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An Experimental Test Device for Accelerated Endurance Evaluation of Compressor Valve Assemblies

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AN EXPERIMENTAL TEST DEVICE FOR ACCELERATED ENDURANCE EVALUATION OF COMPRESSOR VALVE ASSEMBLIES

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ABSTRACT

Valve and compressor manufacturers have often sought a means by which the time required to conduct compressor valve fatigue evaluations could be significantly reduced. Screening new concepts and improvements in design, processing and manufacture in a manner which properly simulates the compressor and produces realistic valve failure modes has often been a concern in initiating development activities. A technology improvement program has addressed the need to rapidly establish the endurance characteristics of complete valve assemblies; such as plate, ring and channel configurations, in such a way that reasonably realistic valve cycle dynamics and failure modes are achieved.

A valve endurance test device is described which permits the accelerated fatigue evaluation of valve elements as part of their complete seat and stop assemblies. The test device is a multi-chamber machine with a rotating ported plate which defines passages to and from each of three valve port openings. As the ported plate rotates it sequentially exposes inlet and exhaust ports to rapidly open and close the valve twice per port-plate revolution. Three valve port openings allow experimental assemblies to be run in direct comparison with baseline valves at the same time and under the same operating conditions. The basic design of the device, its control features and the instrumentation used to monitor valve motion and pressure differential are discussed.

A test program was conducted to establish the operational characteristics of the machine and to obtain baseline valve failures over a range of operating conditions. Valve impact velocity was varied by adjusting pressure differential through automatic control circuits. Typical failure times within the development program averaged twenty hours in comparison to the six to twelve month life observed in production machinery for the same valve design. A number of representative test results are presented including the valve motion profile and failure mode. An experimental failure for a plate valve is compared with a sample of a similar failure obtained from a production machine.

INTRODUCTION

The objective of this activity was to obtain a means by which compressor valve assemblies could be evaluated in fatigue as rapidly as possible. To achieve a high level of confidence in the results obtained from such a test it was decided that a number of criteria were to be met:

- Failures for a particular valve design must be representative of those observed on a statistical basis under actual compressor operating conditions.
- The means by which the failure mode is achieved should simulate the true valve cycle in an operating compressor as nearly as possible. This factor would allow a more accurate assessment of modifications or designs leading to more efficient operation and possible changes in dynamic performance.
- Since each component of a valve assembly was to be carefully scrutinized, it was important to be able to test the complete assembly. A design modification made to one component could influence the life of another component.

The incentive for the development of such a device was the need for a readily available engineering tool to permit the manufacturer to rapidly evaluate complete compressor valve assemblies. The basis of a valve test in such a device may be a research experiment to more clearly define the nature of valve failures or an engineering evaluation to screen new ideas in a realistic manner prior to a field trial or commercial introduction.

To achieve the desired objectives, a development program was undertaken to design a test device which could produce representative failure modes in a relatively short time span. Among the considerations addressed during the specification phase were the range of operating and control parameters required, the ability to run multiple valve assemblies concurrently and the need to make the device fully automated to allow unattended operation.

Based upon the existing valve population in the popular compressor frame sizes, it was decided to design the machine to accommodate valve sizes ranging from 3.5 inches up to and including 6.5 inches. That is, for any particular size valve, the machine should be able to accommodate three complete assemblies at one time. This would allow combinations of valves to be run at the same time and under the same conditions. For example, one baseline or standard valve and two experimental assemblies could be run concurrently. In this manner, each valve is assured of seeing the same test conditions and variations from test to test can be more readily identified.

The maximum design pressure for the device was chosen to be 100 psi. It was generally felt that combinations of chamber pressure at levels far less than the maximum would induce valve element impacts sufficient to cause failure. A nominal maximum cycle rate of 150 cycles per second was chosen for the valve element which is approximately 7.5 times the operating speed of valve assemblies in typical high speed compressors. Selecting a control system which allowed unattended operation would permit more running time and allow screening and comparative evaluation to be completed more efficiently.

