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J. S. Patton
*Hoerbiger Corporation of America*

T. Kriechbaum
*Hoerbiger Corporation of America*

S. Lach
*Hoerbiger Corporation of America*

F. Ottitsch
*Hoerbiger Corporation of America*

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*J. S. Patton, Ph.D., Manager Research and Development, Hoerbiger Corporation of America, 3350 Gateway Drive, Pompano Beach, Florida 33069, USA, Tel: 954/623-2053; Fax: 954/974-2425
E-Mail: spatton@hoerbigercorp.com *Author of Correspondence

Thomas Kriechbaum, Research and Development Engineer, Hoerbiger Corporation of America, 3350 Gateway Drive, Pompano Beach, Florida 33069, USA, Tel: 954/623-2051; Fax: 954/974-2425
E-Mail: tkriechbaum@hoerbigercorp.com

Steve Lach, Research and Development Engineer, Hoerbiger Corporation of America, 3350 Gateway Drive, Pompano Beach, Florida 33069, USA, Tel: 954/623-2031; Fax: 954/974-2425
E-Mail: slach@hoerbigercorp.com

Franz Ottitsch, Ph.D., Vice President Technical Services, Hoerbiger Corporation of America, 3350 Gateway Drive, Pompano Beach, Florida 33069, USA, Tel: 954/623-2004; Fax: 954/974-2425
E-Mail: fottitsch@hoerbigercorp.com

## ABSTRACT

It is quite difficult in actual field applications to properly assess the lifetime of non-metallic sealing elements for valves used in reciprocating compressors. This difficulty is due to the wide variety of operating conditions and contaminants these sealing elements encounter while in service. If one is to determine which of these non-metallic materials will function optimally as sealing elements, a standardized method for quantifying the lifetime of these materials must be developed. Further, due to the large number of new non-metallic materials available, this standardized test method must be capable of reaching conclusions rapidly. Numerous design approaches were considered, including an existing design for this application. It was determined, however, that a completely new approach should be employed for this standardized test method of producing controlled sealing element failure. Theoretical models were generated to assure the new device would produce appropriate impact velocities to generate failure in a timely manner. Upon analysis of these models, hardware designs were developed with the adaptation of a large bore V8 engine at the center of this new machine design. The use of a V8 engine also has the added benefit of allowing for the examination of up to four test materials simultaneously. Special attention was given to the minimization of the clearance volume for the test section and associated piping, as well as to the temperature control of the system. The new machine was also analyzed theoretically to determine the effects of varying the pressure, lift and RPM on overall lifetime of the test materials. After a thorough analysis had been performed, the system was manufactured. Testing of the new system showed that the increase in capacity did not diminish its performance when compared to an existing device used for similar applications. Additionally, this new lifetime tester was capable of a wider variety of operating conditions than the existing device, allowing for tailoring the machine for the material to be tested. This study focuses on the theoretical development, manufacturing and commissioning of a new concept for the lifetime testing of non-metallic sealing elements.

## INTRODUCTION

A vital component of a reciprocating compressor is the valve sealing element. Historically, these sealing elements have been metallic plates or rings. After the advent of non-metallic materials (plastics) in the 1950s and 1960s, the reciprocating compressor industry recognized the importance of these new materials as sealing elements. Early non-metallic sealing elements were usually some form of laminated material, such as thermoset. The advantage found in impact resistance of non-metallics plates/rings soon became evident and non-metallics became the material of choice in the reciprocating compressor market.

Today, the reciprocating compressor market not only demands long lifetime from these non-metallic sealing elements, but also demands high strength to withstand high differential pressures and new dynamic unloaders, such as found in hydraulically actuated devices. These exigent demands can only be accomplished by the use of highly engineered non-metallic materials. This market demand has led to the development of materials for various temperatures and the use of the highly unique PEEK material for reciprocating compressors. To increase the strength of these non-metallic materials, glass and carbon fibers were introduced into the matrix materials. Thus, with the impact resistance advantage and the improved strength non-metallic materials have gone from novelty to state of the art for valve sealing elements.

