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SUMMARY REPORT OF THE DESIGN AND OPERATION OF THE WPAFB TURBINE RESEARCH FACILITY

C. Haldeman
M. Dunn

Calspan Corp
Advanced Technology Center
PO Box 400
Buffalo NY 14225

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CHRISTIAN E. RANDELL, Lt, USAF
Turbine Design Engineer
Turbine Engine Division

Charles D. MacArthur

CHARLES D. MacARTHUR
Chief, Turbine Branch
Turbine Engine Divsion

Richard J Hill

RICHARD J. HILL
Chief of Technology
Turbine Engine Division
Aero Propulsion & Power Directorate

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C. Haldeman M. Dunn

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Advanced Technology Ctr
PO Box 400
Buffalo NY 14225

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This summary report is intended to provide an overview of the Wright Lab Turbine Research Facility (TRF). The format that will be used is to provide initially an overview of the facility components and operation with detailed information concerning the individual sub-systems following in separate appendices. The Turbine Research Facility discussed herein has the potential to be a world-class experimental facility capable of providing timely data of significant importance to the country's turbine designers.

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The facility design, construction, and development program described in this report was supported by the United States Air Force, Wright-Patterson Air Force Base, Ohio under Contract F33615-C-88-2825. We wish to express our appreciation to all of the people at the Aero Propulsion and Power Laboratory of WPAFB who have contributed to the success of this program, but there is not sufficient space here to acknowledge them by name. Therefore, we have elected to limit the formal acknowledgements to those who served in the role as technical monitor of the effort. The contract was initiated in May 1989, out of the Turbine Components Office for which Dr. William Troha was Technical Area Manager, the technical monitor at that time was Mr. Greg Cala, and the contracting officer was Lt. George Dunning. In August of 1990, Lt. Barry Cohrs became the technical monitor on this effort; in January 1992 Mr. Chris Murawski became the technical monitor; in January 1994 Capt. John Finnegan became the technical monitor; and in January 1995 Dr. Charles MacArthur became the technical monitor. The authors would like to express their appreciation to all of these people for their support and patience during the difficult times leading to the completion of this project.

NOMENCLATURE

General

h = total enthalpy

L = losses

N_{Phy} = rotor physical speed

P_o = total pressure of incoming gas

P_{ref} = reference pressure, 14.7 psia

Q_w = heat transfer to walls

T_o = total temperature of incoming gas

T_{ref} = reference temperature, 516°R

W = measured work done by turbine

$\dot{W}$ = weight flow of test gas

δ = nondimensional pressure, P_o/P_{ref}

γ = specific heat ratio

η_{ad} = adiabatic efficiency

η_{fu} = fundamental efficiency

η_{meas} = measured efficiency

θ = nondimensional temperature, T_o/T_{ref}

Subscripts

d = downstream of stage

d,is = ideal, isentropic conditions downstream of stage

u = upstream of stag

1. EXECUTIVE SUMMARY

Design of the WPAFB turbine facility described in this report was initiated with a feasibility study conducted in 1986 under the direction of the Allison Gas Turbine Company. In May 1988, a pre-proposal bidders conference was held at WPAFB to describe a 60 month, 30 person-year effort that would be composed of four phases and would result in an operational turbine test facility at WPAFB. A detailed historical review of this contract effort is provided in Appendix A of this report.

Calspan Advanced Technology Center (as prime contractor) teamed with Belcan Engineering (Cincinnati, Ohio), Allison Gas Turbine, and the MIT Gas Turbine Laboratory to respond to solicitation F33615-88-R-2825. The facility that was to be constructed was referred to at that time as the Transient Turbine Test Rig (T^3R). Later, this facility would be re-named the Advanced Turbine Aerothermal Research Rig (ATARR) and then still later it would be re-named the Turbine Research Facility (TRF). Calspan Advanced Technology Center was awarded Air Force Contract F33615-C-88-2825 in May 1989 with a planned completion date of July 31, 1992.

The original intent of the T^3R was that it would be a relatively long run time (1 second duration) short-duration heat-transfer facility. In early 1990, the facility goal expanded from being a heat-transfer facility to being both an aerothermal and an aeroperformance facility; the supply tank volume was increased thus increasing the test time achievable, and hence the change in name from T^3R to ATARR.

By November 1992, the facility components were designed, constructed, and assembled. The plan at the initiation of the program was that Belcan would turn over to Calspan a fully operational facility in about March of 1992 and that the demonstration measurements would follow and be complete by July 1992. However, as a result of schedule slips for multiple reasons, the target date for initiation of the demonstration measurements slipped to November 1992. When November 1992 arrived, there were difficulties with several of the essential components which precluded a fully rotating measurement program. Rather than stop and fix those problems, the decision was made to proceed with the vane-only measurements to determine what other component might become a problem.

The Calspan demonstration run series was initiated with run #14 on December 9, 1992 using the General Electric XF-120 high-pressure vane row (with nitrogen as the test gas) for a supply tank pressure of 345 kPa at room temperature (run #14). Subsequent room temperature runs were successfully performed at 487 kPa (run #15), 104 kPa (run #19), and 345 kPa (run #20). On December 14, 1992 heating of the supply tank and the nitrogen test gas to 500 °K was completed and the tank pressure was topped off at 620 kPa in preparation for the high temperature data runs. Data were successfully obtained at 620 kPa and 500 °K (run #25) and at 345 kPa and 500 °K (run #26) on December 16, 1992. However, on the low pressure run (run #26) performed at 500 °K, the main valve failed to close upon command. The problem was traced to excessive friction between the cast iron bushings and the valve slider under supply tank conditions of elevated temperature and low pressure.

At the time in the demonstration runs when the main valve failed to close, there were other problems that had to be fixed before a rotating demonstration could be attempted and the decision was made to stop and fix all of these problems prior to going further. Specifically, the following items needed immediate attention: (a) the main valve bushings were in need of redesign and rebuild, (b) the isolation valve was in need of redesign and rebuild, (c) the rotating assembly was in need of rework and balancing, (d) the slip ring mounting technique needed to be redesigned, (e) the torque meter needed to be put into working order and calibrated, (f) the data acquisition software needed to be verified using turbine data, (g) the drive motors for the rotating system needed to be installed and proper operation needed to be demonstrated, and (h) the eddy current brake operation needed to be verified. In the initial proposal cost estimate, all of the items except for (f) were the responsibility of Belcan. However, Calspan was the prime contractor, and as such assumed responsibility for the integrity of the design and operation of the individual components.

In an effort to avoid further contract costs, the Air Force and Calspan agreed to work the problems noted in the previous paragraph as a co-operative effort with Calspan doing items (a) through (f) and WPAFB attacking items (g) and (h). At the conclusion of the work on (a) through (f), Calspan had exhausted the remaining funds that were planned for the remainder of the demonstration measurements and additional funding was not available. Therefore, the decision was made by the Air Force that they would assume responsibility for the rotating demonstration experiments with consultation to be provided by Calspan if WPAFB felt it to be necessary. The material that is contained in this document is, therefore, consistent with what we knew to be the status of the facility and the components as of our last presence in "J"-bay, which was December 17, 1992. Many changes have likely been made to the facility components that we are not aware of, and we would rely upon those associated with the facility to use this document as a starting point and to keep a living log of the facility evolution.

2. INTRODUCTION

Appendix A of this report provides a rather complete history of the design, construction, and operation of the WPAFB blowdown facility which was initiated in February 1989 and the initial vane-only demonstration measurements were performed in December 1992. Vane-only data were obtained, but it was not possible to complete the full test matrix that was planned because of a supply tank main valve problem noted in the previous section. The previous section also indicated several reasons why the full-stage rotating turbine measurements could not be conducted at the planned time, but all of the problems cited have since been corrected and the facility should very soon be operational. This summary report is intended to provide an overview of the facility as it was when we last were associated with it. The format that will be used is to provide initially an overview of the facility components and operation with detailed information concerning the individual sub-systems following in separate appendices. The Turbine Research Facility discussed herein has the potential to be a world-class experimental facility capable of providing timely data of significant importance to the country's turbine designers.

For the past 15 years, several groups have pioneered the development of short-duration facilities and the associated instrumentation for the investigation of phenomena relating to high-pressure turbines. The term short-duration has been used to mean test times on the order of tens of milliseconds to a few hundred milliseconds. The short-duration test capability is becoming an increasing attractive alternative to conventional "long run-time" testing. By "long run time" has been meant test times on the order of hours. The promise of major cost savings coupled with the ability to measure quantities that are of interest to the turbine designer but which can not be measured in conventional facilities has motivated this interest in short-duration facility development. One of the most significant aspects of the TRF is that even though it is considered to be of the short-duration class, the test time is on the order of seconds instead of milliseconds. An earlier description of the ATARR (the name by which the facility previously was known) was given in Haldeman, et al., 1992.

By way of historical review of short-duration facility development, the application of the isentropic light piston compression tube for turbine research was pioneered at Oxford University by Schultz and co-workers (e.g., see Schultz and Jones, 1973), and a sector of high-pressure turbine vanes was instrumented with thin-film heat-flux gages and used as the test article. The test time for the Oxford facility is on the order of a few hundred milliseconds. Dunn and co-workers at Calspan used the shock tunnel to initially obtain measurements for a sector of a high-pressure turbine vane row (e.g., see Dunn and Stoddard, 1977) followed by replacement of the vane sector with a full stage rotating turbine (e.g., see Dunn and Hause, 1982). The test time for the Calspan facilities is on the order of tens of milliseconds. Louis, 1973 at the Massachusetts Institute of Technology investigated the use of both the shock tube and the blowdown facility for the investigation of factors affecting heat transfer in turbines. The test times for his facilities were also on the order of milliseconds. Richards and co-workers at the von Karman Institute also developed a light piston facility (e.g., see Richards, 1975) to perform measurements on a high-pressure turbine vane sector (e.g., see Consigny and Richards, 1982). Epstein and co-workers at the Massachusetts Institute of Technology designed and built a low-pressure blowdown facility (e.g., Epstein, et al., 1984) to perform measurements on a high-pressure turbine vane row. This facility is different than the one described in Louis, 1973. The test time associated with the MIT blowdown turbine facility of Epstein, et al. is on the order of a few hundred milliseconds.

The primary force driving the development of ATARR at WPAFB was the potential for being able to measure heat transfer and aero-performance simultaneously for advanced technology military engines. To this end, it was decided to build a large blowdown facility with a test time on the order of one to five seconds. The test time duration for this particular facility is determined by the weight flow rate that must be supplied to the turbine and by the amount of power that the eddy current brake must absorb because of work extracted by the turbine rotor from the test gas. One objective of those developing ATARR is to measure either the cooled or uncooled turbine efficiency to within ± 0.25% of the "true" value within a 95% confidence limit. Achieving this goal will make ATARR competitive with the best conventional facilities for aero-performance evaluation. Haldeman, et al., 1991, and Haldeman and Dunn, 1991 address the experimental and instrumentation difficulties associated with such a measurement. Another objective of the facility is to determine the thermal (cooling) performance of new turbine designs.

In the remainder of the report, Section 3 presents a discussion of the facility and its components, Section 4 presents a brief description of the operation of one of the major components (the main valve) and Section 5 presents a brief description of an uncertainty analysis used to define the instrumentation and facility parameter requirements. There are many aspects of the development of this facility that can best be documented in Appendix A which appears at the end of this report. Specific facility component issues have been addressed in separate volumes during the course of this contract and copies of these reports are included as attachments 1 through 12.

3. DESCRIPTION OF THE FACILITY

It was noted earlier that ATARR was designed and constructed to meet the specific needs of the turbine components group at WPAFB. This group is charged with the responsibility of developing new engine technology and, in particular, with the development of more advanced, higher work output, and higher operating temperature turbines for future military applications. The goal is to achieve significant increases in turbine inlet temperature while at the same time reducing the flow rate of cooling air accompanied by work and speed increases. The increases in material stress associated with this goal are substantial. There are a number of new design concepts that have promise for increases in turbine performance such as super effective cooling designs, 3-D aerodynamic design, vaneless HP/LP systems and metal/non-metal composites. These concepts can be more reliably incorporated into military engine design if extensive testing has been performed to validate their usefulness.

The process of making the ATARR a reality has been a cooperative effort with Calspan, MIT, Belcan, Allison, and the USAF all contributing. The facility is designed to accommodate full scale (either vane row alone or full stage) engine hardware and to subject this hardware to test conditions consistent with actual engine operation. By taking advantage of scaling relationships, the important non dimensional groups which determine the behavior of the turbine stage can be reproduced and at the same time operate at test conditions that do not subject the instrumentation to conditions as harsh as those associated with engine conditions. The blowdown facility is one for which the supply tank temperature and pressure change during the course of an experiment and it is, therefore, necessary to carefully measure the flow path parameters so that the appropriate non dimensional groups can be duplicated. The specific parameters that can be duplicated with this facility are: flow function $\left(\dot{W}\sqrt{\theta}/\delta\right)$, corrected speed $\left(N_{Phy}/\sqrt{\theta}\right)$, specific heat ratio of the turbine inlet gas (γ), pressure ratio across the stage, ratio of gas temperature to wall temperature, ratio of gas temperature to coolant temperature, Reynolds number, Mach number, and Prandtl number. These parameters will be duplicated during a portion of the test time, but not during the entire test time. Each experiment is designed to maximize this portion of the test time within the constraints imposed by the power absorbing device (eddy brake). The eddy brake is programmed to maintain the proper corrected speed for the maximum period of time. This maximum operating time of the brake is determined by the temperature increase of the drum during the blowdown time resulting from dissipation of the power extracted from the test gas by the turbine rotor.

Figure 1 is a sketch of the ATARR. The test gas supply tank shown on the far left has a volume of approximately 3,200 ft.^{3} and is designed to be pressurized to 180 psia while being heated to 550°F. Any combination of pressure and temperature between these maximums can be accommodated. The test gas would normally be nitrogen or a mixture of nitrogen and carbon dioxide in order to duplicate the appropriate non dimensional groups. The supply tank is insulated with four inches of fiberglass with a 0.020 inch aluminum jacket to minimize heat loss to the room. Not shown on the sketch, but located internal to the supply tank is a variable speed fan and an electrical heater. The supply tank insulation and fan/heater combination were designed to produce axial temperature uniformity on the order of 0.8°F (over the 20 ft. length of the tank). It is estimated that for a typical run, the majority of the test gas would be taken from the one-third of the supply tank nearest the valve. The supply tank is instrumented with resistance temperature detectors (RTD's) in order to measure the axial and the radial temperature uniformity. Temperature measurements are currently underway, but not available for presentation at this time.

Located internal at one end of the supply tank is a fast acting valve (which has moving components weighing about 600 lbs.) that is designed to open in approximately 100 milliseconds, remain open for a pre-determined time period, and then close in approximately 100 milliseconds. Careful control of both the opening and closing of the valve are critical to avoid structural damage. Of particular concern is the requirement that valve closing must be done in a way that closes off a large portion of the flow area very quickly, but then covers the remaining portion of axial travel at a lower velocity in order to avoid hard impact between the valve and the bumper. The bumper is spring loaded and designed to accommodate a reasonable impact velocity, but not a velocity that it so large that the springs become fully compressed. It is important that this valve close within the prescribed time interval because the eddy brake is not designed to absorb the power extracted by the turbine indefinitely. There is sufficient gas in the supply tank to cause turbine runaway if the supply tank valve were to remain open and if there were no other way to terminate the flow. The isolation valve will be routinely operated prior to a run in order to isolate the dump tanks from the test section in order to permit pressurization of the test section and thus calibration of the pressure transducers. It is suggested that this valve should be operated at some point in time after each run when the facility is in use in order to increase the probability that it will operate as designed if needed. A word of caution to the user when pressurizing the test section; be very careful not to overpressurize the slip ring coolant unit which is potentially exposed to the test section pressure if that pressure persists at an elevated level for a significant period of time.