Overall, it was anticipated that the combination of higher operating frequency and the potential to increase impact velocity would allow valve failures in a relatively short time span. The area to be addressed during testing was that of the mode of valve failure and how it compared to typical compressor failures.

EXPERIMENTAL APPARATUS

A number of techniques were carefully considered and analyzed during the early phases of the development program. Assembly vibration, self-contained air sources and air-choppers were among the methods studied from both a practicality and cost standpoint. The method adopted involves a rotating port plate and three chambers at different pressures. The valve element would be rapidly opened and closed by cyclically venting the pressurized air to and from the valve assembly by rotating the ported plate.

The basic concept was not new to Ingersoll-Rand. In 1965, W. Fraize and J. L. Dussourd designed and built a small scale chopper-plate device which was capable of testing one or two channel valve elements at a time. The test program produced a number of improvements to the channel valve design.

The new device can best be described by referring to Figure 1 which represents a simple schematic of its internal structure. The device is comprised of four separate chambers, a central plate which houses the test valves and a shaft which rotates the ported plate and a balance piston. Figure 2 depicts the relationship of the ported plate to the valve port opening. In position A, the supply chamber is vented through the ported plate to the seat-side of the valve assembly. Since the downstream chamber is maintained at a specified lower pressure than supply, the valve element is snapped open. When the ported plate rotates to position B, the seat side of the valve assembly is vented to the exhaust chamber which is held at a pressure lower than that in the intermediate chamber. The valve element is then snapped shut. In Figure 1, the solid arrow represents the flow path for position A while the dashed arrow represents the path for position B. Two sets of supply and exhaust ports are cut in the port plate. Consequently, two valve cycles are completed for each rotation of the port plate. The fourth chamber is the balance volume at the rear of the machine and behind the rotating balance piston. The pressure in this chamber is adjusted depending upon the operating point and the relative position of the rotating port plate to the stationary valve plate. Proximity probes were used to assure that a particular stand-off distance was maintained.

The control aspects of the device permit the tests to be conducted over a range of conditions. Each chamber has associated with it an automatic control valve which senses the pressure within the chamber, compares it against a preset value and compensates automatically. Another variable is machine speed. The variable speed control allows port plate rotation to vary between 1800 and 4500 cycles per minute. (This corresponds to 3600 to 9000 valve element cycles per minute.)

The independent pressure adjustment for each chamber affords the opportunity to control the pressure differential across the valve in both the forward (valve-open) and reverse (valve-closed) directions. That is, the pressure differential from supply to

