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UNIVERSITY OF LOUISVILLE

PART I

THE SEPARATION OF ZIRCONIUM AND HAFNIUM BY DISTILLATION
"

PART II

AN ENGINEERING APPRAISAL OF ALUMINUM STRUCTURAL MATERIALS

A Thesis

Submitted to the Faculty
of the Graduate School
of the University of Louisville
in Partial Fulfillment
of the Requirements
For the Degree of

MASTER OF CHEMICAL ENGINEERING
Department of Chemical Engineering
Everard G. Baker, Jr.
"

1949

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PART I

THE SEPARATION OF ZIRCONIUM AND HAFNIUM BY DISTILLATION

PART II

AN ENGINEERING APPRAISAL OF ALUMINUM STRUCTURAL MATERIALS

Everard G. Baker, Jr.

Approved by the Examining Committee

Director Gordon C. WilliamsDirector W. B. WendtW. R. BarnesR. C. Ernst

December, 1949

PART I

THE SEPARATION OF ZIRCONIUM AND HAFNIUM BY DISTILLATION

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ABSTRACT

A compilation of references dealing with the separation of hafnium and zirconium is presented, together with an evaluation of their possibilities. It is concluded that a distillation procedure holds the greatest promise. The theory of the separation of hafnium and zirconium by distillation of suitable compounds is given and experimental investigations are presented for confirmation.

INTRODUCTION

The element zirconium has been known since the latter half of the eighteenth century. (77) Early chemists isolated the oxide and silicate from various sands found throughout the world and for several decades it was thought that compounds prepared from these ores were pure. However, the presence of a second material was suspected as early as 1900 (107) when variations in physical properties were found if the compounds were prepared from raw materials from different sources. It was not until 1923 that conclusive proof, was discovered and the impurity was proven to be a new element (78). This new element, which has received the name of hafnium, was found later in all zircon sands in varying amounts in a metal concentration ratio from less than two-tenths per cent by weight to as much as sixteen per cent (64). The average concentration however, was approximately three per cent by weight hafnium in the naturally occurring ores. During the years following the discovery and isolation of hafnium, much work has been done on its separation, and the literature contains numerous references to the problem, but to this time no completely satisfactory method for the separation of zirconium and hafnium has been found.

The object of this thesis was to develop those phases of the research preceeding the development of a pilot plant for the separation of zirconium and hafnium by a distillation process.

The problem was to produce zirconium containing less than a hafnium-zirconium ratio of 0.01/100 by weight, from commercial grade zirconium tetrachloride. This commercial grade

zirconium tetrachloride contained an approximate ratio of 3/100 hafnium tetrachloride, by weight, with lesser amounts of iron, titanium, aluminum, and chromium. These lesser impurities were not considered in this problem as their removal has been successfully accomplished in subsequent operations by other methods.

This research has been conducted at the University of Louisville Institute of Industrial Research as a part of contract research for the Atomic Energy Commission.

HISTORICAL

Zirconium was first isolated, in compound form, and identified by M. H. Klaproth (77) in the late eighteenth century. He precipitated the compound from a dilute solution with potassium carbonate. This precipitate did not display the properties by which other then known elements were identified, and Klaproth proposed it as a new earth.

In 1824, J. J. Berzelius (77) isolated the metal from the salt that Klaproth had described, and confirmed the discovery of zirconium.

The remainder of the nineteenth century passed with the study of the chemistry of zirconium and the establishment of its physical and chemical properties. Complete agreement on the physical properties was not possible because of the existence of the element hafnium, which was not then known and which occurred in all zirconium ores, but much of the chemistry of zirconium was determined, because as was proved later, the chemistry of hafnium and zirconium was practically identical.

In 1911, G. Urbain (78) isolated a material from the rare earths, which he called Celtium, and he claimed it to be element number seventy-two, which from the periodic chart, now would be hafnium. In later years, this identification was proved to be incorrect as his actual work was not duplicated.

In 1921, J. W. Marden and M. N. Rich made a reasonably complete (75) survey of the literature of zirconium. This survey makes no mention of the element now known as hafnium, indicating that little then was known about it. Published information and much of the original work by the United States,

Bureau of Mines during World War I were included in this survey.

In 1922, A. Dauviellier (78) obtained the first X-ray spectrum of an element admitted to be number seventy-two.