There are constantly new non-metallic materials and material combinations for non-metallics developed which could be used as possible candidates for sealing elements. For evaluation of these new materials in the harsh environment of a reciprocating compressor, a test method has to be defined. One method would be to produce a number of sealing elements using these test materials, along with the current standard non-metallic material, and send these samples to the field for evaluation of their relative performance. This approach, however, is impractical due to the large number of candidate materials and the length of time needed to properly assess their performance. Perhaps another method for determining the best materials is to allow the competition to determine the best materials and copy their product line. This method, however, would not be desirable for any company that is, or wants to be, a leader in the field.

This problem was first addressed in Vienna, Austria in the early 1990s by an accelerated lifetime testing machine. The device uses a compressor to accelerate a plate between two seats at high lift and, therefore, relatively high impact velocities. This accelerated lifetime testing machine has been utilized by Vienna to standardize on three main non-metallic sealing element materials, with either glass or carbon reinforcing fibers. Although this device has served well, it has become evident that with the large number of new materials to test, it has been proven to be inadequate to meet the demands of the research and development groups. It was for this reason that it was decided to pursue a new concept for the accelerated lifetime testing of non-metallic sealing elements.

## THEORETICAL DEVELOPMENT

The accelerated lifetime tester in Vienna was to serve as a basis for the new design of the machine. The major difference between the existing accelerated lifetime tester and that envisaged locally is that this new system would be capable of testing four plates simultaneously. To test four plates simultaneously, a V8 engine was chosen for the drive system. Further, it was desired to decrease the time needed to cause failure of the sealing elements. Several options were available for this undertaking. First, the lift could be increased, or made variable. Another option would be to increase the operating pressure. Finally, the RPM could be increased, or made variable, thereby increasing the number of impacts for a given amount of time as compared to the Vienna device.

It was determined that a big block V8 was to be used for the “compressor” since this engine has cylinder volumes necessary for this type of device. The head and pushrods were removed because these components would not be required for the accelerated lifetime tester.