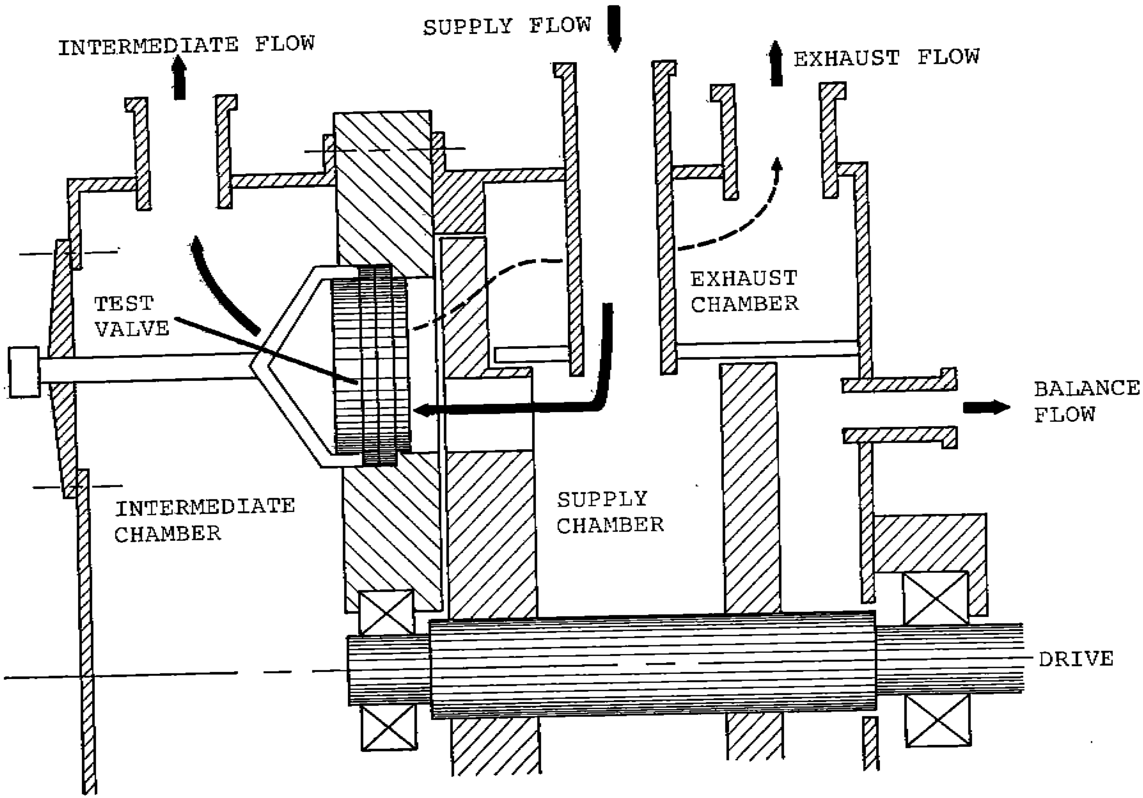
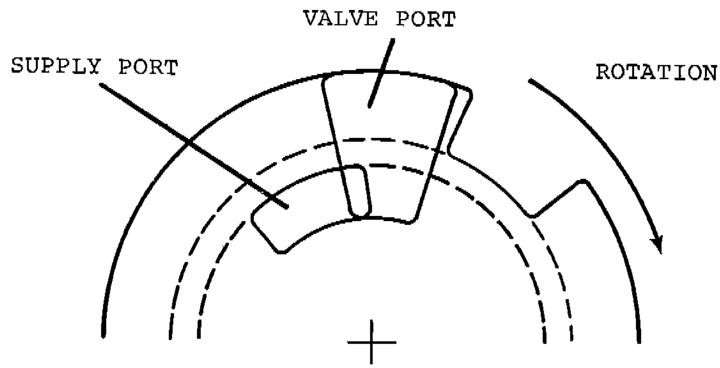
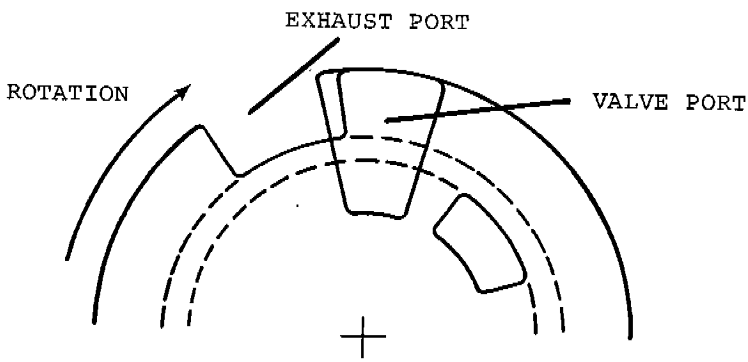


FIGURE 1 ENDURANCE TESTER CROSS SECTION



POSITION A

BEGIN VALVE PORT ALIGNMENT
WITH SUPPLY PORT



POSITION B

BEGIN VALVE PORT ALIGNMENT
WITH EXHAUST PORT

FIGURE 2 ENDURANCE TESTER
PORT PLATE ORIENTATION

intermediate need not be the same as that seen from intermediate to exhaust. The ability to control the pressure differential implies that the severity of the opening and closing events may, to a degree, be dictated for a particular test. Consequently, if one relates valve failure to the stress developed upon impact with a stop or seat, it is plausible that the severity of the event can be enhanced by increasing the impact velocity through changes in the pressure differential. Thus, the failure event can be accelerated by two factors:

- The device cycles the valve faster than a conventional high speed compressor.
- The impact velocity may be increased, to a degree, by controlling the pressure differential across the valve.