For several years before Dauviellier's work there was a protracted discussion between the followers of Urbain, who would class element number seventy-two as a rare earth, and those who would class it as a homologue of zirconium. This discussion continued for some years even after the actual discovery.

In January, 1923, D. Coster and G. von Hevesy (6)(78) separated a material from zirconium and titanium compounds having an X-ray spectrum matching that obtained by Dauviellier. Element number seventy-two, if considered as a homologue of zirconium could be suspected to be present with naturally occurring zirconium. Furthermore, it was established that the X-ray spectrum agreed with the Bohr Theory for this new element.

Thus, the discovery of hafnium, element number seventy two, was firmly established. It was named hafnium, for an ancient name of the city of Copenhagen, Denmark where Coster and Hevesy worked.

The chemical similarity of zirconium and hafnium directed much of the research connected with them toward methods for their separation. Both elements belong to the RO_2 family of the periodic group IV. Moreover, hafnium's properties are closer to those of its lower homologue, zirconium than they are to those of its higher homologue thorium (57). Until a satisfactory method for separation could be perfected, the determi-

nation of the properties of the pure elemental zirconium could not be advanced further, nor could the properties of the new element hafnium be established.

Following the discovery of hafnium many attempts were made to purify and isolate either or both hafnium and zirconium, and the literature contains numerous articles reporting a variety of approaches to the problem.

In the year 1923 a re-evaluation was made of the hafnium content of many zirconium ores, by G. von Hevesy and V. T. Jantzen. (62). It was found that all zirconium ores were similarly contaminated, and the hafnium concentration ranged from less than two tenths per cent in some to more than sixteen per cent in a few. In the same year these men established a method of separation by fractional crystallization of the double alkali fluorides (63).

In the year 1923 also Gloeilampenfabrieken N. V. P. obtained a series of British patents for the separation of hafnium from zirconium. Some of the methods of separation covered by these patents are:

- (1) Fractional crystallization of sulfates (40).
- (2) Fractional crystallization of oxychlorides (41).
- (3) Fractional crystallization of fluorides (43).
- (4) Fractional crystallization of higher oxy salts (42).
- (5) Fractional crystallization of oxalates (44).
- (6) Distillation of complex chlorides (45), formed from zirconium and hafnium tetrachlorides and phosphorous pentachloride. It was reported that the hafnium fraction distilled

from 230° C. to 360° C., and that the zirconium fraction distilled from 360° C. to 410° C.

In 1924, Gloeilampenfabrieken, N. V. P. (55) obtained a United States patent covering item number six (6) listed above, but which further states that other complexes formed from elements of the fifth and sixth groups of the periodic chart with zirconium and hafnium tetrachlorides may also be distilled.

A. E. Van Arkel and J. H. De Boer in 1924, (101) published a procedure for separation of the two elements by what they termed a fractional sublimation of the complexes formed with phosphorus pentachloride. They further presented the formula of the complexes as $2 MCl_4 \cdot PCl_5$ where M represents either metal. The freezing point for the zirconium complex, $2ZrCl_4 \cdot PCl_5$ was determined as 164.5° C. and the boiling point as 416° C. At this same time A. E. Van Arkel and J. H. De Boer prepared the phosphorus oxychloride complexes (77), and determined their boiling points as approximately 360° C. A fractional distillation was carried out, and the research of this thesis is a direct outgrowth of their work. Van Arkel and De Boer filed for a United States patent covering fractional crystallization of double fluorides in 1924.

Also in 1924, D. Coster and G. Von Hevesy filed for United States patents covering the following methods of separation:

- (1) Fractional precipitation as the hydroxides (9).
- (2) Fractional precipitation as the sulfates (10).

- (3) Fractional crystallization as double fluorides (11).
- (4) Fractional crystallization as oxy-halogen compounds, (12).

A method of separation using the double ammonium citrates, was published in 1925, by D. H. Drophy and W. P. Davey (31). A good separation was reported as the hafnium compounds are more soluble than the corresponding zirconium compounds.

M. Marquis (76), in 1925, reported separation of hafnium and zirconium from the ore, malacon, by a fractional precipitation of the sulfates similar to that previously patented.

British patents covering further separations were granted to Gloeilampenfabrieken, N. V. P., in 1925:

- (1) Separation of hafnium from zirconium by selective precipitation in phosphate solutions (47).