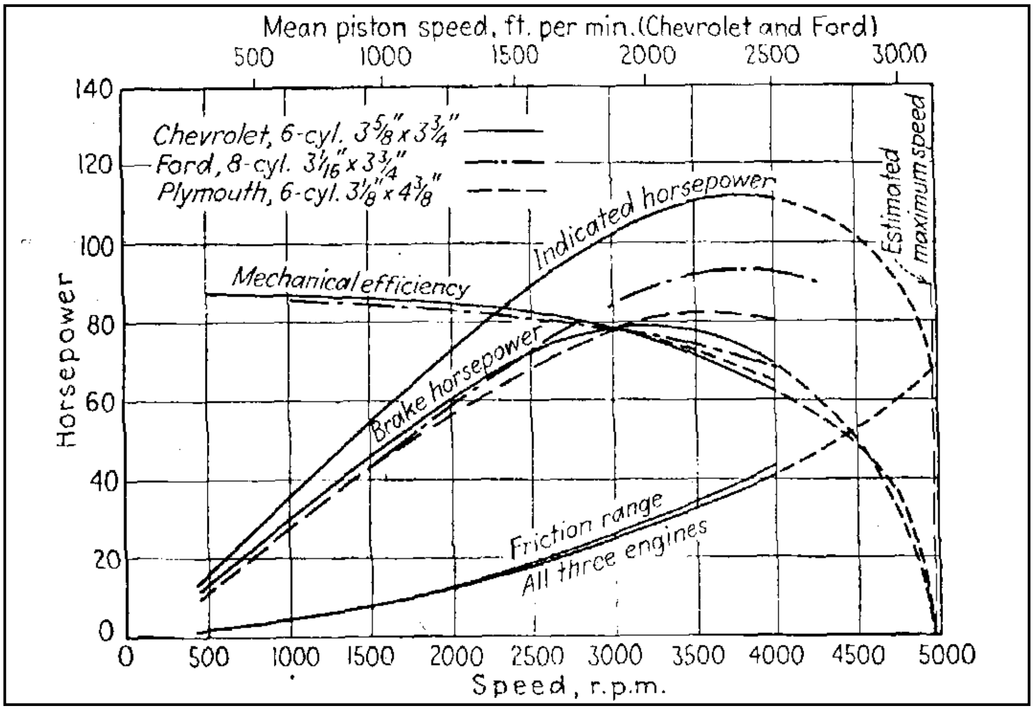



**Figure 2: Chart Used for Sizing Electric Motor**

Assuming that this V8 engine is to be used as the centerpiece of this new design, an electric motor would need to be chosen to drive this engine. To determine the required horsepower of the electric motor to drive the V8 engine, figure 2 was employed [ref. 1]. Assuming that we would want to drive the V8 at a maximum of 3000 RPM – 3500 RPM, it was determined that a 40 hp electric motor would be sufficient and give a safety margin to account for the difference in size of the V8 engine used for the compressor and those reported in figure 2.

**<u>Theoretical Model for Predicting Impact Velocities</u>**

To assess the impact velocities one can expect with the new accelerated lifetime tester, Newton's Second Law of Motion can be expressed in terms of displacement $x$ as:

$$Force = mass\frac{d^2x}{dt^2} = m_{plate}\frac{d^2x}{dt^2}$$

The force acting on the plate is generated by a pressure difference across the plate multiplied by the area of the plate, $f_0$, so that:

$$\Delta P(t) f_0 = m_{plate}\frac{d^2x}{dt^2}$$

As notated in the above expression, $\Delta P$ is a function of time that corresponds to the pressure due to the compression and expansion strokes of the "compressor" and, therefore, the motion of the pistons on each side of the sealing element.

To solve the above equation for plate displacement as a function of time, the pressure difference must be handled properly. The pressure issue can be dealt with in three different manners. First, one can curve fit the pressure difference across the plate and solve the problem in a closed form. Another way in which to solve this problem is to directly integrate the pressure as a function of time to produce a closed form solution. This method, however, is quite cumbersome. The final means to solve this problem, and the one employed in the study, is numerically.

Further, the pressure difference across the plate is directly influenced by the clearance volume of the "compressor". Thus, the impact velocity is directly related to the clearance volume and, therefore, the pressure. This motion equation allowed for the influence of these variables to be examined before the accelerated lifetime tester was constructed and proved to be of great benefit.

**Pipe Losses**

In addition to the clearance volume mentioned above, the frictional losses within the piping were estimated. Due to the geometry of the V8 engine, minor losses could also be estimated. Further, the need to keep the velocity within the piping at a reasonable level required the piping size to be established. The benchmark for this velocity was to keep the Mach number less than 0.3 at 300 K. Using this Mach number as a starting point, coupled with the extended Bernoulli equation:

$$\Delta P = \frac{1}{2}\rho u^2\left[f\frac{L}{D} + \sum K\right]$$

one finds, after extensive analysis of the design, that the Reynolds number is $Re = 1.26 \times 10^5$ producing a friction factor from the Moody diagram as $f = 0.02$. For the design shown in figure 3, $L/D = 20$ and the summation of minor losses is $\Sigma K = 2.92$ producing a pressure drop of

$$\Delta P = 8350\ N/m^2$$

**Heat Transfer Considerations**

Using this pressure drop, along with the volumetric flow rate, one finds the average dissipative energy per unit time produced by the flow at 3000 RPM to be:

$$Power = \Delta P\dot{V} = 0.65kW$$

which is the power needed to be removed from the system to control the temperature properly.