ENDURANCE TESTER AND VALVE INSTRUMENTATION

Specialized instrumentation, calibration fixtures and techniques were developed as required to properly control the critical test variables and monitor machine condition for safe operation. The test stand was fully automated allowing unattended operation and automatic shutdown when a valve failure occurred or an inspection was required. Figure 3 shows the basic elements of the test stand including the piping circuit and the individual automatic control valves for each chamber.

The instrumentation utilized and the measurements made on the test stand can be classified in one of two groups; primary or secondary. Primary measurements are those required to maintain the critical test parameters. Accurate monitoring and control of the test parameters is required to maintain consistency from test to test. The important test parameters are the individual pressures maintained in each chamber, the rotative speed of the ported plate and the resultant gas flow within the machine. Each chamber has its own automatic control valve and signal conditioning circuit. The pressure within each chamber is continuously monitored and compared against preset values. Any tendency to drift is automatically corrected through control panel pneumatic circuitry to maintain the desired pressures. The settings are critical since they directly influence the pressure differential across the valve element and bear upon the resultant impact velocity at the stop and seat. Test device speed is also monitored closely to assure consistency from one test to the next.

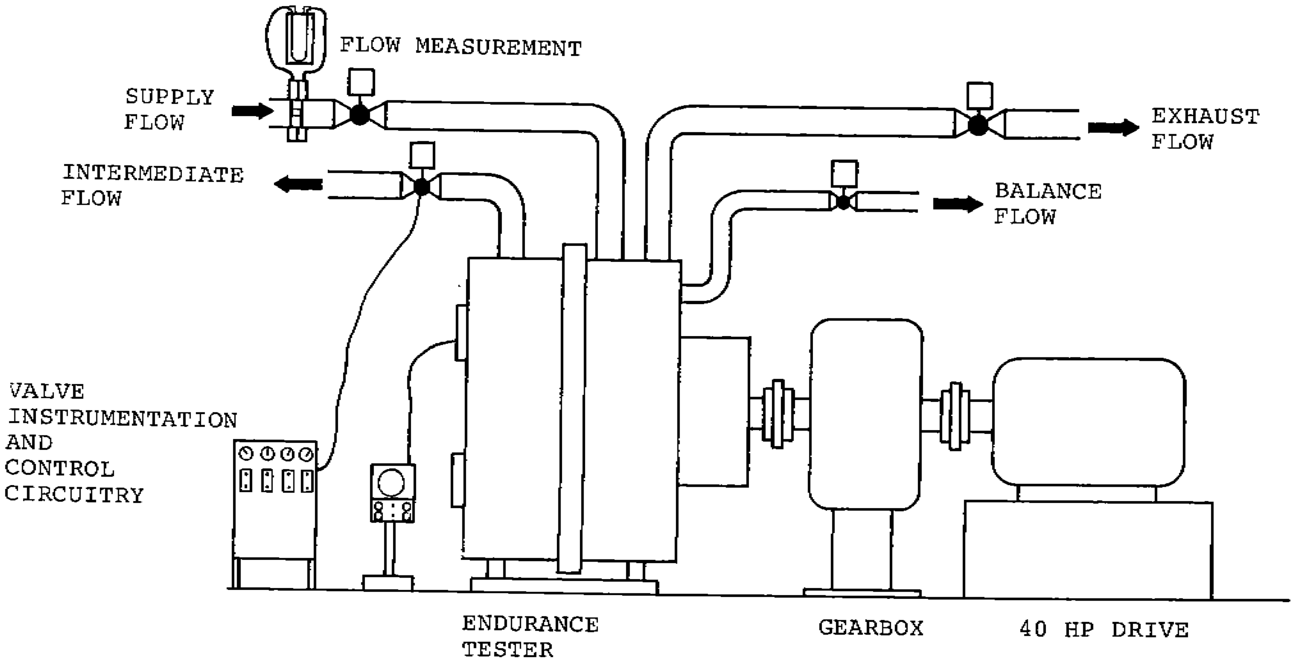


FIGURE 3 TEST STAND SCHEMATIC

A second set of primary measurements are those indicating the net gas flow through the machine and the net gas flow through the intermediate chamber. Both measurements prove extremely useful in test evaluation. The net flow is of particular importance when adjusting pressure settings to compensate for differences in efficiency from one valve design to another. The net flow through the device was maintained at a constant