Downstream of the supply tank main valve is the test section which houses the turbine that is being investigated. Internal to this test section are several other essential components and instrumentation

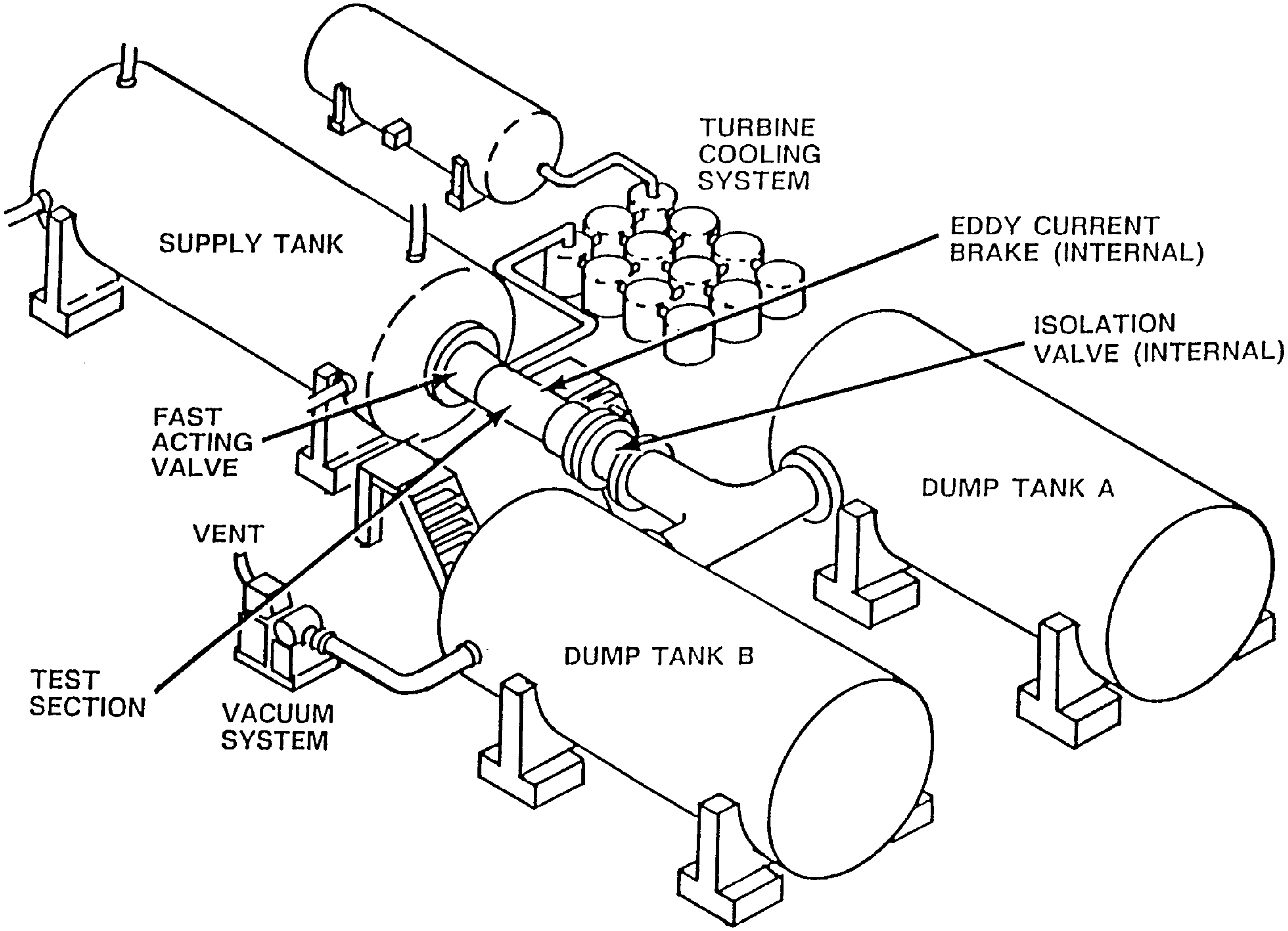

Figure 1 Sketch of The Advanced Turbine Aerothermal Research Rig (ATARR) Configuration

associated with the facility. The shaft on which the rotor component is mounted contains a torque meter which derives its signal from strain gauges mounted on a necked-down portion of the drive shaft. The torque meter was calibrated prior to final assembly of the rotating package to an accuracy of 0.25% of full scale. Data obtained with this device will be used as part of the turbine stage efficiency determination which will be described in Section 4. The rotating component is initially brought to the proper speed in the evacuated test section using a variable speed electric motor. This motor is attached to the end of the shaft nearest the return iron of the eddy current brake. At the other end of the shaft a drive system engages a 200 channel slip ring unit which is used to transfer the data from the rotating component to the laboratory data recorders.

The downstream isolation valve (which also serves the purpose as an emergency flow control valve), shown in Figure 1, serves the function of providing a downstream flow control device which is used to achieve the desired stage pressure ratio by adjusting the flow area. Further, this valve can be used to isolate the test section from the dump tank permitting pressurization of the test section prior to and after an experiment in order to obtain a calibration of the pressure transducers. For the purposes of this calibration the Baratron pressure measuring device, which has a detector in the test section as well as the supply tank, is considered to be the standard against which the calibration is performed.

Two dump tanks of volume equal to approximately 3,200 ft.^{3} each are connected to the test section as shown. Prior to a run, the dump tanks and the test section are evacuated using the Stokes vacuum pump and Roots blower shown on the schematic of Figure 1. The dump tanks and the test section are routinely evacuated to a pressure of approximately 0.7 torr prior to initiation of an experiment. The eddy current brake noted on Figure 1 is a scaled up version of the one used at MIT (Epstein, et al., 1984) and was designed by Dr's. G. Guenette and A. Epstein of MIT. As previously noted, the turbine inlet total temperature decreases as the supply tank blows down. The current supplied to the coils of the magnets surrounding the rotating drum is on the order of 600 amperes of pulsed DC current supplied by a programmable SCR power supply. The brake can absorb power at a maximum of 4 megawatts at 7,500 rpm. The current to the magnets is programmed in order to maintain proper corrected rotor speed during the blowdown process. The rotating component of this brake is constructed from an Inconel 718 forging and can be heated to approximately 1,000°F without significant loss of strength. It would be desirable to continuously monitoring the brake surface temperature, but at the present time a technique for doing so is not available. It is suggested that in the future consideration be given to installing a pyrometer to view the brake drum surface in order to monitor this temperature. For a large high pressure turbine of the 25 megawatt class (engine conditions), the time for the brake temperature to reach the 1,000°F limit is estimated to be about two seconds. In general, either the vane exit or the rotor exit (or both) of the turbine stage would be choked during the experiment. Regardless of whether or not the stage is choked, the previously mentioned isolation valve (which also serves as an emergency shut off valve) will remain choked for a wide range of conditions which serves to maintain the proper pressure ratio across the turbine stage.

Figure 2 is a sketch of some of these components and the facility instrumentation locations. Table 1 is a tabulation of the specific (non-stage) instrumentation location, type, and expected accuracy.

Table 1 describes the instrumentation located in the supply tank. The primary instrumentation at location 1 are the RTD's and the Baratron unit. Ahead of the turbine stage there is a boundary layer bleed designed to remove the boundary layer associated with the incoming flow. Also located ahead of the turbine stage in the flow path are rakes of total pressure and total temperature. Similar rakes of total pressure and total temperature are located in the flow path downstream of the rotor. For the demonstration experiments, these rakes were fixed in position, but in the future traversing units will be added to this configuration. A photograph of one of the downstream total temperature rakes is given in Figure 3(a). The thermocouple housed in the individual probes is butt welded Type E wire and is 0.001-in. diameter. The design and construction of the thermocouple probes is very similar to that reported in Dunn, et al., 1984. A close-up photograph of one of the pressure probes is given in Figure 3(b). Wall static pressure is measured at the rake locations.

Both the vane and the blade of the particular turbine stage being used for the demonstration experiments were instumented in detail. This turbine stage had previously been run in the Calspan short-duration turbine facility. Figure 4(a) illustrates miniature flush diaphragm Kulite pressure transducers placed at mid span on both the pressure and suction surfaces of the vane. The pressure surface is clearly visible in the photograph. Though the entire suction surface can't be seen, the coverage is comparable. Figure 4(b) illustrates a similar pressure transducer installation at the mid-span location on the blade. Figure 4(c) is a photograph of two contoured strip inserts (at mid span) containing platinum thin-film heat-flux gages. The Pyrex substrate upon which these gauges are painted is relatively thick, being on the order of 0.125 inches. Figure 4(d) is a photograph of a contoured leading-edge insert with platinum thin-film gauges painted on it and installed at mid-span in the blade. This particular insert is three to four times thicker than the inserts installed on the vane. Figure 4(e) is a photograph of numerous button-type heat-flux gages located at 20%, 50%, and 80% of span in the vane surface and on the hub and tip endwall. Figure 4(f) is a photograph

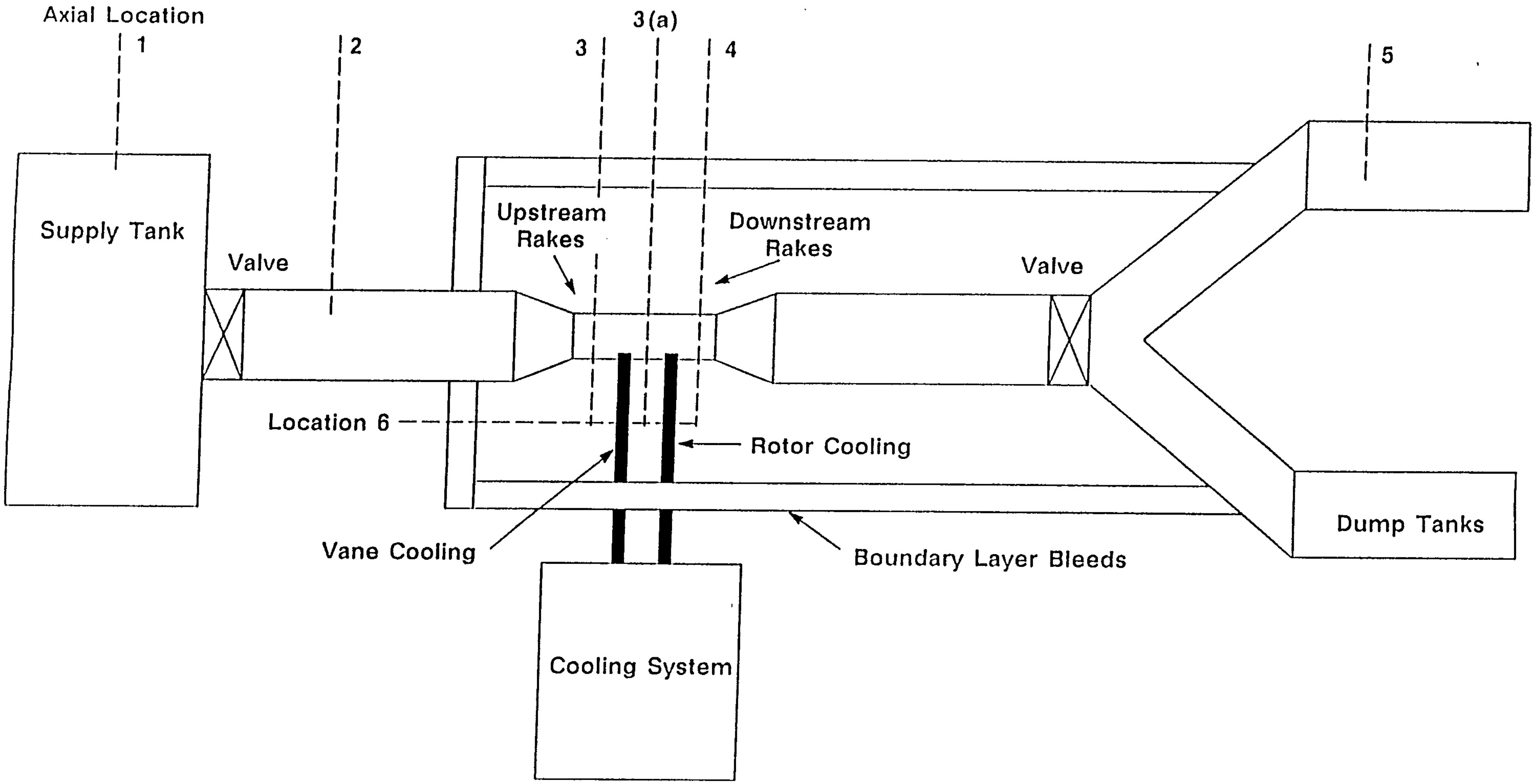

Figure 2 Sketch of The ATARR Instrumentation Locations

Table 1 Facility Instrumentation

Location	Type of Sensor (number)	Expected Accuracy
Axial location 1: Supply Tank	RTD's (20) Baratron Units (1) Endevco 8540-100	.1°K or .02% FS .1 psi (.1% FS) Need to Calibrate
Axial Location 2: Inlet	Baratron Units (1)	.1 psi (.1% FS)
Axial location 3: Upstream Rake Position	1 Total Temp. Thermocouple Rake (4 sensor Type E 1 Mil) 1 Total Press. Rake (4 sensor Endevco 8534A-100) 2 static pressure Endevco 8530C-100	Need to Calibrate Need to Calibrate Need to Calibrate
Axial Location 3(a) Torque meter Located on Drive Shaft	Strain gauges	Calibrated to within 0.25% FS
Axial Location 4: Downstream Rake Position	1 Total Temp. Thermocouple Rake (4 sensor Type E 1 mil) Total Pres. Rake (Endevco 8534A-100) 2 static Press (Endevco 8530C-100)	Need to Calibrate Need to Calibrate Need to Calibrate
Axial Location 5: Dump Tank	Static Pressure (Endevco 8530C-100)	Need to Calibrate
Axial Location 6: Cooling Lines	Total Temp. Thermocouples (4) Pressure (not specified)	Need to Calibrate

of the button-type heat-flux gauges installed in the blade at mid-span, at 10% span, and at 96% span. This photograph shows most of the pressure surface button-type heat-flux instrumentation and a portion of the suction surface instrumentation. Figure 4(g) is a photograph of button-type heat-flux gauges installed in the blade tip. Similar instrumentation was also installed in the stationary shroud above the blade tip.