If one assumes that the method for removal of the energy from the system will be a simple single pass heat exchanger using water as the working fluid and that the system can be evaluated as steady state, then one may write:

$$UA_{air} = \frac{1}{\dfrac{1}{h_{air}A_{air}} + \dfrac{1}{2\pi kL}\ln\left(\dfrac{r_{water}}{r_{air}}\right) + \dfrac{1}{h_{water}A_{water}}}$$

where $U$ is the overall heat transfer coefficient, $h_i$ are the film coefficients, $L$ the length, $r_i$ are the inner and outer radii, $k$ is the thermal conductivity and $A_i$ rear the areas.

The heat transfer area can be estimated as:

$$Q = UA\ \Delta T$$

where Q is the heat to be removed from the system and ΔT is the temperature difference. Using this equation $UA$ can be determined, which in turn allow for the solution of the area $A$. This results for $A$ assumes that $A_{air} = A_{water}$ in the above heat exchanger equation. From this it can be concluded that the operating temperatures can be as low as 60 ºC.  Based on this heat transfer results, an adequate cooling system was designed.

**Pressure Pulses**

The pressure pulses in the system can be estimated by the following equation:

$$P = \rho(cU) = \rho(\gamma RTU)$$

For a piston velocity of U = 16 m/sec and air at pressure and temperature of 2 bar and 300 K, respectively, one can find that the pressure pulses are on the order of:

$$P = 0.1 bar\ to\ 0.2\ bar$$

which is 5 – 10% of the total pressure and, therefore, an acceptable level for the system being considered.

## TEST MEASUREMENTS AND DISCUSSION

With the design specifications and the theoretical development completed, attention was given to the construction of the device.  Figure 3 shows the actual picture of the device.  It should be noted that only one of the four legs, or test sections, are shown in figure 3.