level for equal valve sizes to obtain a true representation of valve performance within an actual compressor. The intermediate chamber flow represents the difference between the flow passing through the valve during its opening cycle minus that which returned to the exhaust chamber during the closing process. Early experiments indicated that this flow could be used as one means of detecting a valve failure. A measurement of pressure differential across an orifice in the intermediate chamber flow path is monitored automatically in the control circuitry. A change in flow of predetermined magnitude will shut the system off for test valve inspection.

Another major set of primary test measurements is derived directly from the test valve instrumentation. Proximity probes located in the valve assembly are used to monitor valve motion as a function of time on a continuous basis. From this data the individual valve dynamics are examined as well as the impact velocity at the stop and seat. Impact velocity was used as one indication of valve performance under the conditions of the test device. A second set of data derived from valve instrumentation was a direct measurement of the pressure differential across the valve assembly. After it was determined that commercially available differential pressure transducers could not provide the required frequency response, a new Ingersoll-Rand proprietary design was developed and employed within the test program. Pressure differential across the assembly was scrutinized carefully to determine its relationship to observed valve dynamics and as one indication of component failure. A schematic representation of an instrumented valve assembly is shown in Figure 4. Fixtures and measurement devices allowing in situ calibration of both the proximity probes and differential pressure transducers were developed during the program.

Secondary measurements taken during test rig operation are less specialized in nature but are nonetheless important to system operation. Measurements incorporated within the automatic control circuitry