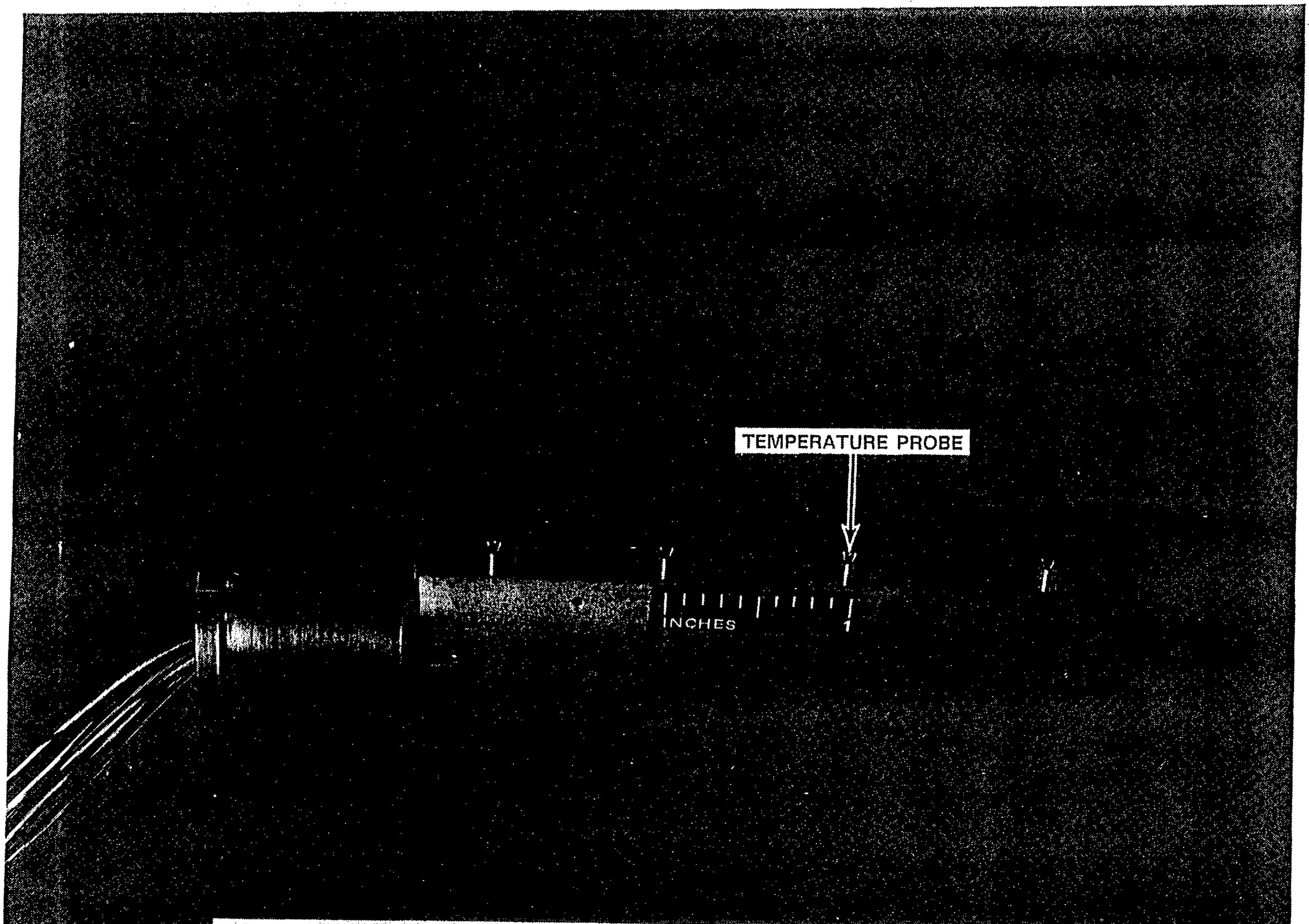

Figure 3(a) Photograph of Downstream Temperature Rake

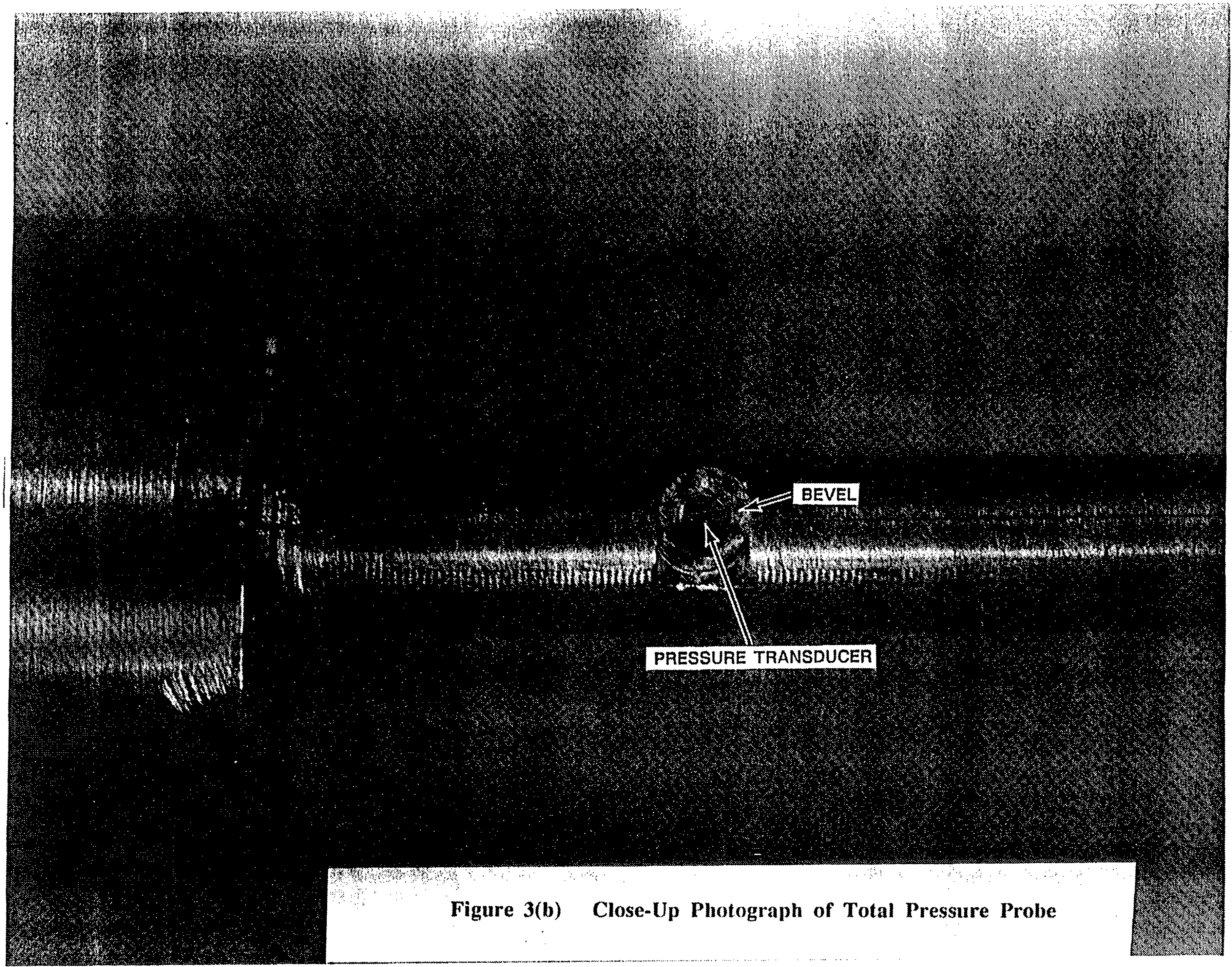

Figure 3(b) Close-Up Photograph of Total Pressure Probe

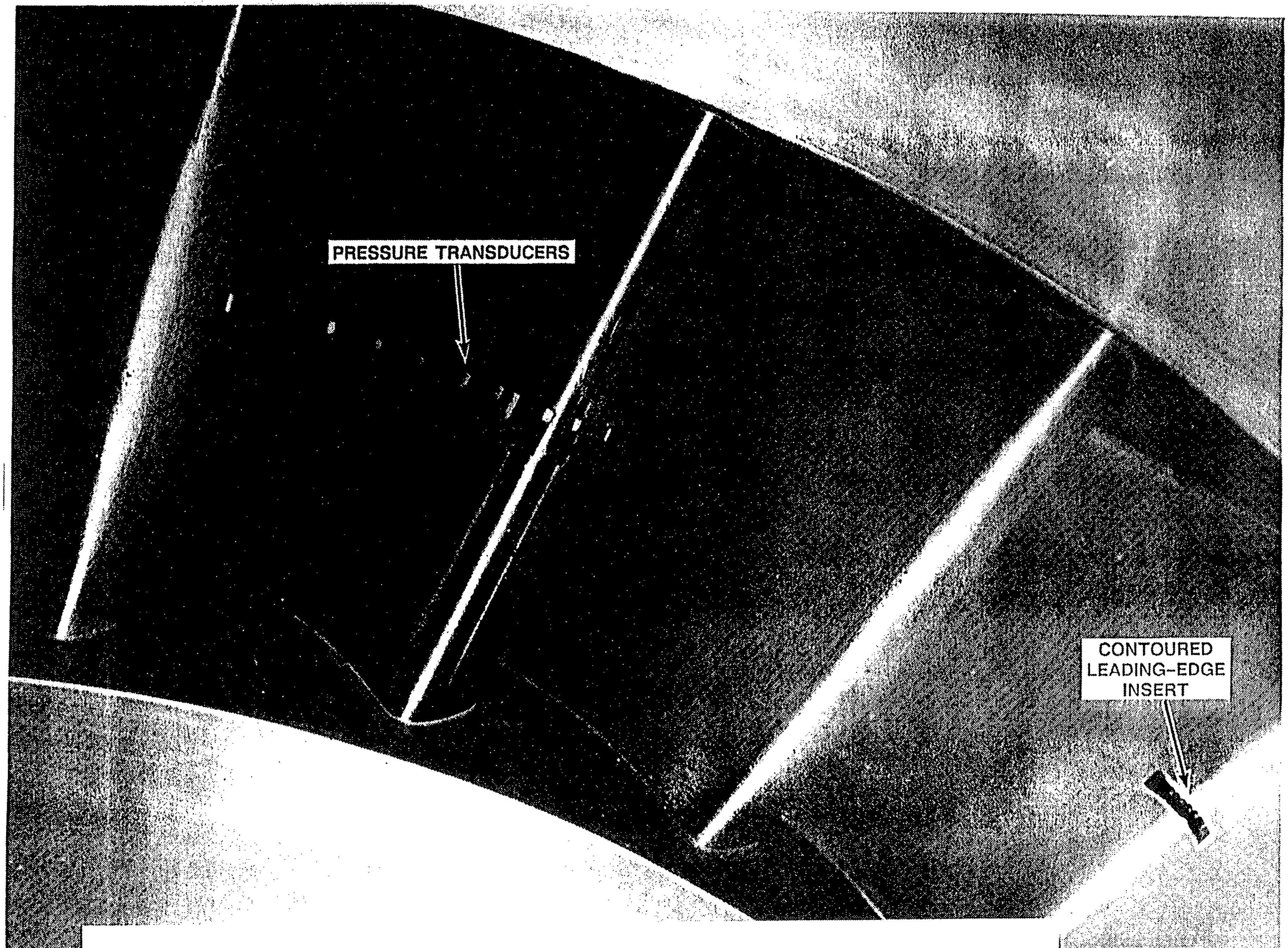

Figure 4(a) Photograph of Miniature Kulite Pressure Transducers in Vane

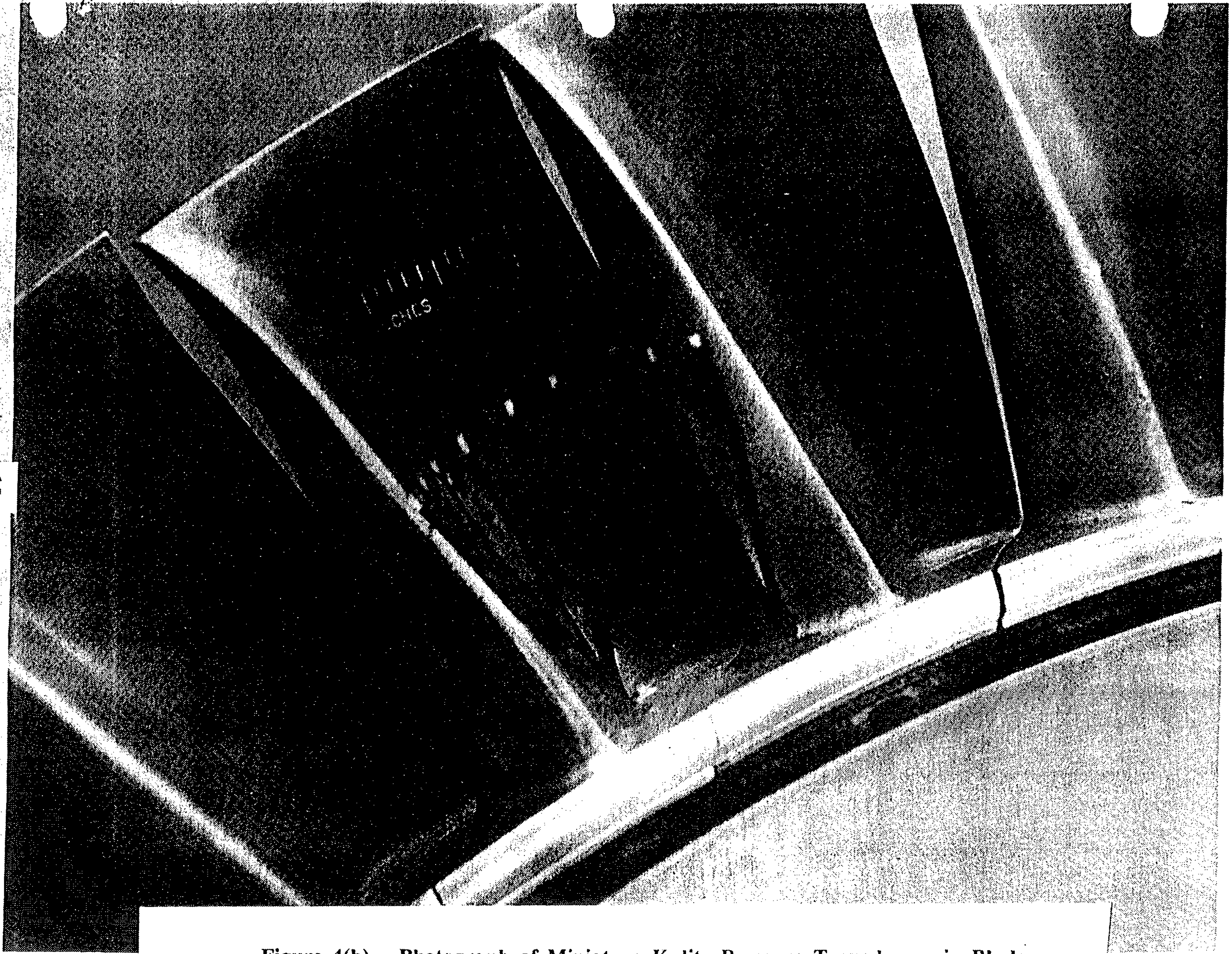

Figure 4(b) Photograph of Miniature Kulite Pressure Transducers in Blade

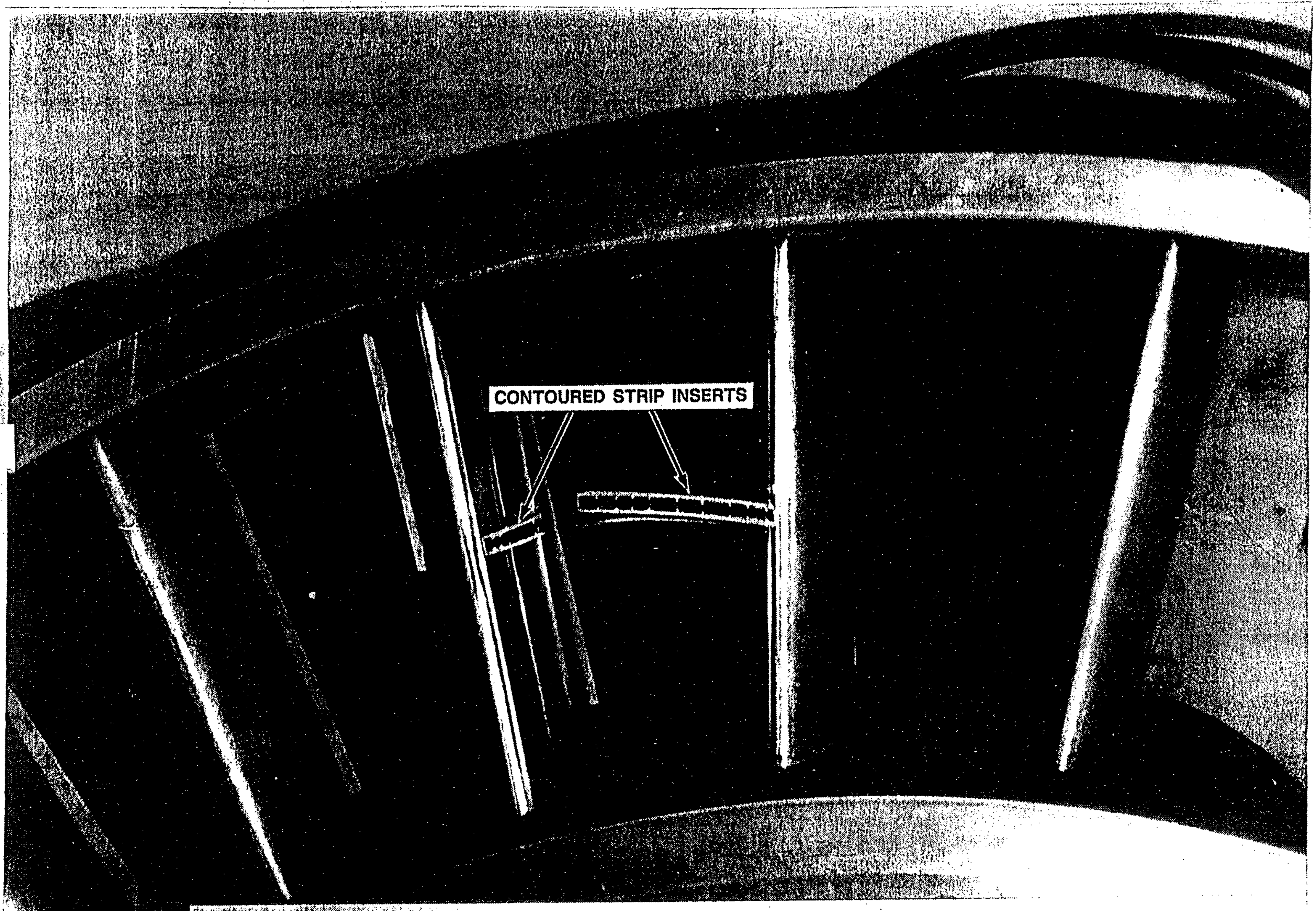

Figure 4(c) Photograph of Heat-Flux Gauges on Contoured Insert Installed in Vane

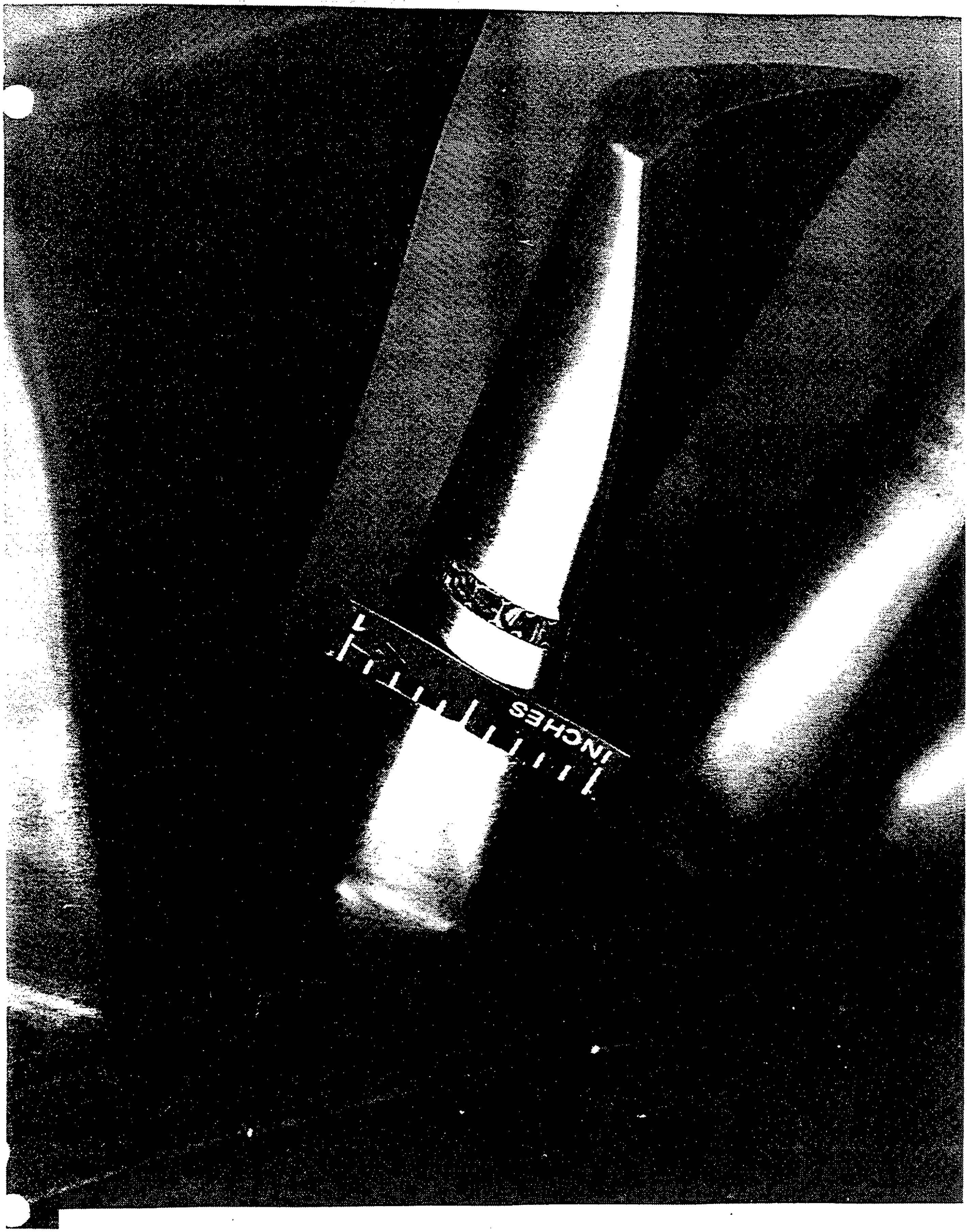

Figure 4(d) Photograph of Heat-Flux Gauges on Contoured Insert Installed in Blade