- (2) Depositing of metallic hafnium or zirconium on electric lamp filaments from the gas phase by control of temperature (48).

G. von Hevesy and E. Madsen (65) claim separation by use of alkali double fluorides in a series of fractionations to produce 99.9 per cent hafnium. The greatest purity obtained to this date. A large number of steps were probably necessary to obtain this figure.

The following methods of separation:

- (1) Fractional precipitation of oxides (94).
 - (2) Fractional distillation of halides (91).
 - (3) Fractional crystallization of phosphates in the presence of an organic solvent (95).
- were covered in Canadian patents issued in 1925, to A. E. Van Arkel and J. H. De Boer. They also obtained several United

States patents and among them:

(1) Phosphates dissolved in Oxalic acid and fractionally precipitated with hydrochloric acid. (101).

In 1926, J. Kendall and W. West (70) attempted a separation by the ionic migration method using complex oxalates. The degree of separation was not great.

D. Coster and G. von Hevesy (18) obtained a Canadian patent in 1927 covering precipitation of higher basic compounds from ether solutions.

J. H. De Boer published two articles in 1927. One, on the separation of hafnium from zirconium as the phosphate from sulfuric acid solution (21), the other method was the fractional decomposition of the phosphates in hydrofluoric acid solution by use of boric acid, or other boron compounds. (23).

During the late 1920's many of the above mentioned authors obtained patents in several different countries, covering their particular methods of separation.

In 1930, G. von Hevesy and H. O. Wagner (66) reported that hafnium halides were less soluble than zirconium halides in concentrated hydrofluoric acid.

J. H. DeBoer and J. Broos (29) reported in 1930 that by using a sulfuric acid fractionation, the second fraction eliminated all zirconium. It would seem, however, that this is in error inasmuch as others have used essentially the same method without such phenomenal results.

In 1931, a government document, by P. M. Tyler (90) presented a discussion on methods of separation of hafnium and

zirconium, up to that date with information on the preparation of pure hafnium salts.

W. Prandtl (83) in 1932, fractionated hafnium from zirconium in a solution of ammonium sulfate and oxalic acid. He obtained hafnium dioxide of 95.5% purity in three fractionations. In 1935, Prandtl obtained a United States patent using the fractional precipitation of the ferrocyanides to obtain a separation.

G. von Hevesy and W. Dullenkopt, in 1934, fractionally sublimed the tetrafluorides, and only obtained a partial separation, but they did examine the crystals and recorded the crystal constants.

In 1942, W. C. Schlumb and F. K. Pittman (89) re-examined the work of W. Prandtl on the ferrocyanide method. They succeeded in changing the composition of a mixture from a 12/88 ratio of hafnium to zirconium to an 80/20 ratio on the same basis in four fractionations.

E. M. Larsen, (73) in 1943 attempted a new technique on the old method of fractionally crystallizing phosphates from a sulfuric acid solution, as shown by J. H. De Boer in 1927 (22). He sprayed dilute solutions of zirconyl-hafnyl sulfates and phosphoric acid simultaneously into a ten per cent solution of sulfuric acid. The precipitate was treated with sodium hydroxide peroxide solution and digested at seventy degrees centigrade. In seven fractionations the hafnium content was raised from thirteen to ninety three per cent.

H. H. Williard and H. Freund (106) attempted a frac-

tional precipitation of a triethyl phosphate complex. In this method, instead of adding the precipitating agent, it was allowed to form slowly in the mixture by hydrolysis. The separation was not extensive. It was reported in 1946.

A government document (72) published in 1946, by W. J. Kroll and W. W. Schlechten again reviewed the literature on zirconium and refers only vaguely and briefly to hafnium separation. This work of W. J. Kroll and A. W. Schlechten was presumably an extension of the publication of J. W. Marden and M. N. Rich. (75). Other articles referring to the history, preparation and purification of zirconium, some of them as late as 1947, completely ignore the existence of the element hafnium (58) (71) (68).

The reasons for the apparent lack of attention to hafnium are quite simple. Since zirconium and hafnium are so much alike in their chemical properties, they do not interfere with one another in many commercial uses today. Furthermore, there are no significant uses of hafnium alone and therefore, it is not specifically desired in volume.