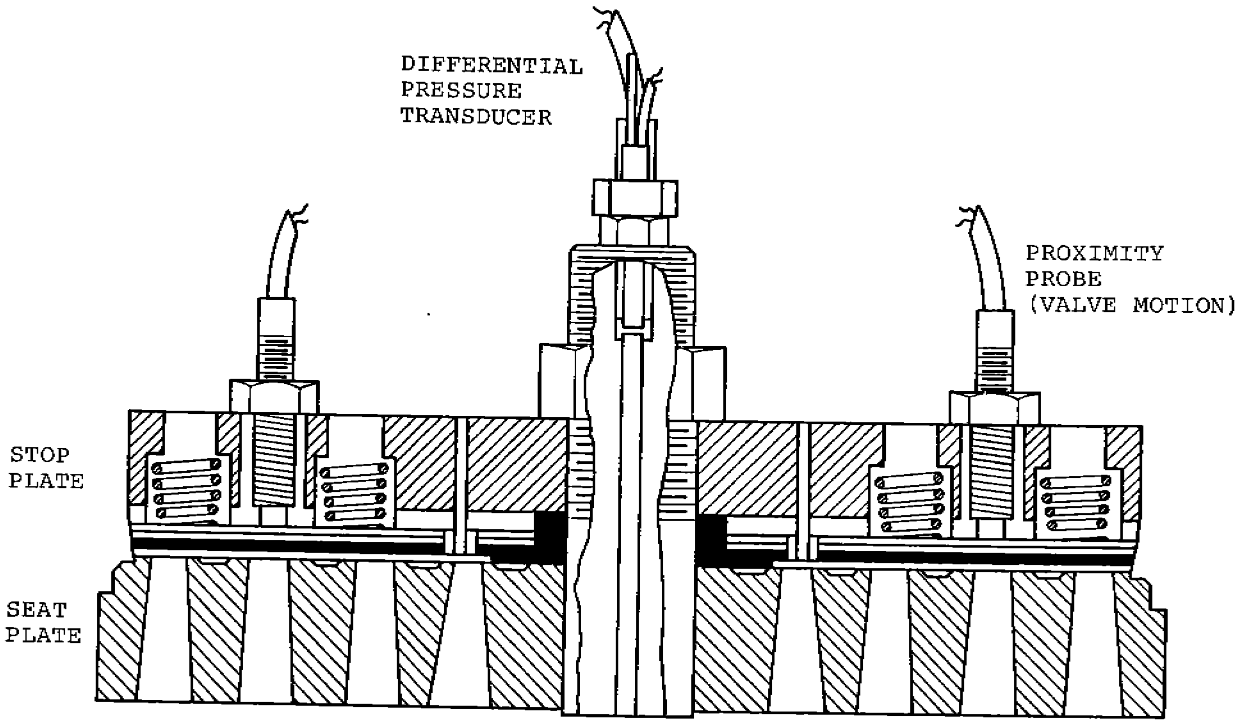


FIGURE 4 INSTRUMENTED PORTED-PLATE VALVE ASSEMBLY

may be simply listed as follows:

- Machine high speed limit.
- Machine low speed limit.
- Bearing oil supply.
  - ..... Flow rate. (Front/Rear)
  - ..... High pressure.
  - ..... Low pressure.
  - ..... High temperature.
  - ..... Low temperature.
- Bearing vibration. (Front/Rear)
- System air supply.
  - ..... Low pressure.
  - ..... High temperature.
- Port plate axial position monitor.

TEST PROGRAM

At the completion of the design, fabrication and assembly phases of the program, start-up and de-bug was begun. During this period the machine was operated over its full range of speeds to determine seal operating clearances, lube system characteristics and any vibration problems which might be cause for concern.

The key to initiation of the endurance test program was a series of experiments designed to establish a relationship between pressure differential across the valve assembly and the impact velocity of the valve element at the stop and seat. Also of interest was the general valve cycle characteristic under a variety of conditions. Figure 5 shows representative valve lift versus time plots obtained from the device while testing a 5-1/2" diameter ported-plate compressor valve. If one follows the valve motion from the seated position a change in velocity is seen to occur through approximately two-thirds of the total lift. This event represents the valve plate contacting the buffer plates used in the particular design. After the valve and buffer plates contact the stop (maximum lift), a rebound and return to the stop are observed before the spring and pressure loading push the valve back toward the seat. Contact at the seat is seen to result in multiple rebounds prior to the valve assuming a fully seated position and the cycle starting over again. As noted earlier, the valve cycles twice per rotation of the ported plate.