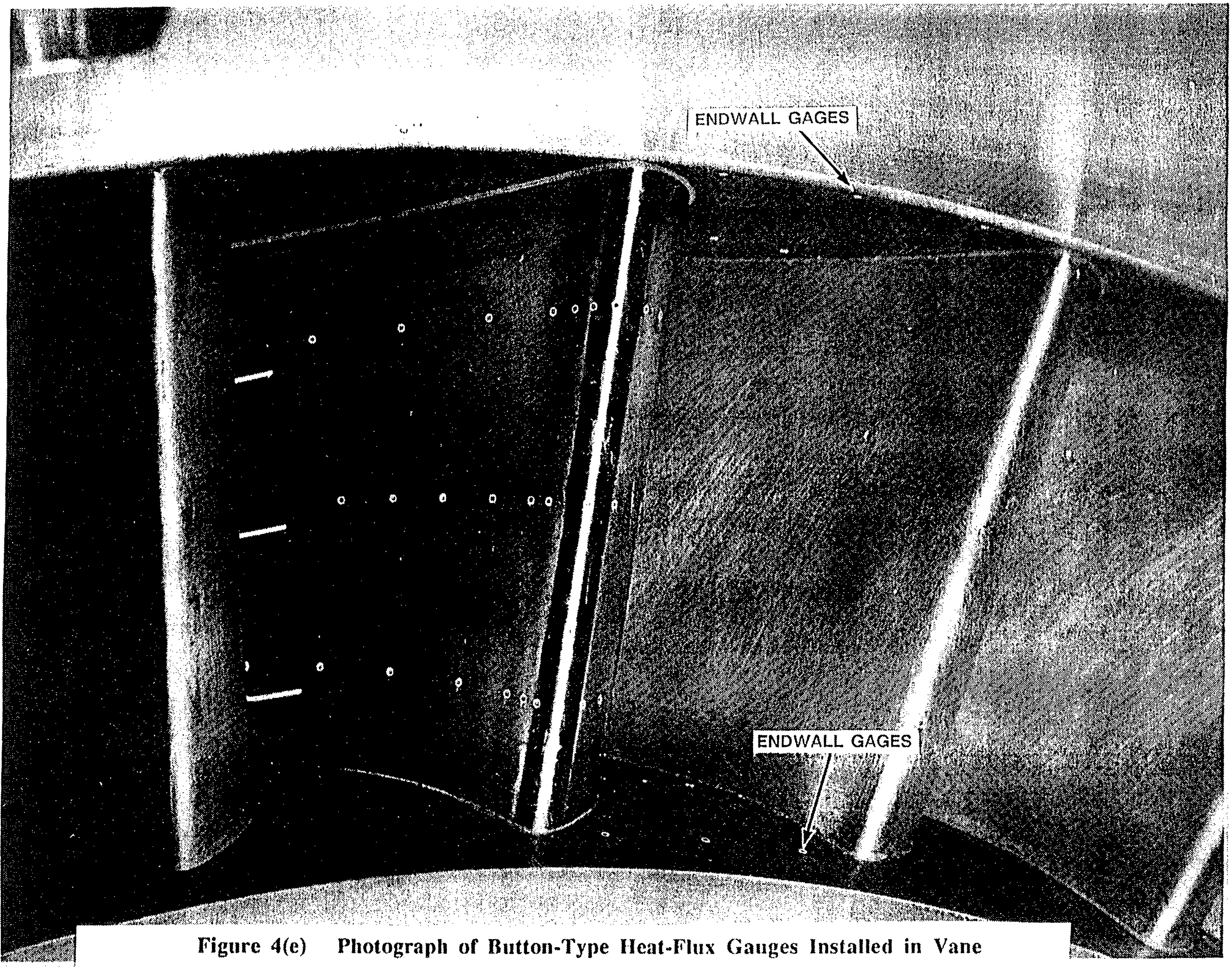

Figure 4(e) Photograph of Button-Type Heat-Flux Gauges Installed in Vane

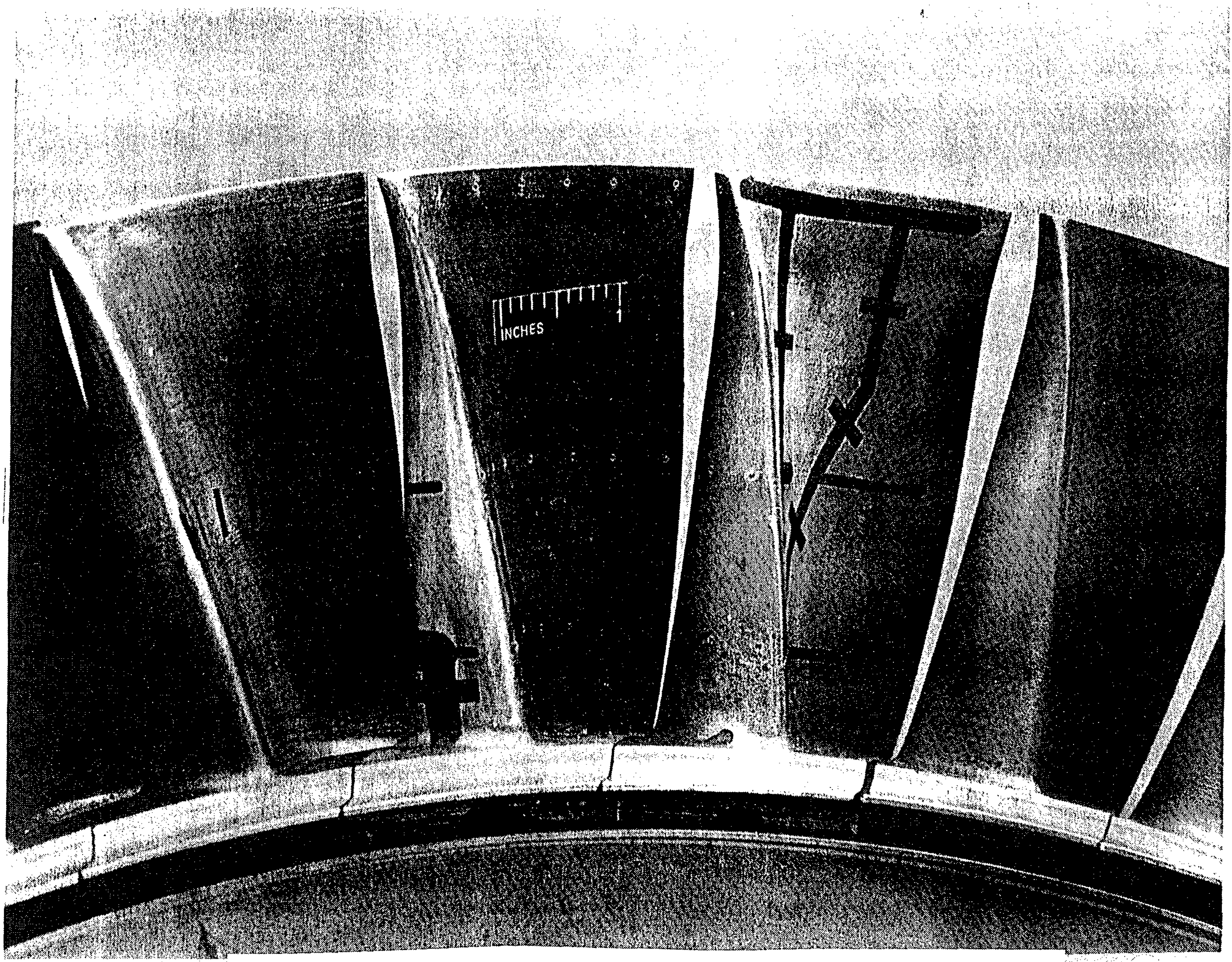

Figure 4(f) Photograph of Button-Type Heat-Flux Gauges Installed in Blade

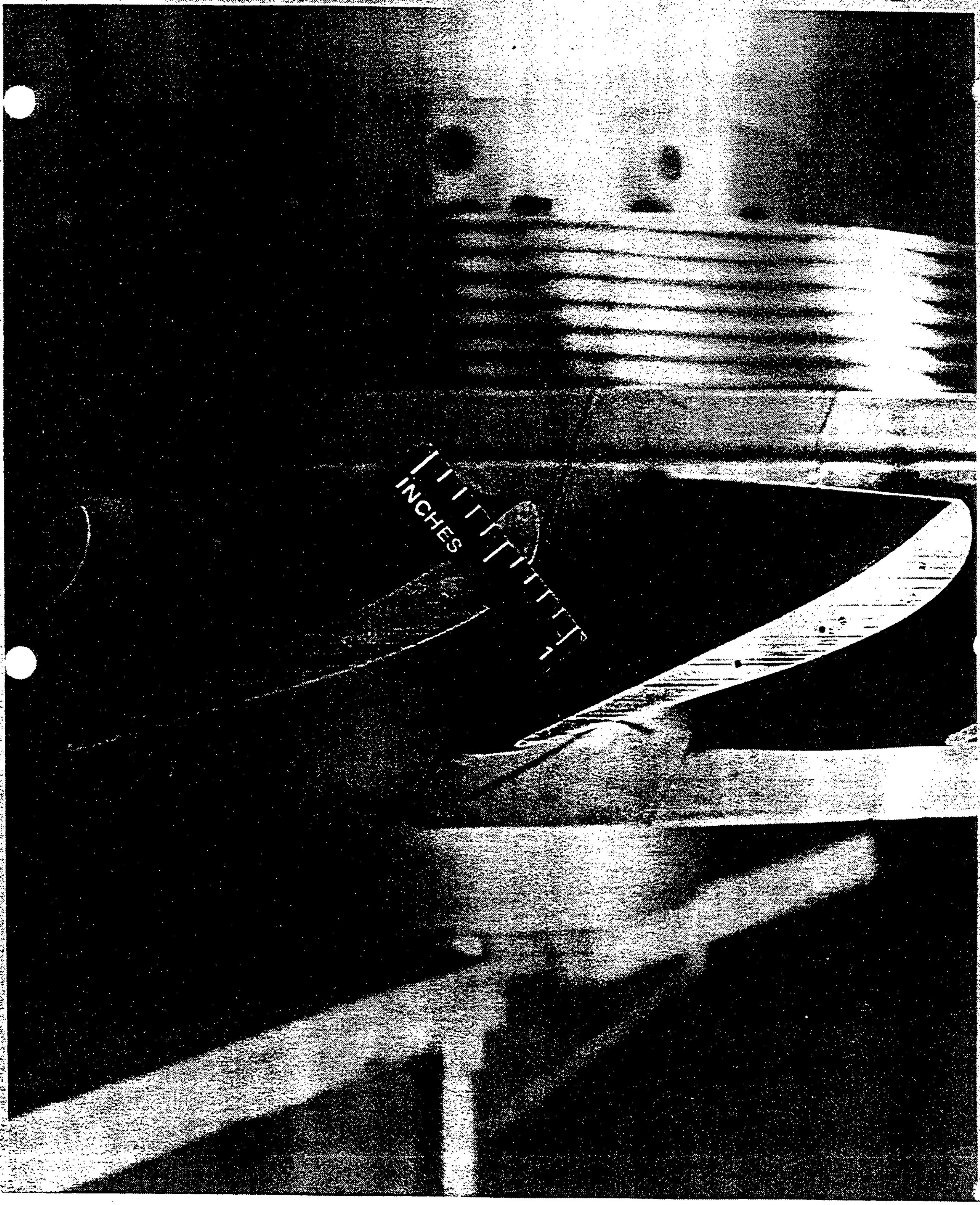

Figure 4(g) Photograph of Button-Type Heat-Flux Gauges Installed in Blade Tip

The Pyrex substrate was designed to be sufficiently thick to avoid backside heating thus preserving the one-dimensional approximation for data reduction. However, it is important to note that this heat-flux instrumentation was designed for use in the Calspan facility for which the test time is much smaller than it is in the ATARR facility. The button gauges are sufficiently thick that for the test conditions associated with the Calspan facility, that there is less than a 1% error in heat flux as a result of backside heating for times of at least 65 milliseconds. By comparison, the inserts are much thicker and the time required for penetration of the thermal wave to the back side is much longer. For the application of this instrumentation in ATARR, it is advisable to read both the heat-flux and the pressure data as early in the test time as is possible. Dunn, et al., 1990 present a discussion of the times for which the one-dimensional heat transfer approximation is valid as a function of the error one would realize in the calculated heat flux for the gauges painted on the inserts described here. This calculation assumes a constant heat-flux level (i.e., that the starting heat-flux loads in the ATARR are not significantly greater than those during the test time). This being the case, it should be acceptable to reduce the data for the gauges painted on the contoured inserts using the one-dimensional heat conduction assumption for times on the order of 1 second after initiation of the flow with an error on the order of 1%. However, a word of caution is that because the Calspan facility and ATARR are different in principle, the starting heat-flux loads in the two facilities may be very different and it is important to look carefully at this issue.

Figure 5 is a photograph of the ATARR as it currently exists. The insulated supply tank can be seen on the far left, the external flange of the fast acting valve is to the right of the supply tank, a transition piece from the valve to the test section which contains the boundary layer bleed cannot be seen, the test section is relatively short in axial dimension and is bounded by the two flanges that can be seen, and the stair up to a platform providing access to one side of the test section is in the center of the photograph. The isolation valve is located just aft of the test section downstream flange. The eddy current brake is internal to the section noted. Further, downstream is a transition piece which provides for axial adjustment that may be necessary to accommodate future test section designs. The corner of one of the dump tanks can be seen on the far right. Immediately to the left of the stair is a climate controlled room which houses the data recording equipment. The facility operations and the data acquisition system (DAS) computer are located in a well-protected room located about 100 ft. from the test section.

The design approach for the control of the facility was to separate the control tasks from the data acquisition tasks in order to simplify the software and to employ lower cost personal computer based control systems. Because of the short duration of the test, no active feedback control is necessary during the data taking period. Conditions such as pressures, temperatures, and the

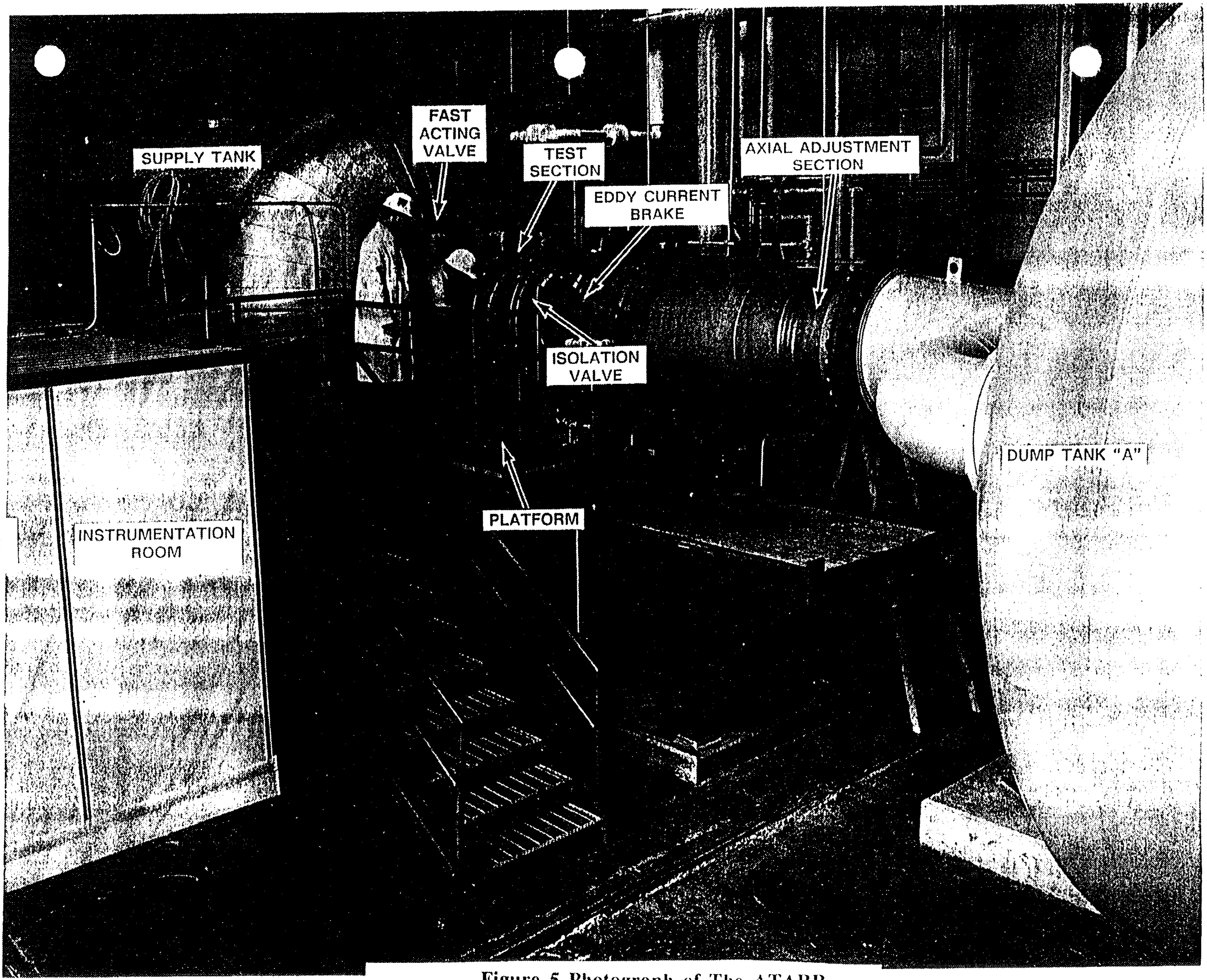

Figure 5 Photograph of The ATARR

turbine speed are set manually prior to the test through the PC control system. Preset sequence timers are activated at the start of the test and all actions occur automatically. The control hardware is a commercial digital system operated from a 386 PC. A menu driven program enables the operator to easily control the test set-up, initiate the preprogrammed test sequence, and perform the post test functions.