Apparently new fields of research are opening up which make a commercial separation of these two elements both desirable and necessary, therefore in 1949, D. M. Gruen and J. J. Katz at Argonne National Laboratories, Chicago, Illinois (56) extended the work of A. E. Van Arkel and J. H. De Boer on the distillation of the phosphorus pentachloride and phosphorous oxychloride complexes. In their results they present a value of relative volatility, α , for the separation of the phospho-

rus oxychloride complexes, and established $1.5 \text{ ZrCl}_4 \cdot \text{POCl}_3$ and $1.5 \text{ HfCl}_4 \cdot \text{POCl}_3$ as more accurate formula for the complexes. In this same work a series of distillations is reported with the use of various types of fractionating columns.

With the exception of distillation, the previously discussed methods for the separation of these two elements are essentially batch operations. Batch techniques are fundamentally expensive and time consuming and to obtain any high degree of enrichment a very large number of operations are necessary. For this reason such methods as crystallization and precipitation are usually left to cases where other procedures fail.

The process of distillation has been developed through many centuries to a point where it may be a continuous operation and because of this, it often excels in comparison with other separations.

A. E. Van Arkel and J. H. De Boer (77) state, in their writings, that other complexes, similar to the phosphorus complexes, may be made of elements of the fifth and sixth groups of the periodic table, however, so far as can be determined no other complexes have been made.

The position of phosphorus in the periodic chart would indicate that, if other complexes could be made, these complexes would be of higher molecular weights and would lead to the conclusion that they would probably have higher boiling points, making them less easily distillable.

THEORETICAL

The separation of hafnium from zirconium as shown in the historical section has been the subject of considerable research, and the methods for separation are almost as numerous as the men who have investigated the subject. However, there are no commercial methods for separating the two elements in existence today. Many variations have been proposed for fractional separation by means of crystallization, precipitation, decomposition, etc. but there have been only a limited number of references to distillation procedure. This is somewhat surprising as a distillation process is normally much more efficient than any of the other proposed operations. The reason for this lack of adaptation of distillation to the problem is probably because as far as is known, there are only two relatively stable compounds of zirconium and hafnium which will undergo distillation, they are $1.5 \text{ MCl}_4 \cdot \text{POCl}_3$ and $1.5 \text{ MCl}_4 \cdot \text{POCl}_3$ where M refers to the metal. It is reported however that commercial zirconium tetrachloride melts at 437°C . and 25 atmospheres (82). If this is true, it is conceivable that a distillation of the tetrachlorides of these elements could be carried out. However, since it would have to be under pressure, the method would be less desirable.

The theory of distillation is quite well established, and presumably the system could be treated as a simple binary solution composed of $1.5 \text{ ZrCl}_4 \cdot \text{POCl}_3$ and $1.5 \text{ HfCl}_4 \cdot \text{POCl}_3$, other materials present in such small amounts that they could be disregarded.

The difference in boiling points of the two phosphorus oxychloride complexes is apparently very small, and the pure

hafnium complex has not been produced. The boiling point difference is, however, in the range of five to ten degrees centigrade. Because the concentration range is small, the temperature drop across a column is practically zero. Even with complete separation, the change in temperature has been shown to be small, (56) and accordingly the operation approaches adiabatic conditions.

As previously cited the relative volatility for this system has been determined by D. M. Gruen and J. J. Katz (56) as 1.14, and with this value an equilibrium curve has been calculated (Table I) and plotted in Figure 1. The equation for this procedure was the standard form, (105).

$$y = \frac{\alpha x}{1 + (\alpha - 1)x}$$

The commercial zirconium tetrachloride contains approximately a hafnium-zirconium ratio by weight of 3/100. It is desired to remove hafnium from the mixture down to a weight ratio of 0.1/100 or less. This was a seemingly small stripping range, yet with the small relative volatility a large number of plates were considered necessary.