VALVE PLATE LIFT VERSUS TIME

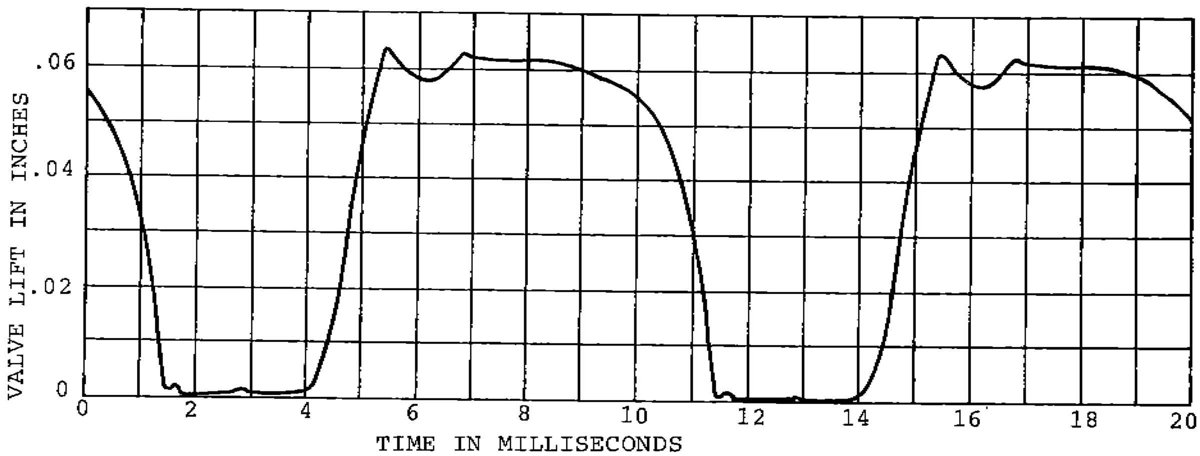


FIGURE 5 ENDURANCE TESTER VALVE CYCLES
5-1/2" PORTED-PLATE VALVE ASSEMBLY
6000 VALVE CYCLES PER MINUTE

Table I is a sampling of the performance map obtained for the 5-1/2" diameter ported-plate valve employed during the pre-test process. The key valve parameter monitored during this process was the impact velocity of the valve element at the seat.

Experiments were conducted to identify whether a straightforward method could be used to determine when the valve element failed during operation. To simulate the void created when a section of a valve fails, holes were drilled in a new plate to approximate an early stage of crack development. Measurements were made comparing the 'crack simulation' valve plate and a new plate to identify changes in a variety of operating characteristics. Structure borne vibration and air borne noise signatures were taken and compared. Flow changes at constant pressure were recorded. A variety of test conditions were set to determine whether characteristic changes occurred under different conditions. Overall, the change in flow from the intermediate chamber seemed to produce the most obvious variation for the valve design analyzed at the beginning of the program. Instrumentation was then added to automatically stop the machine when such a flow change occurred.

RESULTS AND DISCUSSION

Early experiments were continued in an effort to obtain a series of plate failures. Gradually a failure population was established which was associated with a particular set of operating conditions. An average life of 5 million cycles was sought for the baseline plate assembly so that changes in element life could be readily detected rather than dealing with infinite life possibilities beyond the knee of a typical S-N curve. It was also desirable to avoid extremely short tests since the likelihood of experimental error became more predominant and making conditions too severe might mask a subtle design variation.

Once the baseline conditions had been established, comparative tests were initiated between the benchmark assembly and other designs. Designs having new geometry, material choices and manufacturing processes were compared against the baseline using the Endurance Tester over the duration of the program.

One of the early concerns was whether the device would produce valve failures representative of actual compressor valve failures in the field. To obtain a comparative base, a number of field trips were

TABLE I

5-1/2" DIAMETER PORTED-PLATE VALVE

CLOSING IMPACT VELOCITY

POINT	INLET PRESSURE PSIG	DELTA-P OPEN PSIG	BALANCE PRESSURE PSIG	DELTA-P CLOSE PSIG	EXHAUST PRESSURE PSIG	CLOSING VELOCITY FPS
1	20	5	15	5	10	4.44
2	20	10	10	10	0	7.03
3	30	5	25	5	20	5.25
4	30	10	20	10	10	8.23
5	30	15	15	15	0	9.42
6	40	20	20	20	0	11.15
7	19	7	12	6	6	5.88

undertaken to collect samples of field failures. Over three hundred samples representing a number of design types, shapes and sizes were collected from different parts of the country. Each valve style was grouped according to design characteristics and size such that generalizations could be drawn regarding failure modes for each type. Figure 6A and 6B show a comparison between a field failure and a laboratory failure obtained using the Endurance Tester. Although other modes of failure were observed in the field, this mode seems to predominate for the ported-plate valves collected.

One drawback observed during the test program was difficulty in stopping the test at the initiation of the first crack. Although a number of valves were observed during 'first-crack' propagation, in general the test was stopped after a small piece of the valve element had detached. That is, a majority of the tests were stopped after formation of a secondary crack.

CONCLUDING REMARKS

Emphasis during the program was placed upon test evaluation of commercially available and prototype versions of the ported-plate compressor valve. Plans in the near future include fatigue evaluation of other conventional valve designs as well as new experimental prototypes.

In addition to using pressure differential as a controlling variable, the device appears to provide additional means of imposing different types of loading conditions on the valve. During developmental trials a number of conditions were observed in which a chamber resonance was excited resulting in large peak-to-peak pressure pulsations. This may provide an interesting test mode at some point in the development prgram.