The most important part of the control system is the built-in safety features. A redundant system senses an impending turbine over speed and automatically closes both the upstream and downstream valves rapidly. The operator also has a single hardwired "panic button" which quickly shuts the system down safely in the event of any emergency.

Figure 6 is a block diagram of the ATARR data acquisition system. As noted above, there is a temperature controlled room in the test area that houses the transducer excitation bridges power supplies, the signal conditioning amplifiers and filters, and the data recording systems as shown in the lower portion of Figure 6. Table 2 describes the major features of this system.

Table 2 Major Features of Data Acquisition System

- Potential Capacity: 100+ Channels
- Initial Configuration:
  - 40 Low-Frequency Channels (100 kHz)
  - 24 Medium-Frequency Channels (200 kHz)
  - 3 High-Frequency Channels (1 MHz)
- 12 Bit Resolution
- High Resolution Color Graphics Display
- Disk and Tape Storage
- IEEE 488 Data Acquisition Communications
- Ethernet Interprocessor Communications

There are currently 67 12 bit analog-to-digital data channels: 40 with a maximum sampling frequency of 100 kHz, 24 at 200 kHz, and 3 at 1 MHz. These channels are suitable for obtaining either aerodynamic or heat-flux data and can easily be connected to all types of sensors. The low voltage raw data signals are amplified and conditioned by electronics located in the temperature controlled instrumentation room located in the immediate proximity of the test section. During the run, the digitized data are stored in the memory of each data channel. At the conclusion of a run, the data collected are transmitted by an IEEE 488 bus to the data acquisition computer located in the

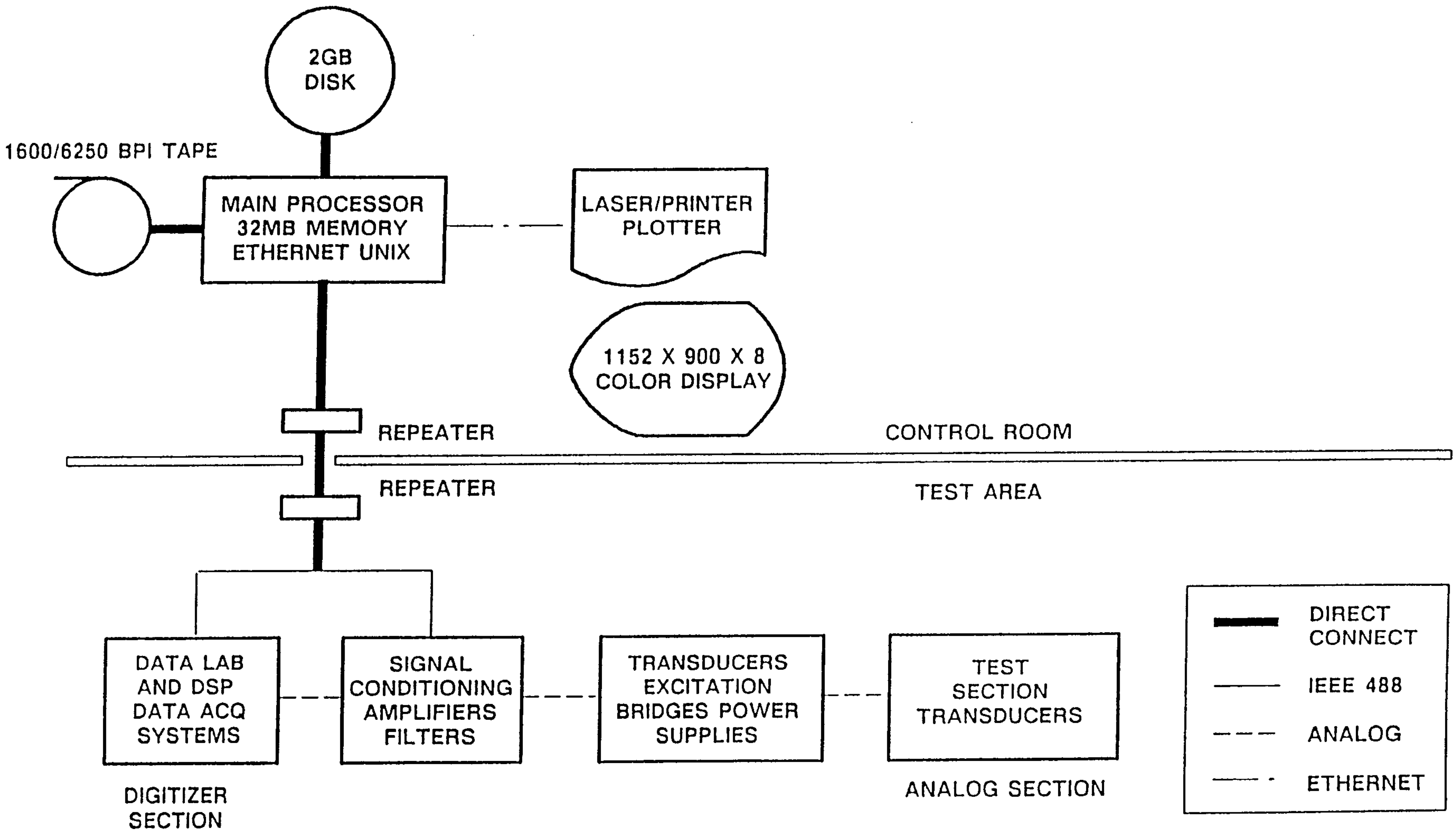

Figure 6 Block Diagram of The ATARR Data Acquisition System

facility control room which is shown in the upper portion of Figure 6. This computer is a Sun SPARCstation 330 running a UNIX operating system. Large capacity disk and tape storage is available for archiving the approximately 1 Gigabit of data than may be generated in each test run. Table 3 presents a summary of the DAS computer system.

Table 3 The ATARR Data Acquisition Computer System

- Sun 4/330 Computer System
- 32 Megabytes of Memory
- 2 x 1.2 Gigabyte Disk Drives (Removable)
- 1600/6250 BPI 9-Track 1/2 Inch Tape Drive
- Sun GX 19 Inch Color Graphics Display
- IEEE-488 (GPIB) Instrumentation Bus
- Ethernet TCP/IP Communications
- Appletalk Based QMS Printer/Plotter
- Sun OS UNIX Operating System

A comprehensive software suite has been written to reduce the raw data to the important engineering results and display them graphically. Figure 7 is a block diagram of the software structure functional decomposition. The data acquisition system consists of three major functions: software interfaces, user interfaces, and system management. Within each of these major functions are several service blocks as noted on the figure.

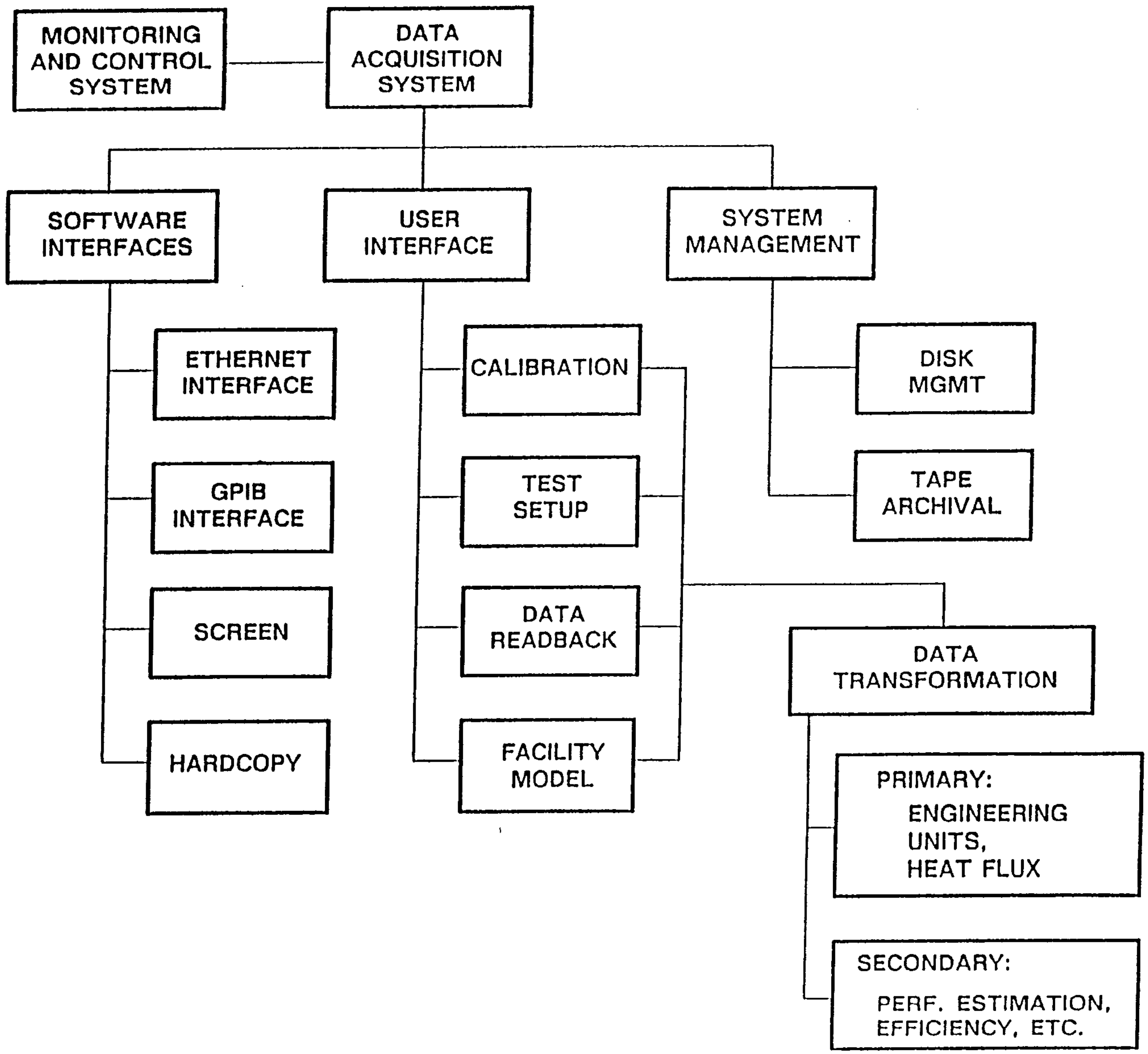

Figure 7 The ATARR Software Structure Functional Decomposition

4. OPERATION OF SUPPLY TANK MAIN VALVE

As previously mentioned, the valve separating the supply tank from the test section is one of the major components of the ATARR. This valve must open quickly, remain open for a prescribed period of time, and close quickly. There are several reasons why proper operation of the supply tank main valve is essential, e.g., safety, flow quality, and avoidance of damage to other facility components. A simple gas dynamic model describing the operation of the actuating cylinder and the main valve which it drives was developed in order to predict the valve operation. Results obtained from the prediction model are compared with experimental results in the following paragraphs.

Figure 8(a) presents a comparison between an experimentally determined axial position vs. time history and a corresponding prediction. The prediction is obtained from an unsteady model initially developed at MIT and modified at Calspan to predict the operational characteristics of the valve and associated activation system. After the supply tank valve has moved approximately 8.5 inches in the axial direction, it is essentially fully open. The weight flow requirements of the turbine stage located in the test section are fully met by the corresponding flow area and any additional area at the valve will not result in additional weight flow. As can be seen from Figure 8(a), the travel for the particular case shown was approximately 10 inches. The time required for the valve to move approximately 9 inches was about 100 ms which is well within the design goal of the system. Closing of the valve is shown on the right side of Figure 8(a). The valve accelerates rapidly from the 10 inch position to about 2 inches in approximately 100 ms and then slows down over the remainder of the axial travel in order to avoid hard impact with the bumper. The time required to close off about 90% of the available flow area is well within the design requirements.

Figure 8(b) presents a comparison between the measured and predicted pressure histories associated with the opening and closing actuator legs of the system. Included on this figure are the pressure in the opening line and the pressure in the closing line. To the left hand side of the figure is the valve opening sequence and at about 2.4 seconds the valve closing sequence is initiated. Thepredicted peak in the opening pressure at about 0.2 seconds is above the data which is characteristic of the model and the closing pressure is under predicted while the valve is open and over predicted while the valve is closed. The opening pressure is well predicted throughout the entire sequence of events. Figure 8(c) presents a comparison between the opening and closing reservoir pressures for the duration of valve operation. In general, for Figures 8(a) - 8(c) the agreement between the prediction and the experimental data is shown to be reasonably good.

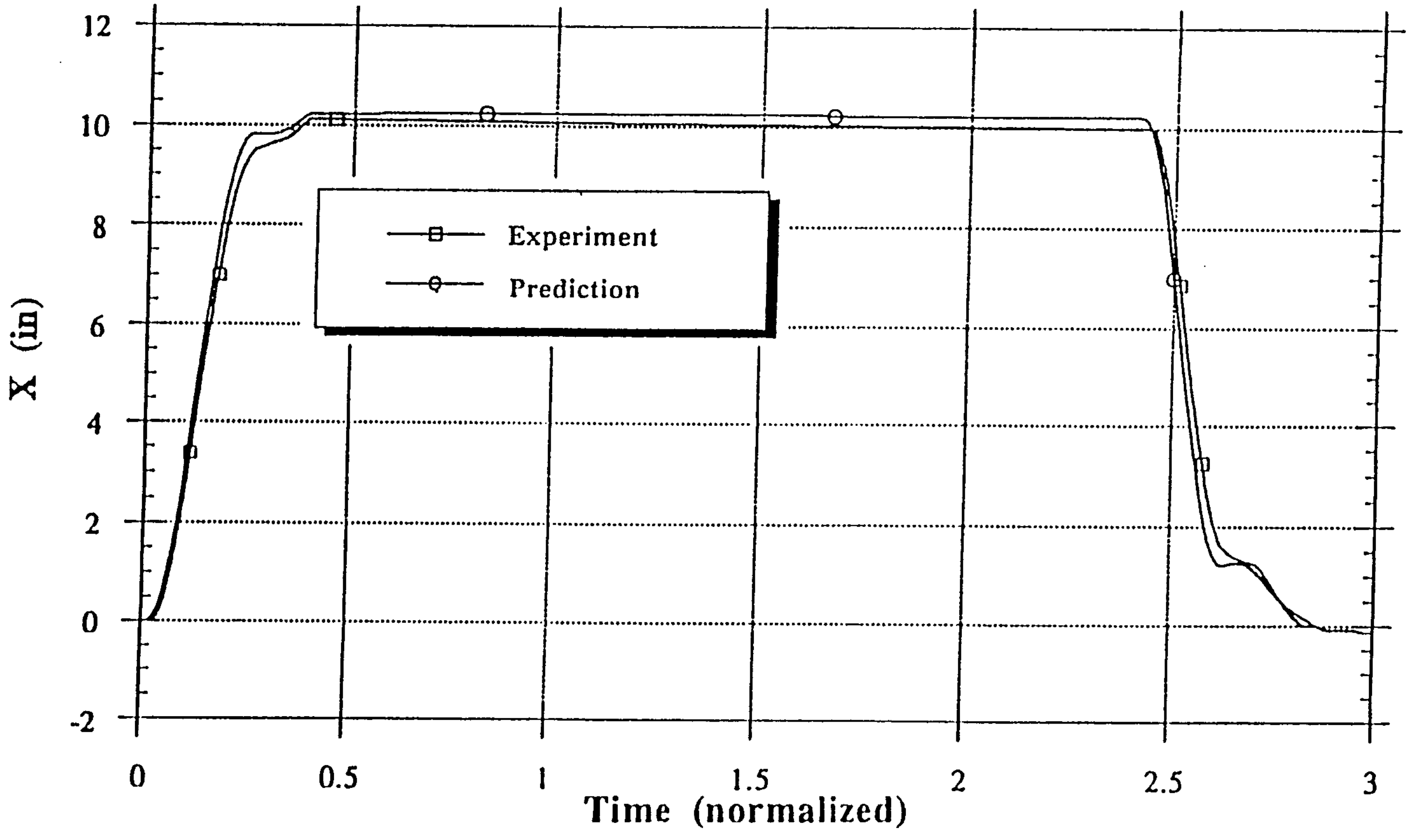

Figure 8(a) Comparison Between Experimental Data and Prediction for Supply Tank Valve Motion