In this distillation the hafnium complex, being the lower boiler of the two complexes, will distill faster and the tops product will be rich in hafnium. In batch operations silicon tetrachloride with its low boiling point of 57° C., if present in the system, will distill off early since apparently it does not form a complex. Titanium complex should distill off early in the operation. The ferrous chloride, aluminum,

TABLE I
CALCULATIONS FOR EQUILIBRIUM CURVE

$$y = \frac{\alpha x}{1 + (\alpha - 1)x} = \frac{\alpha x}{(1-x) - \alpha x}$$

x	α	$x\alpha$	$1 + (\alpha - 1)x$	y
.001	1.14	.00114	1.00014	.00114
.002		.00228	1.00028	.00228
.003		.00342	1.00042	.00342
.004		.00456	1.00056	.00456
.005		.00570	1.00070	.00569
.006		.00684	1.00084	.00683
.007		.00798	1.00098	.00797
.008		.00912	1.00112	.00911
.010		.01140	1.00140	.01138
.020		.0228	1.0028	.00273
.030		.0342	1.0042	.03406
.040		.0456	1.0056	.04535
.050		.0570	1.0070	.05660
.070		.0798	1.0098	.07903
.090		.1026	1.0126	.10132
.12		.1368	1.0168	.13453
.15		.1710	1.021	.16748
.20		.2280	1.028	.22178
.30		.3420	1.042	.32821
.40		.4560	1.056	.43181
.50		.5700	1.070	.53271
.60	1.14	.684	1.084	.631
.70		.798	1.098	.7268
.80		.912	1.112	.82014
.90		1.3026	1.126	.91119

and chromium complexes remain as impurities in the bottoms product (20). In the case of a continuous operation the tops product will be contaminated with the low boiling impurities, the bottoms product, with the high boiling impurities.

Batch distillations have been carried out successfully by D. M. Gruen and J. J. Katz, and the Foote Mineral Company, Philadelphia, Pennsylvania. The data from these sources are shown in Table II and Plotted in Figure 2. It has been noticed

**Figure 1. Calculated Equilibrium Curve,
 $1.5 \text{ HfCl}_4 \cdot \text{POCl}_3 - 1.5 \text{ ZrCl}_4 \cdot \text{POCl}_3$**

that the data as obtained by D. M. Gruen and J. J. Katz, and the data from a few runs from the Foote Mineral Company agree exceptionally well. These data as taken from the original reports were in the form of Hf/Zr ratios x 100 by weight and were converted to mol per cent before plotting on Figure 2.

Since batch distillation results had been in substantial agreement between the Argonne and Foote Laboratories it was decided to direct the attention of this investigation to the continuous procedure, particularly as a continuous distillation procedure has three distinct advantages over the batch operation.

(85)

- (1) Uniform and high grade product
- (2) Heat economy
- (3) Labor economy

A uniform and high grade product is the result of the constant conditions which exist at any particular point in the system, once equilibrium has been established. There is a continuous and uniform change in the material passing through the system, but a constant set of conditions for any particular point in the system from one time interval to the next. Conversely in a batch operation, the conditions are constantly changing not only for any point within the system, but also for the end conditions. The composition of the material leaving the system is constantly changing, and because of this, a non-uniform product results. The heat economy of a continuous operation comes from the absence of the numerous intermediate fractions which use up large quantities of heat

TABLE II - BATCH DISTILLATION DATA

Gruen and Katz				Foote Mineral Company							
Tops	Tops	Residue	Residue	Run D-2				Run D-4			
Fraction	Fraction	Hf/Zr x	Mol % Hf	Tops	Tops	Resi-	Resi-	Tops	Tops	Resi-	Resi-
Hf/Zr x	Mol % Hf	100	Complex	Frac-	Fraction	due	due	Frac-	Frac-	due	due
100	Complex			tion	Mol % Hf	Hf/Zr	Mol %	tion	tion	Hf/Zr	Mol %
				Hf/Zr	Complex	x 100	Hf Com-	Hf/Zr	Mol %	x 100	Hf
				x 100			plex	x 100	Hf		Com-
									Com-		plex
									plex		
18.9	8.83	1.44	0.73	8.4	4.1	1.14	0.58	7.20	3.55	1.84	0.94
10.4	5.05	.77	.39	3.9	1.95	0.56	.285	10.00	4.86	1.20	.61
5.2	2.59	.36	.18	3.05	1.54	0.21	.11	5.36	2.66	.75	.38
1.7	.86	.29	.15	1.28	.65	0.05	.026	4.50	2.25	.40	.20
1.0	.51	.26	.13					1.17	.595	.185	.095
1.4	.71	.17	.087								
0.94	.48	.13	.066								
0.25	.13	.12	0.061

in the batch processes. The labor economy for the continuous operation is due to the few intermediate products which must be handled while the batch process needs a relatively large number of unskilled laborers for this work.