To date, over 250 test builds have been evaluated in the Endurance Tester while accumulating over 4500 hours of operation. Figure 7 shows the tester in operation at the Ingersoll-Rand Research Facility in Princeton, New Jersey. The entire test loop has since been moved to the Ingersoll-Rand Gas Compressor Division in Painted Post, New York. The Endurance Tester is now playing an important role in a number of compressor valve development programs.

ACKNOWLEDGEMENTS

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FIGURE 6A PORTED-PLATE VALVE FIELD FAILURE

FIGURE 6B PORTED-PLATE VALVE TESTER FAILURE

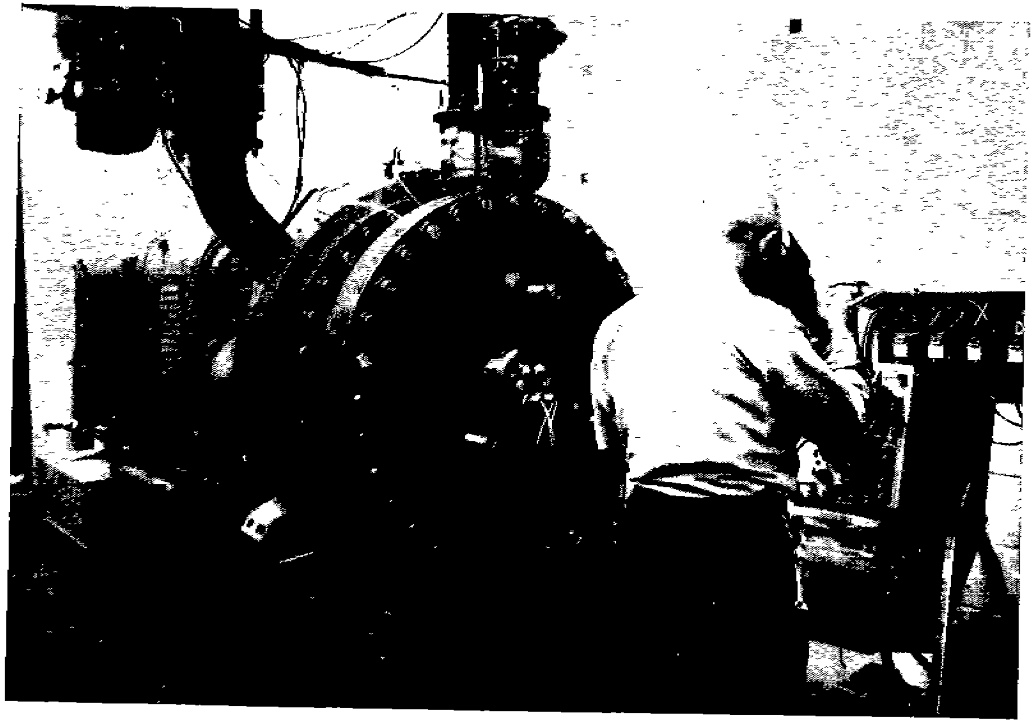

FIGURE 7 ENDURANCE TESTER INSTALLATION IN PRINCETON, NEW JERSEY

IMPACT STRESS WAVE PROPAGATION IN A COMPRESSOR VALVE

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ABSTRACT

This paper is aimed at the fundamental understanding of the impact failure mechanism of the compressor valve plate. The analytical solution of the displacements of the half-space due to a point impact load as a Green's function is derived . The numerical solution of the displacements and stresses in a plate due to the axisymmetric impact pressure are obtained after applying the special convolution and superposition algorithm developed by using the half-space solution. The wave effect on the material failure is clearly demonstrated and the new S-N curve in consideration of the wave propagation due to impact is recommended.

1. INTRODUCTION

There are two types of stresses, bending and impact, associated with a reed valve dynamics. The bending stress develops near the clamped end of a reed as the valve opens and closes. Significant impact stress is generated when the tip or any other portion

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* Work was performed while a Graduate Research Assistant at the Ray W. Herrick Laboratories, Purdue University.