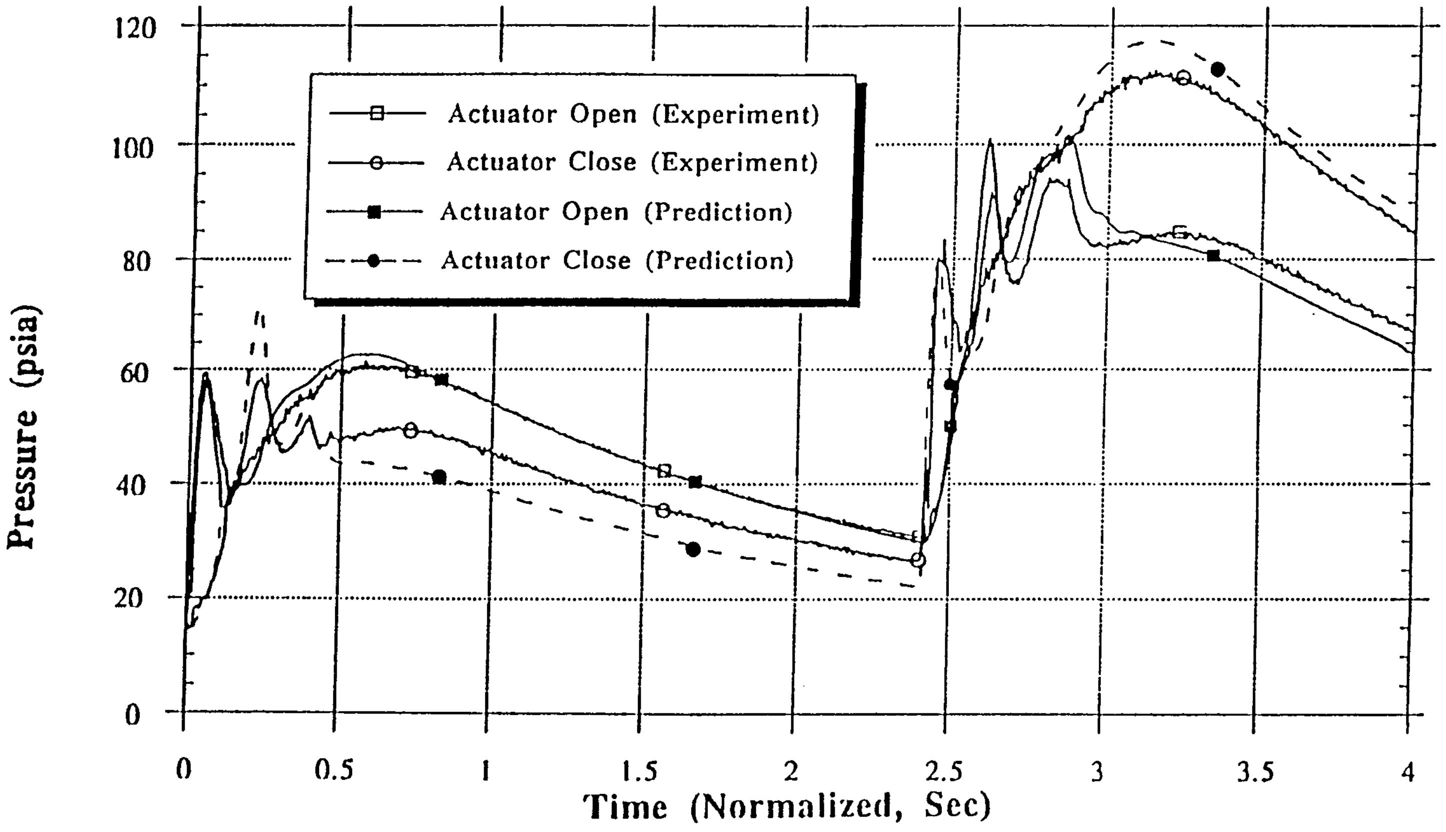

Figure 8(b) Comparison Between Experimental Data and Prediction for Valve Pressure Histories

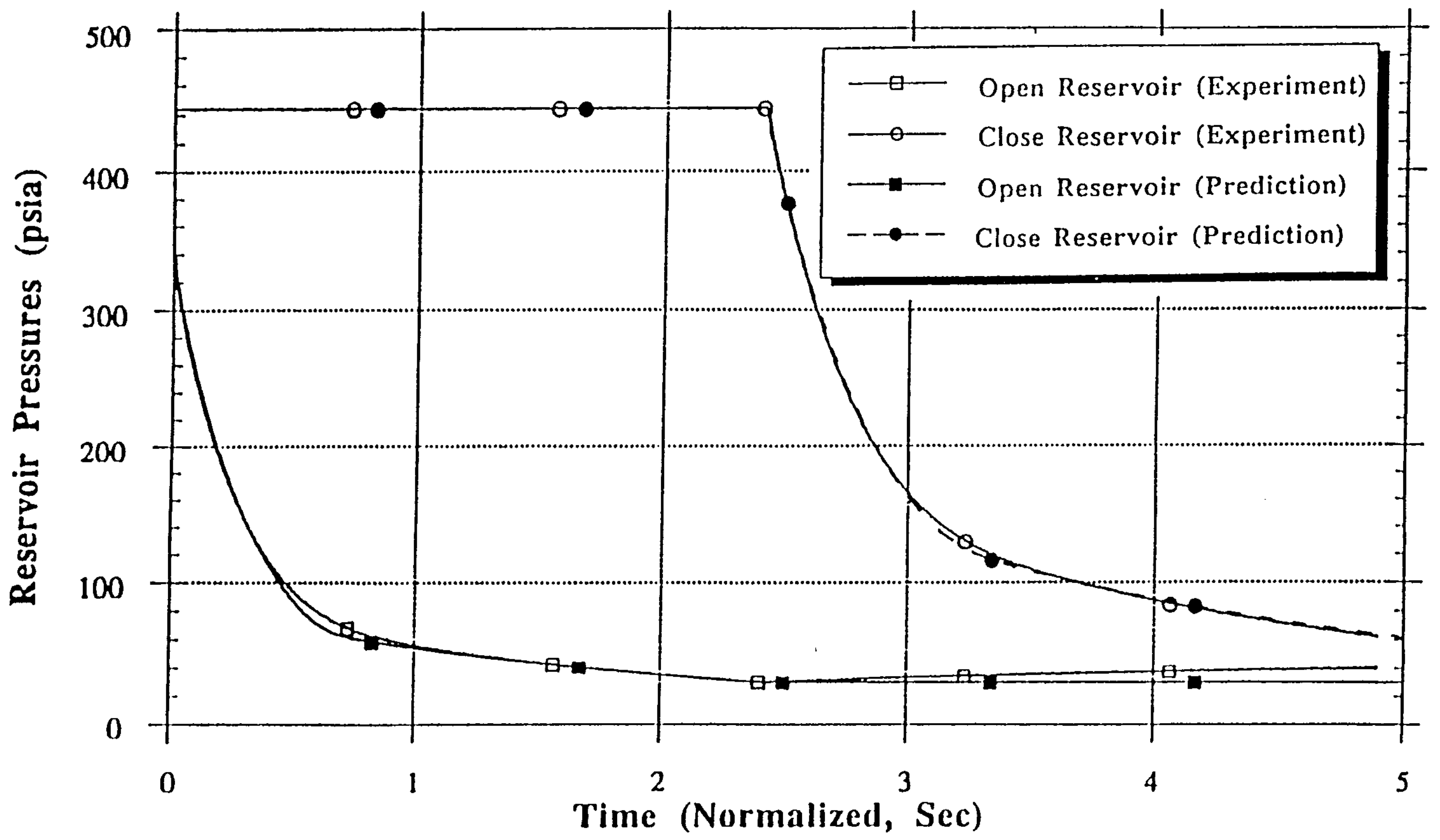

Figure 8(c) Comparison Between Experimental Data and Prediction for Reservoir Pressure Histories

5. SUMMARY OF UNCERTAINTY ANALYSIS FOR AEROPERFORMANCE MEASUREMENTS IN THE ATARR

There are many problems associated with making aeroperformance measurements of turbine stage efficiency in any facility, long run time or short duration. The goal set for the ATARR was to be able to measure turbine efficiency to within ± 0.25% of the "true" value within a 95% confidence limit. Because a great many of the assumptions used in the calculation of efficiency cannot, in general, be verified independently, the "true" efficiency becomes a function of the assumptions made about the testing process, the working fluid, etc. which comprise the basis of the efficiency calculation. Within any given basis, preliminary estimates described in detail in Haldeman, et al., 1991 suggest that single-sample data of approximately ± 0.8% accuracy can be obtained through the use of common statistical techniques. The material presented here is a brief summary of the material presented in Haldeman, et al., 1991 which is a condensation of a more detailed report Haldeman and Dunn, 1991. The topics addressed in Haldeman, et al., 1991 include: the accuracy required in each measurement quantity, the choice of alternative (but equivalent) efficiency definitions, the determination of the proper working fluid and the working fluid properties.

The desired 0.25% efficiency accuracy for the ATARR facility could easily be overshadowed when comparisons are made with data taken in other facilities because of differences in the testing methods. It is argued in Guenette, et al., 1989 that the proper way of comparing efficiencies taken from different facilities is to "correct" the indicated efficiency to account for losses and obtain an efficiency measure which is independent of the test process. Uncooled turbines operate in long-duration facilities at conditions which are close to adiabatic, while the same turbines in short-duration facilities would have higher heat-transfer losses. However, the assumption of adiabatic conditions is not appropriate for either long or short-duration facilities when cooled turbines are tested. Cooled hardware in short-duration tests would be expected to experience additional heat-loss effects above those that would occur if the same turbine were tested in a long-duration facility. To compare measurements taken in these two facilities one has to correct for the fundamental differences in the testing process.

The thermodynamic efficiency measured in any facility is given by:

$$\eta\Big|_{\text{meas}} = \frac{\text{Measured Change in Energy State of the Working Fluid Across a Turbine}}{\text{Ideal Change in Energy of the Fluid for the Same Pressure Change}}$$

which for constant mass flow and no energy addition or removal (adiabatic flow), translates into:

$$\eta\Big|_{meas} = \frac{h_u - h_d}{h_u - h_{d,is}} \qquad (1)$$

Where the subscripts u and d represent the conditions upstream and downstream of the stage, respectively and $h_{d,is}$ represents the resulting enthalpy of the fluid if it were to be expanded isentropically to the measured downstream pressure. Equation 1 represents the measured efficiency in any testing facility. But this measure can be influenced by energy losses which are not directly related to the stage performance. They would include energy loss by heat transfer to surfaces and mass flow leakage through seals. An accounting process must be done since any energy lost in this manner is not available to do work on the turbine. If the sum of all the losses are labeled as L then the fundamental efficiency is:

$$\eta_{Fu} = \frac{h_u - h_d - L}{h_u - h_{d,is}} \qquad (2)$$

The work described in Guenette, et al., 1989 has only been concerned with the heat-transfer losses which occur during the testing of a turbine stage. Accounting for only these losses (Q_w, the heat transfer to the walls) creates an adiabatic efficiency:

$$\eta_{ad} = \frac{h_u - h_d - Q_w}{h_u - h_{d,is}} \qquad (3)$$

There is the possibility that losses exist in both the testing facility and the stage which are not heat-transfer losses, and thus an adiabatic efficiency could still be dependent on the testing process. Only a measurement of efficiency which accounts for all losses (such as equation 2) can be used when comparing data taken in different facilities.

In general, long-duration facilities are assumed to have no heat losses and negligible mass flow losses (although these assumptions need to be verified for each facility) implying that L=0. Under these assumptions the long-duration facility measures the adiabatic efficiency and the fundamental efficiency. In a short-duration facility there will be heat transfer because of the isothermal nature of the facility and the enthalpy change would need to be corrected for these losses to determine the adiabatic efficiency. Further to convert to a fundamental efficiency, other losses besides heat transfer need to be quantified. Thus to convert an efficiency measurement in any testing facility to an adiabatic efficiency requires the knowledge of one of two variables: the adiabatic enthalpy ($h_{d,ad}$) or the heat-transfer losses in the system (Q_W). But to convert to a fundamental efficiency which is the only efficiency measurement which is independent of the testing process, requires a knowledge of all the losses in the system (L). To avoid the problem of trying to determine L accurately in a short-duration facility, a second method, using the work extracted by the turbine, can be used to determine the change in enthalpy across the stage. If all the energy dissipated by the gas across the stage is transformed into work then:

$$W = h_u - h_d - L \tag{4}$$

and W can replace the numerator in equation 1-2. These two methods are commonly referred to as the thermodynamic method and the mechanical method for measuring efficiency.

One of the unique differences between the thermodynamic technique and the mechanical technique is that the mechanical method provides the fundamental efficiency directly. Using the thermodynamic technique introduces a dependency on the testing process which directly influences the loss term L and complicates the process of comparing data taken in different facilities. The mechanical method also has its drawbacks. It assumes that all the energy change that occurs across the turbine stage gets translated into useful, measurable work and not other forms of potential energy (such as turbulence) which are not directly measured.

In addition to the testing process, assumptions about the gas properties and other topics which might seem extraneous to the main uncertainty analysis play key roles in determining the context in which the efficiency measurements are made. It is clear that as long as this "context" or "basis" remains consistent, efficiency measurements can be directly compared. For these reasons the analysis described here is not an error budgeting process, rather it is directed towards evaluating different measurement uncertainties and grouping them according to different data processing procedures. In this way estimates can be made as to how much the final uncertainties can be reduced. Thus, for the majority of this work we will be using single-sample data. Discussion of statistical techniques which could be used to combine different measurements and increase the accuracy beyond the point of the individual measurements are described in Haldeman, et al., 1991.

Several different problems which confront the engineer when measuring efficiency are examined in Haldeman, et al., 1991, but the details of that examination cannot be repeated here. Because the ATARR will be used to test a variety of turbines, specific estimates of the obtainable accuracies are not given in detail; rather, the equations are developed which will allow adequate prediction of the uncertainty in the measured efficiency for any stage configuration.

It can be shown that the definition of efficiency and the physical basis for its determination are more significant in comparing data from different facilities than the repeatability of the measurements themselves. Within the constraints of consistent definition and basis, efficiency measurements with accuracies better then 0.25% are achievable. In programs where test data are to be compared with data from other facilities, the specific method of determining efficiency must be carefully considered. Factors such as the particular gas properties, the defining equation of state of the gas, and the isentropic relationships used, can result in differences in the obtained efficiency. Whether the thermodynamic or the mechanical method is better for measuring efficiency is strongly dependent on the objectives of the testing program as well as the turbine configuration and how the loss term is treated. If a satisfactory estimate of the loss term is not available, then realistically only the mechanical method can be used.

6. CALSPAN VERIFICATION MEASUREMENTS

As was noted earlier in this report, a decision was made in late October of 1992 that the rotating system could not be run at that time for several reasons, e.g. (a) because the downstream isolation valve (which serves the purpose of a facility emergency shutdown if the supply tank valve were to fail to close) was not ready for that type of operation, and (b) the eddy current brake system (which is used to absorb the power generated by the rotor) was not fully debugged. It was decided that it would be prudent to perform a vane-only verification measurement series to determine if there were any other operational problems that needed to be fixed prior to fixing the problems just noted. Accordingly, a decision was made that during November and December of 1992 the facility operation would be checked out at the following test conditions using nitrogen as the test gas; (1) With the supply tank gas at room temperature at pressures of 104 kPa, 345 kPa, and 487 kPa and (2) with the supply tank gas heated to 500 °K at pressures of 620 kPa and 345 kPa. The flowpath pressure transducers and the Kulite pressure transducers on the vane were patched in through the data acquisition system. The heat-flux gauges were not patched into the data acquisition system for this initial series of measurements.

The facility was successfully operated at all of the room temperature conditions given in (1) of the previous paragraph. Pressure data were obtained from the vane transducers indicating arrival of the flow and steady state flow establishment, but quantative values for comparison with the data obtained on the same vane in the Calspan short-duration facility could not be obtained because the transducers could not be calibrated due to the problems with the isolation valve. Figure 9 (a) illustrates the supply tank and test section pressure histories for one of the room temperature conditions (run #20). The supply tank main valve was programmed to remain open for a period of approximately 2 seconds, and it essentially did so as is illustrated. In general, the facility operated about as anticipated at the room temperature test condition. However, the flowpath total pressure transducers and the sidewall static pressure transducers indicated a flow oscillation that lasted for a few hundred milliseconds as is illustrated in the expanded time plot of Figure 9 (b). The source of the pressure field oscillation is not known with certainty, but it needs to be identified.

Having completed the room temperature demonstration runs, the supply tank was pressurized and heated to 500 °K. Results of the initial run (run #25) at elevated temperature and pressure are presented in Figure 10. Once again, the main valve was programmed to remain open for approximately 2 seconds and it performed as intended. The time history of the test section sidewall static and flowpath total pressures measured for run #25 at a location upstream of the vane entrance are presented in Figure 11 (a). Figure 11 (b) is an expanded time history of the measurements

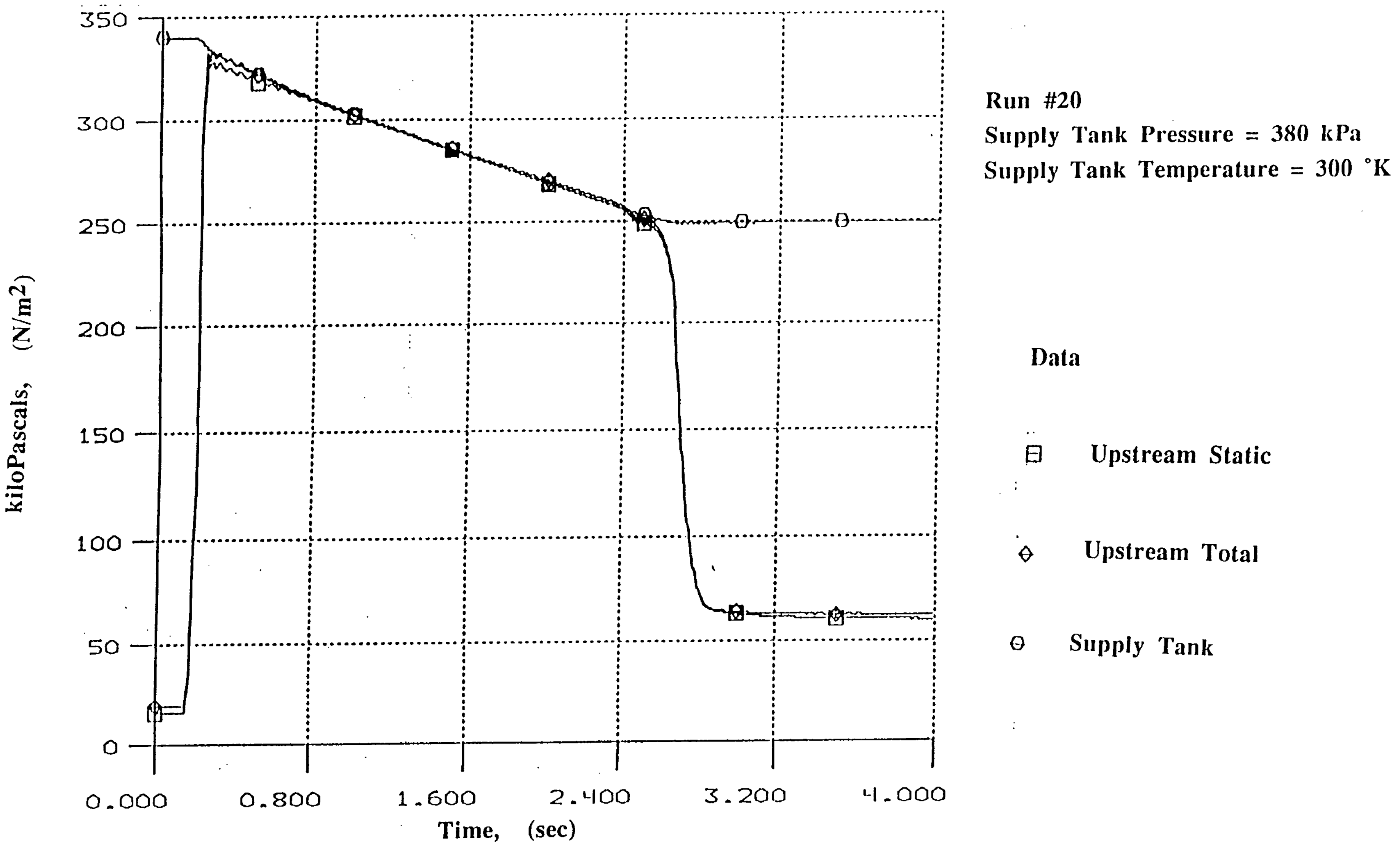

Figure 9 (a) Supply Tank and Test Section Pressure History at 300 °K and 380 kPa -- Long Time Scale