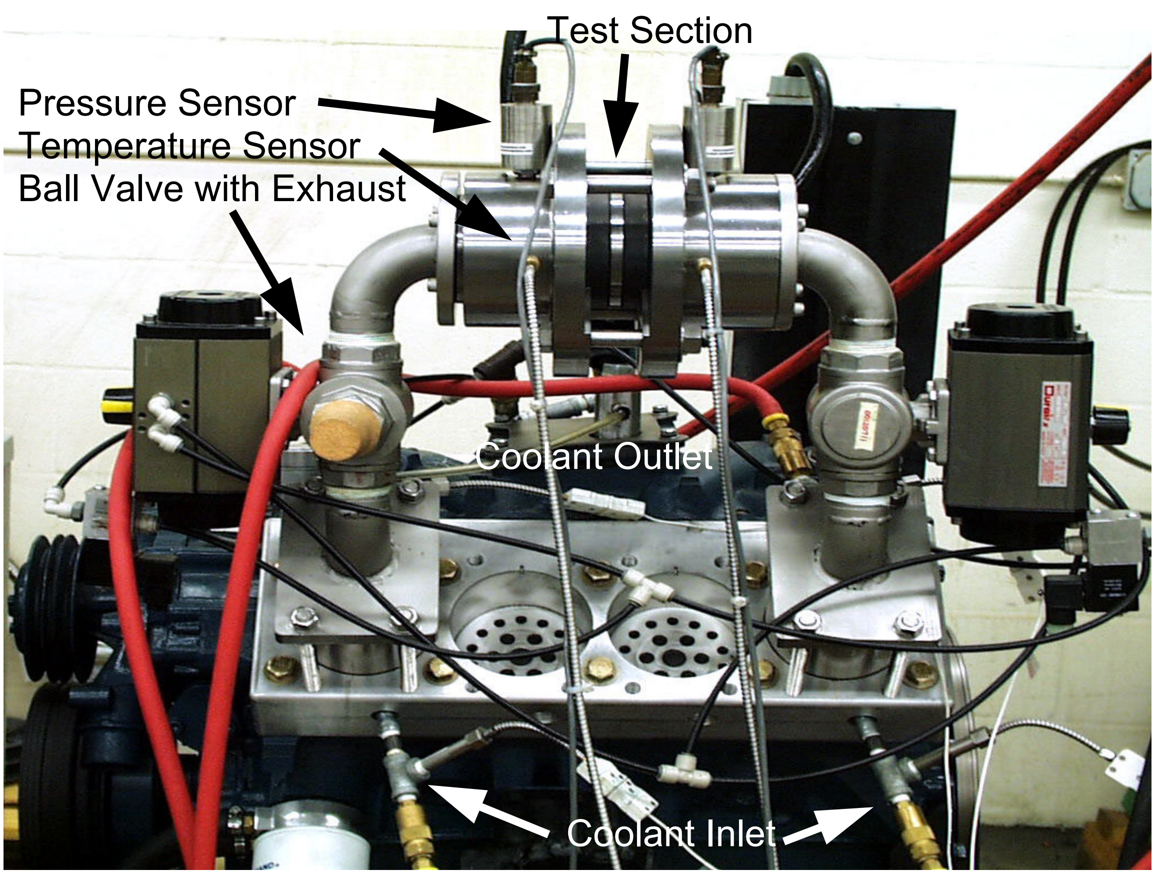



Figure 3:  New Generation Lifetime Tester

Data Acquisition equipment was used to measure:

1. Inlet and outlet coolant temperatures
2. Test section temperatures on both sides of the sealing element
3. Pressures on both sides of the sealing element
4. Temperature of the engine oil

The data acquisition equipment was also used to control the opening of the ball valves upon achieving a certain test section temperature. Therefore the device can be operated without continuous monitoring. The triggering of the ball valves allows changing of failed sealing elements without the need to shut down the device. As a further precautionary measure, a thermal shut off is triggered by the data acquisition equipment in the event that the engine oil overheats.

The impact velocities for the new lifetime tester were measured using photonic sensors and the results were compared to the existing device. Figure 4 shows the data for this comparison which includes various pressures, lift and RPM ranges.

Figure 4 clearly shows that the new device compares quite well to the existing device. In addition, the new device is capable of various RPM ranges, allowing for wider operating ranges. The impact velocities predicted from the theory was somewhat optimistic; however, the theory did guide the design in the proper direction.

