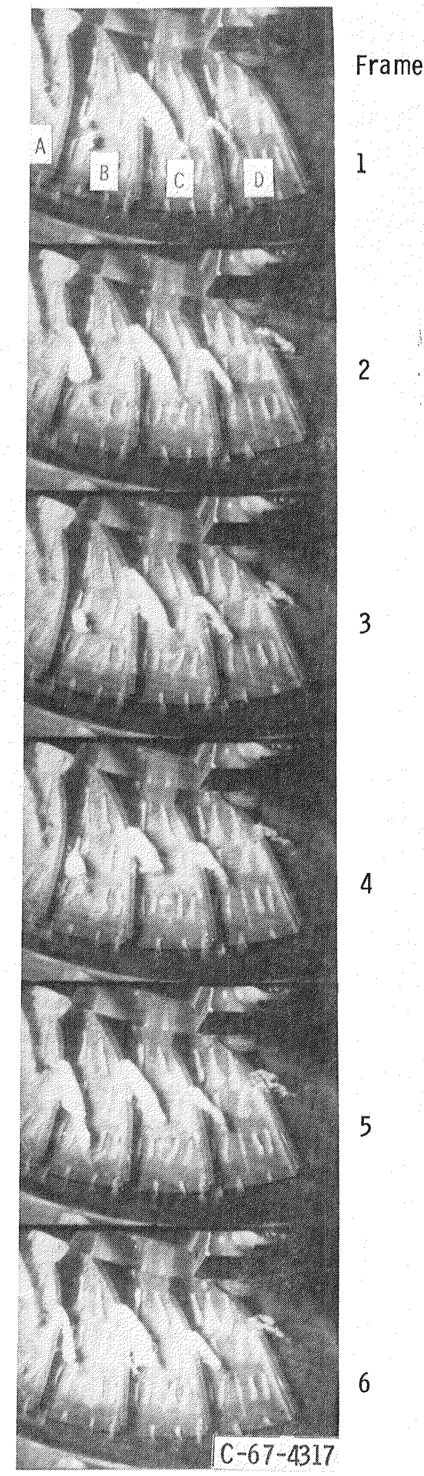
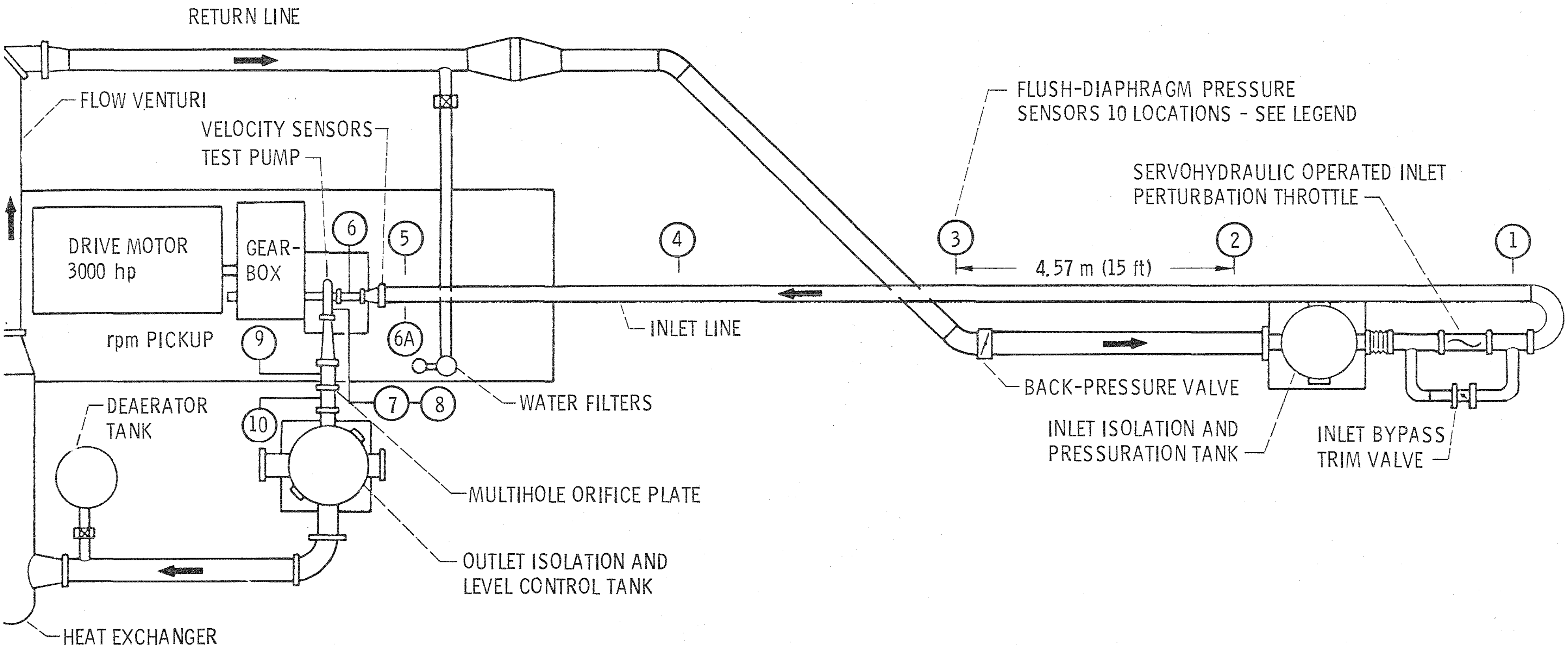