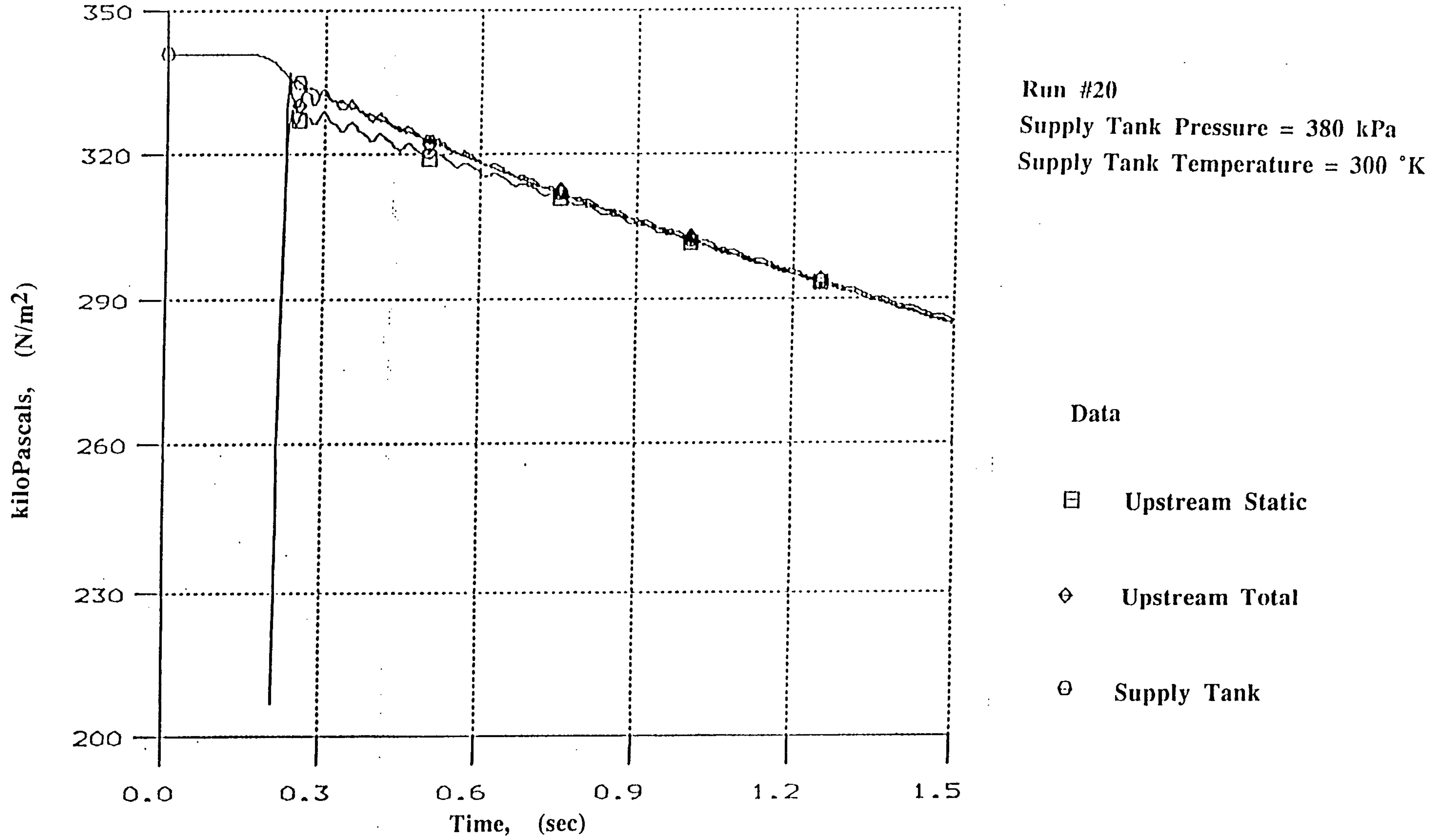

Figure 9 (b) Supply Tank and Test Section Pressure History at 300 °K and 380 kPa -- Short Time Scale

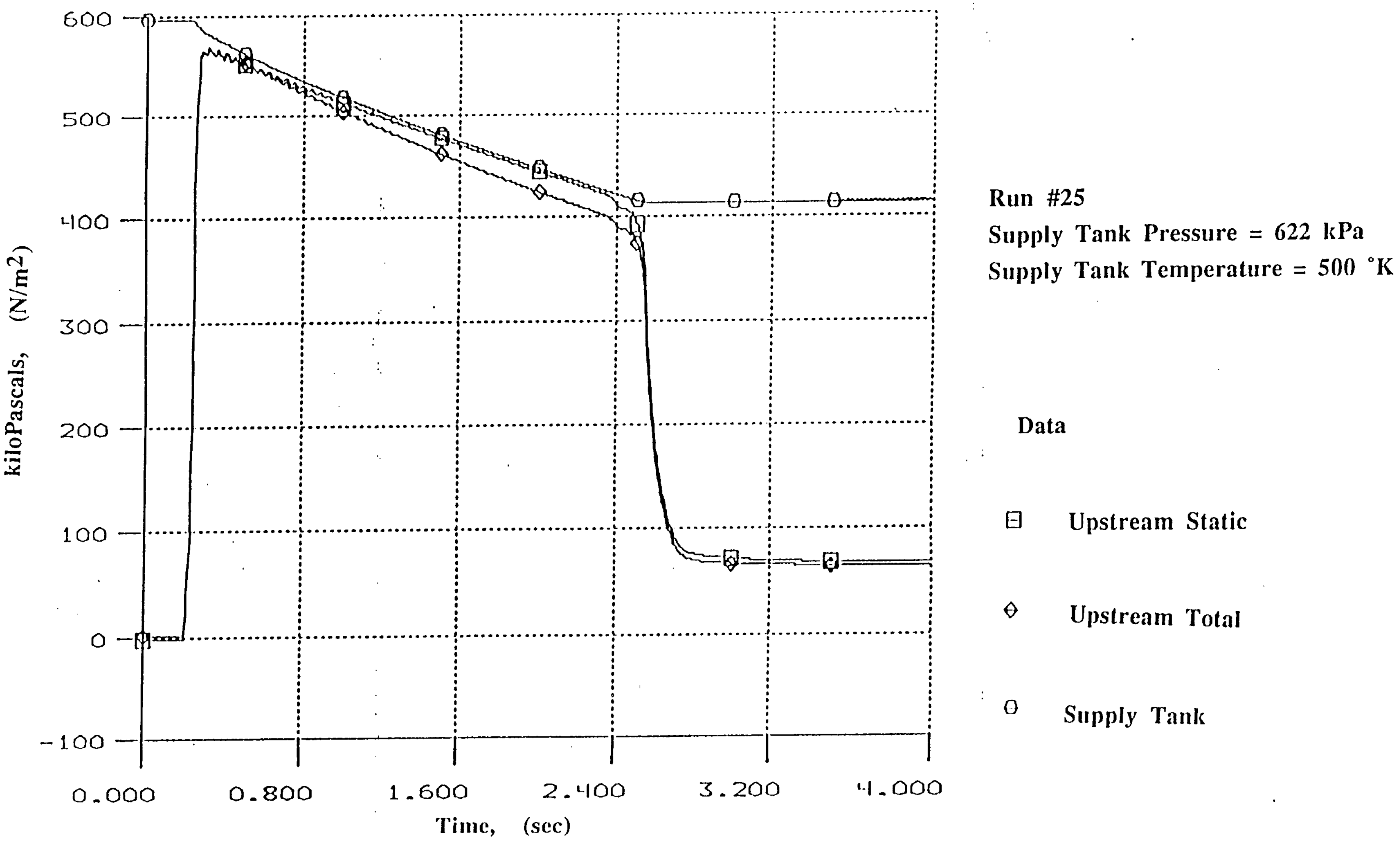

Figure 10 Supply Tank and Test Section Pressure History at 500 °K and 622 kPa -- Long Time Scale

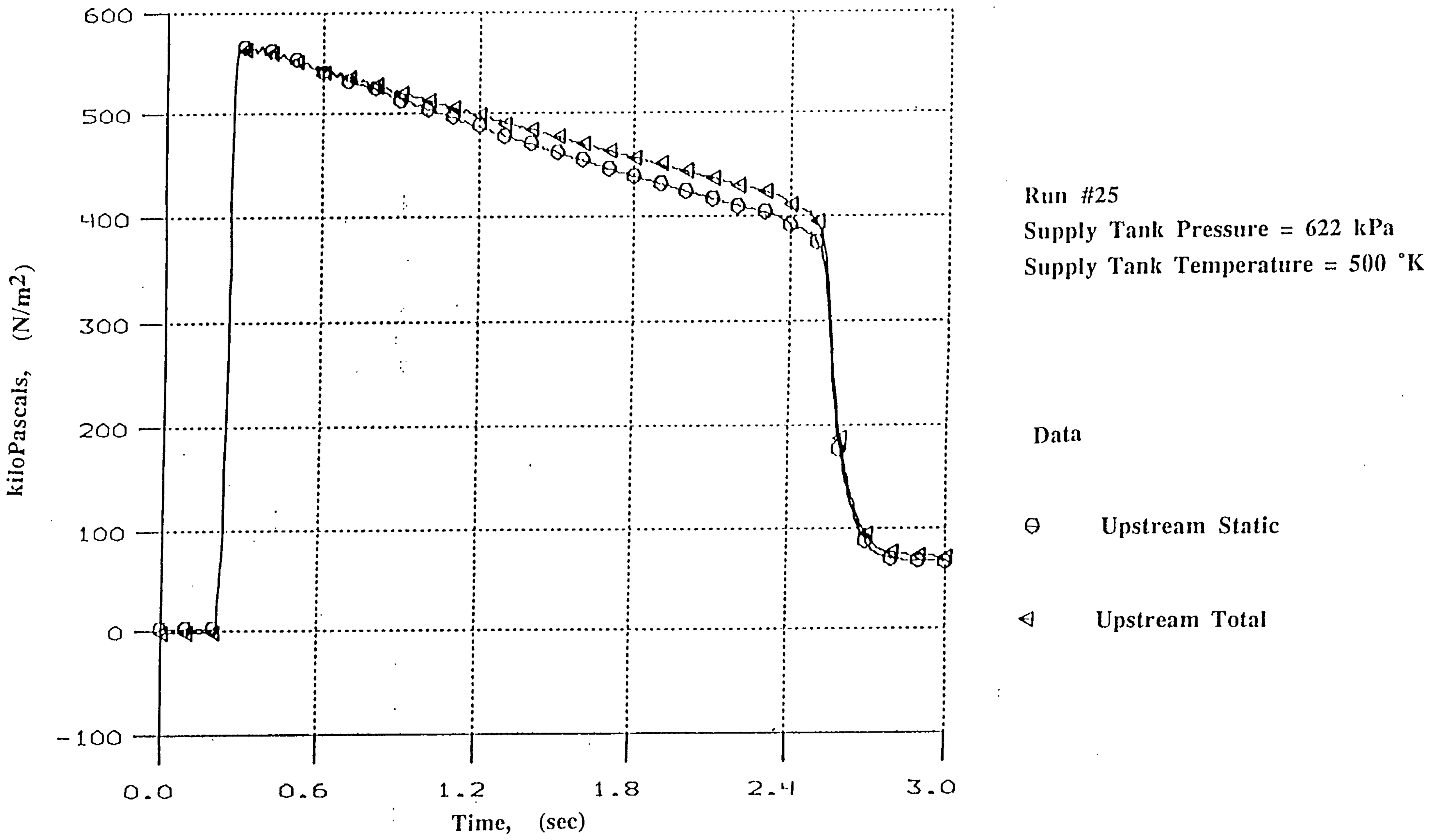

Figure 11 (a) Test Section Pressure History at 500 °K and 622 kPa -- Long Time Scale

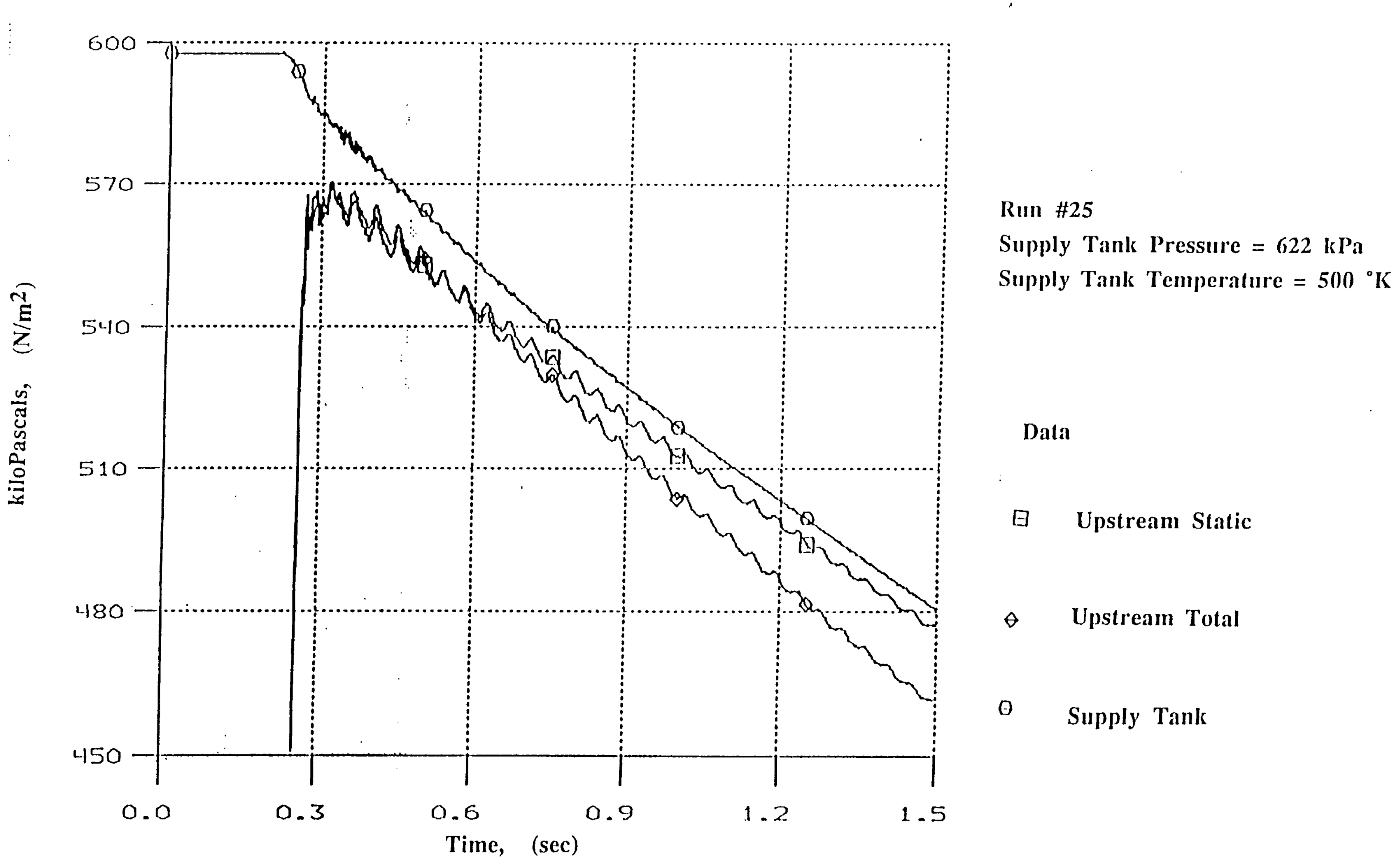

Figure 11 (b) Supply Tank and Test Section Pressure History at 500 °K and 622 kPa -- Short Time Scale presented in Figure 11 (a), but with the supply tank pressure history added to the plot for comparison purposes. The previously mentioned test section pressure oscillation is apparent in these data as it is in the supply tank data.

After running the 500 °K temperature at a pressure of 620 kPa condition, the supply tank pressure was reduced to 345 kPa while maintaining the temperature at 500 °K, and the experiment was repeated. Data were sucessfully obtained from the vane pressure transducers and for the flowpath pressure transducers in the test section. However, the supply tank main valve failed to close at this low pressure condition. As one familiar with large blowdown facilities knows, failure of the supply tank valve to close could be a serious problem if the rotor were installed. Because of this problem, the demonstration series was suspended after run #25 and the supply tank was cooled down to room temperature so that it could be entered to inspect the valve. Supply tank pressure acting on the back side of the valve was a design feature in the closing process and if the friction between the valve slider and the cast iron bushing was greated than anticipated, then the observed event could occur. A detailed inspection indicated that the other components of the system operated as anticipated and that the reason for the failure was excessive friction. This failure required a redesign of the bushing material and tolerances. A furnace test of the entire system was performed to confirm the correctness of the redesign.