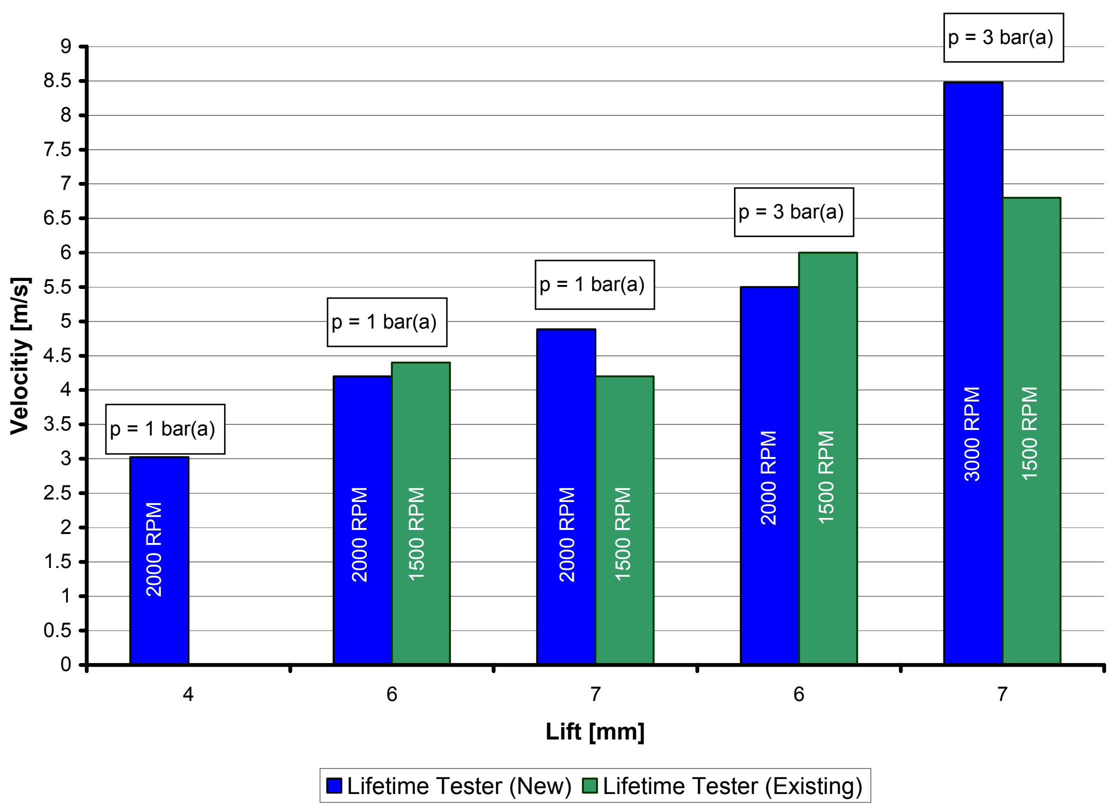
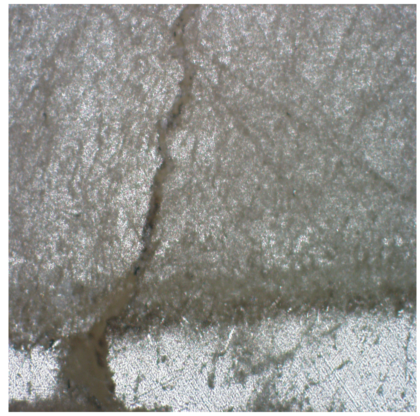



Figure 4: Comparison of the Performance of the New Lifetime Tester with the Existing (Vienna) Lifetime Tester


PEEK,
Runtime 22:30 min
at 2200 RPM



Crack
Propagation in
PEEK Plate

Figure 5: Test Samples from New Generation Lifetime Tester Showing Broken Sealing Elements and Magnification of Crack Propagation through the Sample

Figure 5 shows an example of a failed sealing element. The example depicts a PEEK failure. The failure of this PEEK plate in 22.5 minutes at 2200 RPM indicates the exceptional performance of this new generation lifetime tester. Figure 5 also shows a magnification of crack propagation in the plate which lead to the sealing element failure.

## CONCLUSIONS

A new generation lifetime tester has been developed. An existing device engineered in Vienna was used as the model for this new device. The major advantage of the new device is that four sealing elements can be tested concurrently by using a V8 engine as the "compressor". This innovation has greatly enhanced the ability to identify new non-metallic materials to be used as sealing elements for valves.

Before the design of the new generation lifetime tester was undertaken, extensive theoretical analysis was developed. This analysis served to assure that the device would perform as desired. Impact velocities, pipe losses, heat transfer and pressure pulses were all considered before the detailed design of the device was initiated.

The new generation lifetime tester showed good agreement with both the theoretical analysis and the Vienna device. Impact velocities were comparable to or better than that of the existing machine. In addition, the frequency of impacts can be doubled with the new generation lifetime tester, due to the higher RPM of this new device when compared to the existing lifetime tester. This feature further enhances the ability of the new generation lifetime tester to readily limit the time required to determine the usefulness of a new non-metallic to be used as the sealing element for a reciprocating compressor valve.

In the six months that this new generation lifetime has been in use, it has already advanced the non-metallic knowledge of sealing elements. Several materials have been shown to be unusable for valve service application, while others have shown promise. It is evident that this new generation lifetime tester will prove to be a valuable tool for the identification and development of new and better valve sealing elements well into the future.

## REFERENCES

Lichty, Lester C., Internal Combustion Engines, McGraw-Hill Book Company, Inc., New York and London, 1939.