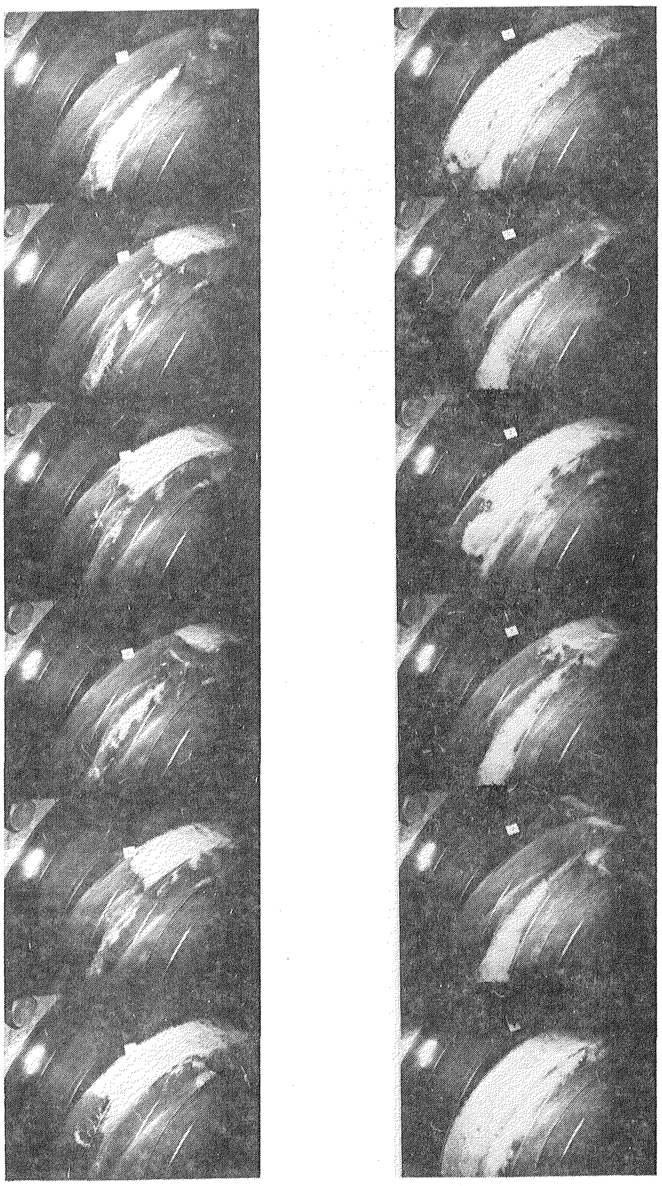