There are two factors often against a continuous operation, and in favor of a batch operation. They are:

- (1) Excessive initial cost of apparatus
- (2) Complicated construction and operation

The excessive first cost of the continuous plant in this case can be shown to be a factor negligible with reference to the operating cost, and no complicated construction appears to be necessary.

For the particular system under investigation the continuous operation holds additional advantages. Some of these are:

(1) Freedom from contact of materials with moisture, which causes a decomposition reaction resulting in a non-distillable compound.

(2) Less contact of personnel with vapors, which are both toxic and highly irritating.

(3) Less decomposition of the complex because of a short heat contact time. It was noted later that there were indications of some type of decomposition due to heat.

(4) Excess phosphorus oxychloride may be recovered in the continuous process.

The method for reporting the hafnium concentrations in zirconium compounds is not uniform. Accordingly, several

methods for converting Hf/Zr x 100 by weight to various other forms are presented.

The molecular weights: Hf = 178.6, O = 16, Cl = 35.46, P = 30.98, Zr = 91.22.

$$\frac{1.5 \text{ Hf}}{1.5 \text{ HfCl}_4 \cdot \text{POCl}_3} = \frac{267.9}{634.04} = 0.4225 \quad \text{Ratio of Metallic Hafnium in } 1.5 \text{ HfCl}_4 \cdot \text{POCl}_3$$

$$\frac{1.5 \text{ Zr}}{1.5 \text{ ZrCl}_4 \cdot \text{POCl}_3} = \frac{136.83}{502.95} = 0.27205 \quad \text{Ratio of Metallic Zirconium in } 1.5 \text{ ZrCl}_4 \cdot \text{POCl}_3$$

Conversion to Weight per cent $1.5 \text{ HfCl}_4 \cdot \text{POCl}_3$ in mixture =

$$\frac{\text{Hf}}{\text{Zr}} \times 100 \left(\frac{0.27205}{0.4225} \right) \times \frac{1}{100} = \text{Weight Ratio} = a$$

$$\frac{a}{1 + a} \times 100 = \text{Weight Per cent } 1.5 \text{ HfCl}_4 \cdot \text{POCl}_3 \text{ in mixture} = b$$

Conversion to weight per cent metallic hafnium in mixture:

$$b \times 0.4225 = \text{Weight per cent metallic hafnium in complex mixture.}$$

Conversion to mole per cent $1.5 \text{ HfCl}_4 \cdot \text{POCl}_3$ in mixture:

$$\frac{\text{Hf}}{\text{Zr}} \times 100 \left(\frac{91.22}{178.6} \right) \frac{1}{100} = \text{Mole Ratio of Complexes} = c$$

$$\frac{c}{1 + c} \times 100 = \text{Mole per cent } 1.5 \text{ HfCl}_4 \cdot \text{POCl}_3 \text{ in mixture.}$$

EXPERIMENTAL

Preliminary Investigation

Before any distillation work was begun, it was desirable to establish the nature of the materials which were to be used and to check certain of the constants which were available in the literature.

It was observed that the zirconium tetrachloride was a light tan color and that it apparently reacted with moisture. This reaction took place spontaneously, upon contact with air, and gave off hydrogen chloride, with an apparent formation of zirconium oxychloride. The pure zirconium tetrachloride is supposedly a white salt, and the color in the commercial grade may be attributed to impurities in the nature of iron, aluminum, titanium, etc.

The $1.5 \text{ ZrCl}_4 \cdot \text{POCl}_3$ complex was prepared very readily. A quantity of zirconium tetrachloride was transferred to a flask and an equal molal weight of phosphorus oxychloride was added slowly to avoid foaming. The reaction was exothermic to a certain degree. After the mixture had spontaneously reacted, apparently to completion, there was a light tan, porous, spongy solid and a quantity of phosphorus oxychloride left in the bottom of the flask. By gently applying heat, the spongy mass apparently reacted further with the phosphorus oxychloride and seemed to melt to a dark green liquid.

In preparing the phosphorus pentachloride complex it was necessary to alter the method somewhat, since both compounds are solids. Equal molar quantities of the zirconium

tetrachloride and the phosphorus pentachloride were used in this case also, but these powdery solids were mixed thoroughly and heated. This reaction was not exothermic or spontaneous and it was necessary to apply heat throughout the reaction period. This reaction similarly produced a dark green liquid.