Another potential problem that became apparant in reviewing the data after completion of run #25 was that the output of the pressure transducers can be significantly influenced by temperature. Figure 12 is a plot of the test section total pressure minus the test section static pressure for runs performed at the same supply tank pressure but at supply tank temperatures of 300 °K and at 500 °K. The flow Mach number in the test section upstream of the vane row is relatively low (being on the order of 0.1) so the total pressure should be just a little greater than the static pressure. The data obtained at 300 °K are as anticipated with the total pressure being an appropriate amount greater than the corresponding static pressure for the expected Mach number. However, the 500 °K data suggest a static pressure that is greater than the total pressure indicating that the total pressure transducer output is being influenced by temperature. Our experience has been that the result of increasing temperature is to reduce the transducer output. One cannot conclude on the basis of these data that the sidewall static transducer is not also being influenced by temperature. The influence of temperature on semiconductor-type pressure transducers is well known and has troubled researchers for many years. Because of this, Calspan has been developing a compensation technique that appears to be able to minimize this particular problem.

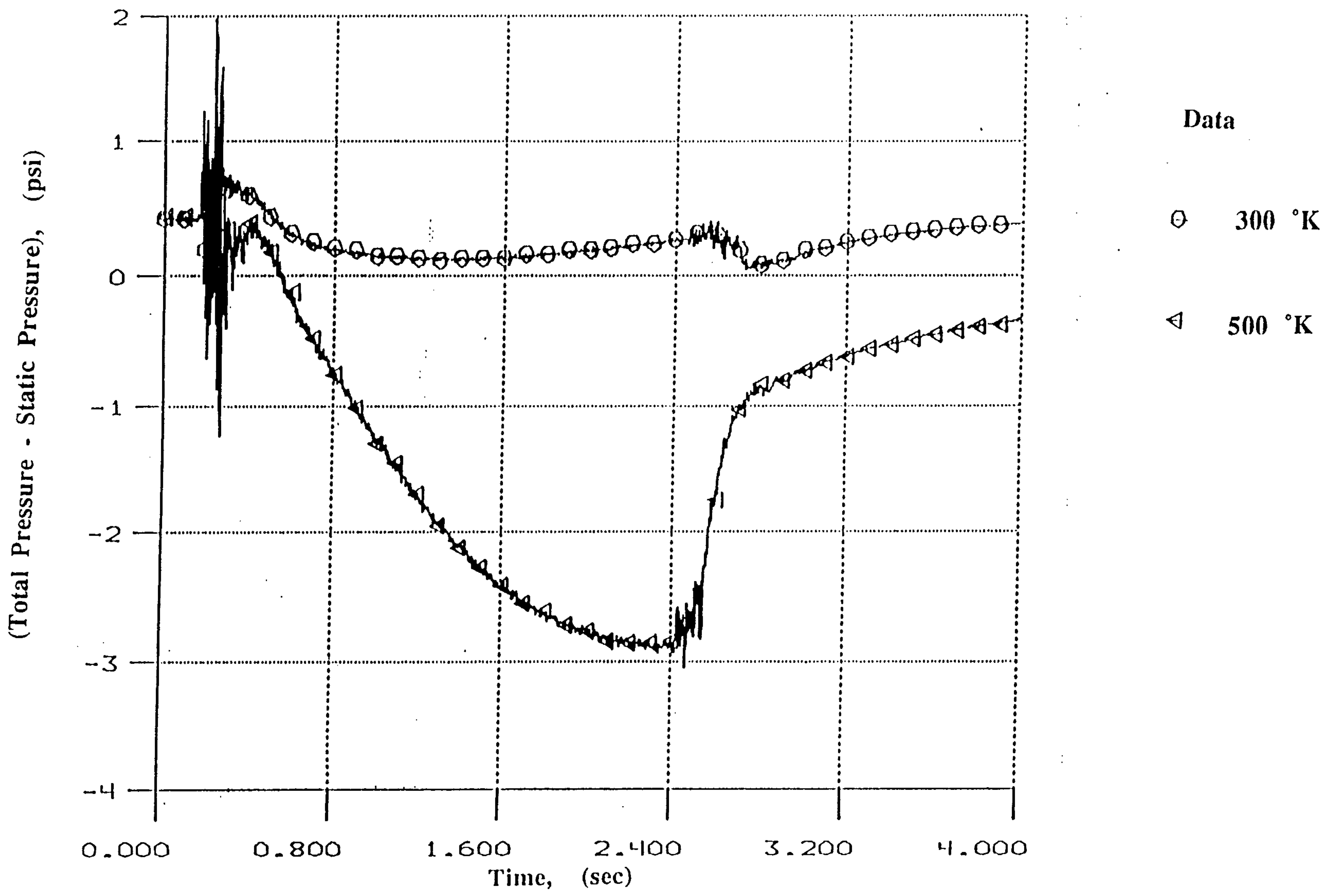

Figure 12 Influence of Temperature on Output of Total Pressure Transducers

Having completed the demonstration runs described in the previous paragraphs, the decision was made to stop running the facility and to fix the problems that had been defined to date. It was noted in the **Executive Summary** that to save expenditures, WPAFB and Calspan agreed to work the problems as a cooperative effort. The problems that were to be worked by each group are outlined in that section. It was mutually agreed that upon satisfactory correction of the problem areas outlined, WPAFB would then assume responsibility for completion of the demonstration runs.

7. SUMMARY COMMENTS

A brief description of the Advanced Aerothermal Research Rig (ATARR) currently under development at the Aero Propulsion and Power Directorate of Wright Patterson Air Force Base has been presented. Turbine Research Facility is the first large scale, short-duration turbine facility specifically designed and built for integrated aerodynamic and heat-transfer testing. It has been built both to extend the capability to validate turbine designs and provide affordable turbine performance testing.

8.
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APPENDIX A: HISTORICAL PERSPECTIVE AND DEVELOPMENT OF THE FACILITY

Design of the WPAFB turbine facility described in this report was initiated with a feasibility study published in July 1987 (Allison Gas Turbine Div., 1987). The prime contractor for the feasibility study was the Allison Gas Turbine Division of the General Motors Corporation and the study was funded via Task IV of Air Force Contract F33615-83-2339. Belcan Corporation of Cincinnati, Ohio was the sub-contractor to Allison who was responsible for providing the facility and test rig preliminary design. Professor Alan Epstein and Dr. Gerry Guenette of the Massachusetts Institute of Technology (MIT) Gas Turbine Laboratory were consultants serving as technical and operational advisors to both Allison and Belcan for the feasibility design study. At the outset of the preliminary study phase, a decision was made to design a scaled-up version of the MIT blowdown turbine facility.

Preliminary analyses of all of the major facility components were completed and are delineated in Allison Gas Turbine Div., 1987. The specifications for each major component were provided with the intention that they would serve as criteria for final design. It was recommended that the best location for the facility would be "J" bay. The details of a cost estimate (≈$2.5M) for final design and analysis, fabrication, and assembly of the test rig are provided in the reference.

On May 10, 1988, a pre-proposal bidders conference (Turbine Research Apparatus Development Program, F33615-88-R-2825) was held at WPAFB to describe a 60 month, 30 person-year effort that would be composed of four phases (Phase I was Final Design of hardware, subsystems, data acquisition system; Phase II was apparatus fabrication, installation, and demonstration; Phase III was advanced optical instrumentation development and demonstration; and Phase IV was advanced turbine tests). The program philosophy stressed that manpower was limited and that it would be necessary to keep things simple. In addition, the importance of reliability was noted and the use of off-the-shelf components was encouraged wherever possible.

Calspan Advanced Technology Center (as prime contractor) teamed with Belcan Engineering (Cincinnati, Ohio), Allison Gas Turbine, and the MIT Gas Turbine Laboratory to respond to solicitation F33615-88-R-2825. Calspan Proposal No. 8872 was submitted in June 1988 for an estimated cost plus fixed fee of $8,579,732 to complete Phases I through IV of the solicitation. The facility that was to be constructed was referred to at that time as the Transient Turbine Test Rig (T^3R). Later, this facility would be re-named the Advanced Turbine Aerothermal Research Rig (ATARR) and then still later it would be re-named the Turbine Research Facility (TRF). An Air Force letter from Lynn A. Warner (Contracting Officer), dated August 31, 1988, asked that the team revisit the requirements and revise the cost. The specific items that were revised in a letter of September 15, 1988 from Mr. Edward Weisbeck (Calspan Advanced Technology Center) to Ms. Joyce Lanford (WPAFB) were as follows:

1. The schedule of Phases I and II was compressed from 30 months to 21 months which reduced overhead expense for engineering, procurement, and facility installation.

2. A significant cost reduction was achieved by assuming that the preliminary design performed in the Allison reference noted above remained valid. Therefore, most support systems could go directly into final inspections after approval by the government.

3. The dump tank would not be used to store the working gas during supply tank inspection and maintenance. As a result, there would be no need for a dump tank isolation valve, stainless steel fabrication, or the 165 psia pressure requirement.

4. Most of J-Bay construction work would be handled more economically through WPAFB with local suppliers. Hence, this work was removed from the proposal.

5. The freon recovery system contained in the original proposal was deleted.

6. Project documentation requirements were reduced to conserve funds. Drawings will be clear and complete, but not fully finalized. Operation and Maintenance instructions will be brief, but complete, and will make use of existing vendor documents. Formal photography will not be a deliverable.

7. The Data Acquisition System (DAS) proposed is a much reduced version of the original suggestion. It is built around a GFE Micro VAX III System; additional savings are achieved by modest reductions in capacity and by use of some GFE components.

8. A significant cost saving is realized during the T^3R/DAS demonstration by using a previously instrumented turbine on which measurements have been made at Calspan. (The XF-120 high-pressure turbine was selected for this purpose).

9. Substantial savings accrue by reducing the three originally proposed optical diagnostic techniques to only one, the Particle Image Velocimetry (PIV) technique. In addition, the MIT effort will now end when the optical diagnostic checkout tests in MIT's rig are complete. As a result, costs associated with transportation to the Aero Propulsion Laboratory (APL) as well as installation and checkout will not be incurred.

A revised cost estimate (Proposal 8872R for design, construction, and check out of T^3R) for $4,863,439, constructed on the basis of items 1-9 above, was transmitted to WPAFB on September 15, 1988. After further discussion, on February 2, 1989, Calspan Advanced Technology Center was awarded Air Force Contract F33615-C-88-2825 for a total amount (when fully funded) of $4,454,116 with a planned completion date of July 31, 1992.

The original intent of the T^3R was that it would be a relatively long run time (1 second duration) short-duration heat-transfer facility. By comparison, the Calspan shock-tunnel facility has a run time on the order of 50 milliseconds and the MIT blowdown facility has a run time on the order of 300 milliseconds, both of which are basically isothermal facilities. Thus the T^3R (and its successor ATARR), with a run time of 1 second (2 seconds in the case of ATARR), are in the intermediate range where the run time is too large to be isothermal and too small to be adiabatic. However, in early 1990 a decision was made to change the role of the facility from one of a heat-transfer facility to one of an aerothermal and aeroperformance facility, hence the change in name from T^3R to ATARR. In an executive overview presented by M.G. Dunn at WPAFB on March 5-6, 1990, the specific changes involved in changing the role of the facility were described. By way of review, some of the design changes that were made (outside the scope of Proposal 8872R) at that time were:

(1) To measure turbine performance (to within 0.25 %) as well as aerothermal parameters.
  - Imposed stringent requirements on the supply tank temperature uniformity.
  - Shaft torque must be known accurately.
  - Traversing rakes were required.

(2) Change from hot-oil to direct-electrical heating of the supply tank (for reasons of safety and cost).

(3) Change of working fluid from argon/Freon (environmental compliance after 1992 forbid the use of Freon) to N_2/CO_2.

(4) Increase in cooling capability
  - from 14 lb/sec at -100°F and 100 psi to 25 lb/sec at -100°F and 200 psi.

(5) Maximum tip diameter increased to 34 inches from 30 inches.

(6) Improved math model and design-phase calculations for ATARR suggested.
  - larger supply tank
  - larger dump tank

(7) Change in working fluid (including air if necessary) led to larger eddy-current brake requirement.

(8) Increased run time from 1 second to 2 seconds (more for smaller turbines).

As design and construction of the facility progressed, the problems associated with meeting the requirements of the items described above increased. As a result of increasing costs, several items that were included in the cost estimate of February 2, 1989 had to be deleted (by mutual agreement between the Air Force and Calspan) from the program, e.g., (a) the design phase of the PIV as described in Bryanston-Cross, et al., 1990 was completed, but the system was not constructed and demonstrated, (b) the turbine cooling system was designed and a report describing that effort, Kim and Dunn, 1992 was submitted, but the system was not constructed, and (c) Calspan performed the initial vane-only demonstration measurements using the XF-120 hardware, but funding was not available to perform the rotating demonstration measurements. Earlier in this report, the many unanticipated problems requiring fixing that precluded completing items (a)-(c) were described as a natural consequence of discussing the state of the facility when we exhausted our available funding.

In July 1991, the contract was re-structured as ATARR for a total contract value of $5,293,100. Then in March 1992 it increased to $5,779,036 due to enhancements to the ATARR as well as to cost growth. In July 1992 it increased to $6,092,420 to include a DAS and user friendliness upgrade as well as a cost growth associated with our facility subcontractor Belcan. In October 1992 the contract value was increased to $6,476,466 to provide facility maintenance, repairs, and upgrades critical to achieving the desired performance of ATARR. The total funds received by Calspan for the effort were allocated as follows: (a) Allison, 1%, (b) MIT, 1.7%, (c) Belcan Engineering, 53.6%, and (d) Calspan, 43.7%.

Subsequent to October 1992, a new work effort (Phase III, ATARR Advanced Instrumentation) was added to the Calspan tasks totaling $303,709 and containing two tasks; (1) the development of a double-sided heat-flux gauge and (2) the development and documentation of a data reduction routine that would accommodate either single-sided or double-sided heat-flux gauges. In April 1993 another new work effort (Option 1) was added to the Calspan tasks totaling $144,340 for the selection and procurement of new data acquisition channels. With the addition of these two modifications, the final contract value came to $6,924,515.

By November 1992, the facility components were designed, constructed, and assembled. The plan at the initiation of the program was that Belcan would turn over to Calspan a fully operational facility in about March of 1992 and that the demonstration measurements would follow and be complete by July 1992. However, as a result of schedule slips because of one problem or another, the target date for initiation of the demonstration measurements slipped to December 1992. When December 1992 arrived, there were problems with several of the essential components which precluded a fully rotating measurement program. Rather than stop and fix those problems, the decision was made to proceed with the vane-only measurements (XF-120) surface-pressure and flow path (total-pressure rake) measurements to determine what else might become a problem. For all of the demonstration measurements, nitrogen was to be used as the test gas. The initial demonstration experiments were performed with the supply tank at room temperature and pressures from 104 kPa to 487 kPa. Upon completion of these room temperature experiments, the supply tank gas was heated to 500 °K and pressurized to 622 kPa in preparation for the elevated temperature measurements that would be performed at two pressures, 622 kPa and at 345 kPa. Data were obtained at both of these test conditions. However, on the test run conducted at the elevated temperature and the lower supply tank pressure, the main valve failed to close upon command. The problem was traced to excessive friction between the cast iron bushings and the valve slider when at the elevated temperature and low pressure. The valve performed as expected at room temperature and low pressure.

As indicated above, at the time in the demonstration where the main valve failed to close, there were other problems that had to be fixed before a rotating demonstration could be attempted and the decision was made to stop and fix all of these problems. Specifically, the following items needed immediate attention: (a) the main valve bushings were in need of redesign and rebuild, (b) the isolation valve was in need of redesign and rebuild, (c) the rotating assembly was in need of rework and balancing, (d) the slip ring mounting technique needed to be redesigned, (e) the torque meter needed to be put into working order and calibrated, (f) the data acquisition software needed to be verified using turbine data, (g) the drive motors for the rotating system needed to be installed and proper operation needed to be demonstrated, and (h) the eddy current brake operation needed to be verified. In the initial proposal cost estimate, all of the items except for (f) were the responsibility of Belcan. However, Calspan was the prime contractor, and as such assumed responsibility for the integrity of the design and operation of the individual components. In an effort to avoid further contract costs, the Air Force and Calspan agreed to work these problems as a co-operative effort with Calspan doing items (a) through (f) and WPAFB attacking items (g) and (h). Calspan completed items (a) through (f) without additional funds being added, but in the process the funds that were planned for the remainder of the demonstration measurements were exhausted. There were no additional funds available for Calspan to continue working the effort. Therefore, the decision was made by the Air Force that they would assume responsibility for the rotating demonstration experiments with consultation to be provided by Calspan if WPAFB felt it to be necessary. The material that is contained in this document is, therefore, consistent with what we knew to be the status of the facility and the components as of our last presence in "J"-bay, which was December 17, 1992. Many changes have likely been made to the facility components that we are not aware of, and we would rely upon those associated with the facility to use this document as a starting point and to keep a living log of the facility evolution.

ATTACHMENTS

1. ATARR DAS Report
2. ATARR Standard Operating Plan
3. ATARR MCS Hardware Reference Manual, Version 2
4. ATARR Facility Model Operation
5. ATARR Main Valve Bearing Rebuild
6. ATARR Cooling System, Final Report
7. ATARR ACQ Final Report
8. ATARR Instrumentation Reference Manual
9. ATARR Uncertainty Analysis, Volume I
10. ATARR Uncertainty Analysis, Volume II

11. ATARR Uncertainty Analysis, Volume III
12. ATARR Manual Listing