er clearances, show leakages which are greater than for the single seal.

### 4.3 Honeycomb Seals

The results of tests for \( \frac{3}{16} \) in. (19 mm) wide honeycomb seals having two cell sizes (\( \frac{3}{16} \) in. and \( \frac{3}{8} \) in. 3.2 and 4.8 mm) and for various clearances are shown in Fig. 13 as a function of pressure ratio.

Notice the general trends with pressure ratio, cell size and clearance are similar to those for the straight and slant seals. Evidently multiple seals or honeycombs are most effective at small clearance where the pitch (spacing) to clearance ratio is large and the carryover is small.

### 5 Conclusion

A study of the results of over twelve hundred tests of straight slant and the honeycomb seals has led to a simpler, more correct, method of predicting seal leakage.

The test data show some of the effects of pressure ratio, seal thickness over clearance ratio, number of seals, pitch over clearance ratio for straight and slant labyrinth and honeycomb seals.

#### References


#### APPENDIX I

**Graphical Method of Predicting the Flow Thru Multiple Seals From the Flow Thru One Seal**

The flow \( W \) thru a single seal can be presented in terms of dimensionless variables by the relation:

\[
\frac{W_{r1}}{A_{r1}} = \text{a function of} \left( \frac{P_{t1}}{P_{t2}}, \frac{\gamma}{\gamma}, \frac{Re}{Re} \right) \quad (1-1)
\]

where

- \( a_{r1} \) = inlet acoustic velocity
- \( A \) = seal area
- \( P_{t1} \) = inlet total pressure
- \( P_{t2} \) = outlet static pressure
- \( \gamma \) = isentropic exponent
- \( Re \) = Reynolds number
- \( g \) = acceleration of gravity

A further simplification can be introduced by ignoring the Reynolds number effect, (due to the fact that the flows are separated) and by dividing thru by the ideal critical (choking) flow.

\[
\frac{W}{W_{c}} = \text{a function of} \left( \frac{P_{t2}}{P_{t1}} \right) \quad (1-2)
\]

Such a relationship is plotted logarithmically in Fig. 14 (a).

If a flow level \( \frac{W}{W_{c}} = 1 \) Line 4 is assumed for the first seal, the flow level for the second seal \( \frac{W}{W_{c}} = 2 \) Line 2 can be obtained by drawing line 1 at 45 deg to the unity pressure ratio line. This is a simple slide rule division of the first seal \( \frac{W}{W_{c}} = 3 \) by the \( \frac{P_{t2}}{P_{t1}} \) to obtain the value of \( \frac{W}{W_{c}} = 4 \) for the second seal. This assumes the total pressure before the second seal is equal to the static pressure after the first seal. Line 2 which is equal to line 4 is the pressure ratio across the second seal.

A continuous application of this method shown in Fig. 14 (a) by following the construction numbers enables one to obtain the flow for two seals.

In Fig. 14 (b) is shown the graphical construction assuming part of the velocity from the first seal is carried directly into the second seal. This, of course, involves the assumption that the discharge coefficient of the first seal is not influenced by the presence of the second seal. Even in the case of a stepped seal the step may influence the flow thru the first seal.

Figure 14 (c) is a case, found repeatedly in our tests, where the carryover line falls to the right of the unity pressure ratio line. This would indicate a loss due to carryover which is greater than the kinetic energy leaving the first seal. Actually, as we found later, the discharge coefficient of the first seal increased when the second seal was added. So, to properly combine seals, one would have to prescribe how much to increase the discharge coefficient of the first seal and next prescribe the amount of carryover to the second seal. The graphical method although useful, as an analytical tool, is complicated to apply.

In Fig. 14 (d) is shown the graphic for the case when the second seal has a pressure rise.

---

**DISCUSSION**

G. Vermes

The information presented in the paper pertains both to conventional seals (straight and slant) and to recently proposed designs (honeycomb type). The leakage data of the straight seals refers to designs which were investigated by this discusser in 1960 (reference [7]). The conclusions of this discusser and those of the authors seem to be at loggerheads. The authors submit that the authors' data on straight seal leakage are

\[
W = \left( \frac{W_{r1}}{W_{c}} \right) W_{c} C_{D}
\]

where \( W/W_{c} \) is the ratio of ideal to choked flow, \( W_{c} \) is the choked flow, and \( C_{D} \) is the discharge coefficient of the particular seal ge
Table 2 Comparison between annular orifice coefficient $K$ based on Meyer-Lowne's data ($K_{ML}$) and Bell-Bergelin's data ($K_{BB}$)

<table>
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<tr>
<th>NUMBER OF SEALING FLUIDS</th>
<th>CLEARANCE (MILS)</th>
<th>PRESSURE RATIO</th>
<th>$K_{ML}$</th>
<th>$K_{BB}$</th>
<th>$K_{ML}$-$K_{BB}$</th>
</tr>
</thead>
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<tr>
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<td>0.66</td>
<td>0.66</td>
<td>$+$</td>
</tr>
<tr>
<td>2</td>
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<td>0.5</td>
<td>0.66</td>
<td>0.66</td>
<td>$+$</td>
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<tr>
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<tr>
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</tbody>
</table>

The authors thank Mr. Vermes for his thoughtful discussion of the paper.

### Authors’ Closure

The interesting discussion by G. Vermes is greatly appreciated. His table of comparison of orifice coefficients using his 1960 formulation shows good agreement with those calculated using the data in the paper. This agreement is easily obtained if one assumes a good average coefficient for the various seals in the labyrinth.

For example, the data of Decker and Chang, Fig. 2, show the large variation in discharge coefficient of a single seal for various pressure ratios across it. Also our data, in the same figure, show how the coefficient is greatly increased by the presence of a downstream seal. To apply Martin’s formula one must therefore use an average coefficient. The first seal with its small pressure ratio would have a discharge coefficient of 0.63 while the last seal, if it has a supercritical pressure ratio, would have a discharge coefficient close to 0.9. Of course, Martin’s formula could be used to calculate an average coefficient from the test data. This has been done by Egli [2] in 1955 and has been used with some success over the past forty years.

However, this method fails to account for the actual carry-over effect shown in Fig. 11. Such an average seal coefficient must itself be a function of all the variables such as number of seals, seal sharpness, seal pitch, and the fluid involved. We may further note that the tested flow variation with the overall seal pressure ratio, shown in Fig. 11, is not the function given by Martin’s formula. A study of Fig. 11 also shows that, unlike Martin’s formula, a single sharp seal gives less leakage than three closely pitched seals. This difficulty will not be avoided by stating that one or two (or three) seals should not be considered truly labyrinth seals.

The main thrust of our labyrinth seal research was directed at sealing against turbine shrouds where very often one to four seals are used. When four seals are used they are usually arranged as two widely separated groups of two seals with no carry over between the groups. If one is seeking a comparison between the various types of seals, labyrinth (straight, slant, wavy) and the honeycomb seal, it is obvious that an equitable method of calculation should be applied to all of the types of seals. How would one apply Martin’s formula to a honeycomb seal?

The method outlined in the paper is applicable to all types of seals and does not assume the individual labyrinth seal coefficients (or their average) to be independent of pressure ratio. The discharge coefficients shown on the curves of the paper are all on an equitable basis. The discharge coefficient is proportional to the leakage flow, corrected for the inlet total pressure, the seal clearance area and the inlet sonic velocity. The variations of $C_D$ shown on the curves is the result of the different geometries and pressures ratios across the seals. It does not involve any assumption with regard to the variation of flow with number of seals, or with pressure ratio as does Martin’s formula.

The authors thank Mr. Vermes for his thoughtful discussion of the paper.