Figure 22. - Film sequence showing positioning of tufts at above-design flow coefficient of 0.532



gure 23. - Pump Perturbations Test Facility, showing measuring stations. For analytical purposes, stations 1 to 5 and 6A are assumed to be attached to ground; stations 6 to 10 are assumed to be attached to the pump and pipe.



(a) (b)

Figure 24. - Unsteady cavitation within the blade passage.

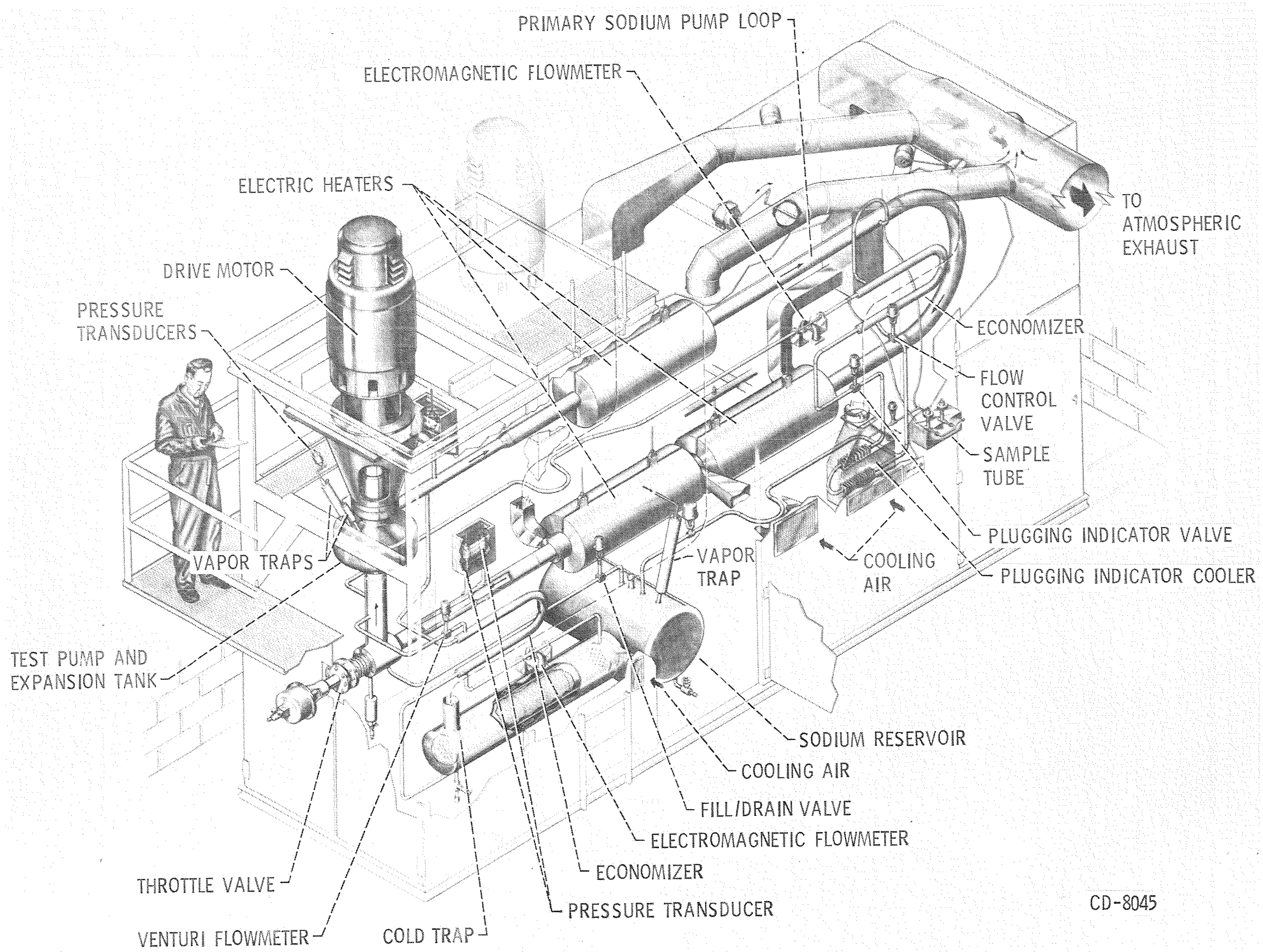


Figure 25. - Alkali-metal pump test facility showing relative size.

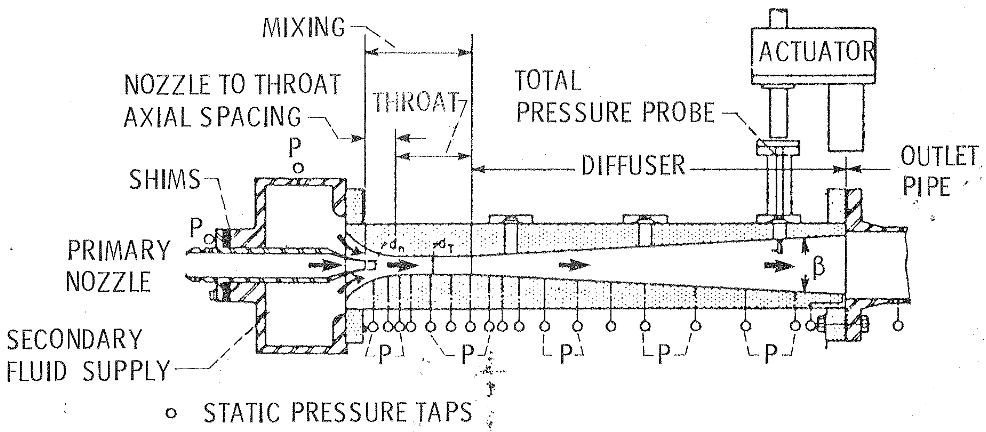


Figure 26. - Water-jet-pump test section showing location of pressure measurements.

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15. Supplementary Notes

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16. Abstract

During the 40-yr period from 1940 to 1980, the capabilities and operating limits of fluid machines have been greatly extended. This has been due to a vigorous research program, much of which was carried out or sponsored by NACA and NASA to meet the needs of aerospace programs. Some of the events which initiated and drove the research programs are reviewed. Overall advancements of all machinery components are discussed first followed by a more detailed examination of technology advancements in axial compressors and pumps. Limited comments on possible future technology needs are made.

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