The removal of the excess phosphorus oxychloride in the preparation of $1.5 \text{ ZrCl}_4 \cdot \text{POCl}_3$ was accomplished by distillation. The excess phosphorus pentachloride used in the preparation of $1.5 \text{ ZrCl}_4 \cdot \text{PCl}_5$ was sublimed off. In each case when a dark green liquid appeared to be refluxing in the flask, it was assumed that the excess phosphorus compound had been removed.

No attempt was made to verify the composition of either of the complexes. A. E. Van Arkel and J. H. De Boer established the composition as 2 moles of zirconium tetrachloride to one mole of either the phosphorus oxychloride or the phosphorus pentachloride. The later work by D. M. Gruen and J. J. Katz has cast considerable doubt on these figures however, and their experiments placed the ratio of zirconium tetrachloride to either of the two phosphorus compounds between one and one and a half to one. The exact stoichiometry of the compounds, therefore, has not been definitely established, but the formulas appear to be as follows:

and will be accepted as such for this work.

The melting and boiling points of both the phosphorus pentachloride and the phosphorus oxychloride complexes were compared with the literature values.

The boiling points were obtained in an oil bath while the melting points were obtained not only in a similar bath, but also with the use of a Fischer-Johns melting point apparatus. The data are shown in Table III and verify the literature values exceptionally well. It is recognized that these values for the zirconium compounds are inaccurate to the extent that the zirconium tetrachloride is impure, as it contains approximately a Hf/Zr ratio of 3/100 by weight.

Since the exact stoichiometry of the complexes has not been established a question of the stability of these materials was raised. It was necessary that the complexes only be stable enough to undergo a distillation and a check was considered to be satisfactory for this purpose.

A fresh batch of the 1.5 $\text{MCl}_4 \cdot \text{POCl}_3$ complex was prepared and a small amount placed in a test tube. The melting point of this specimen was obtained, and the test tube and its contents weighed. The sample then was heated to a slow reflux for thirty-six hours and after this time the melting point and weight again obtained. There was no noticeable change in either of these values. It was observed also that the boiling point did not change during the period of reflux and there was no change in the appearance of the complex.

The same stability test was conducted on the 1.5 $\text{MCl}_4 \cdot \text{PCl}_5$ complex with the same results. On the basis of these

TABLE III
MELTING AND BOILING POINT DATA

	Literature Value Melting Point ° C.	Experimental Value Melting Point ° C.	Literature Value Boiling Point ° C.	Experimental Value Boiling Point ° C.
1.5 ZrCl ₄ .POCl ₃	-----	80° - 130°	360	363
1.5 ZrCl ₄ .PCl ₅	164.5	166	410	416

results, it was concluded that both of the complexes were stable enough to undergo distillation.

Since it was contemplated that this investigation was to be the forerunner of a pilot plant design, a series of simple corrosion tests were made.

A quantity of freshly prepared 1.5 $\text{MCl}_4 \cdot \text{POCl}_3$ was prepared and placed in a test tube. Strips of copper, 302 type stainless steel, 304 type stainless steel, and black iron were placed in the test tube. The corrosion specimens were arranged so that they would be in contact with both the liquid and refluxing vapor, but not each other. After a period of 24 hours of reflux, the specimens were removed for examination. The copper and black iron had been severely attacked and could not be recommended as materials of construction in contact with this complex. The two specimens of stainless steel showed no corrosion and although checked with a micrometer, no reduction in diameter was indicated. These two stainless steel specimens were returned to the refluxing complex for a second twenty four hour period. Again there was no evidence of corrosion.

This same type of test was performed using the 1.5 $\text{MCl}_4 \cdot \text{PCl}_5$ complex with the same general results. However, the corrosion of the copper and black iron was more severe than with the phosphorus oxychloride complex. The stainless steels were tested for the extra twenty-four hours, and as before showed no corrosion. Accordingly, it was judged that a stainless steel would be satisfactory for construction purposes on a corrosion standpoint. Further tests should, however, be conducted in

order to establish which of the stainless steels would best serve the purpose or if the protection might be either temporary or coincidental.

Batch Distillation:

The work of D. M. Gruen and J. J. Katz at the Argonne National Laboratories, Chicago, Illinois, established that the zirconium-hafnium separation could be performed by batch wise distillation in an Oldershaw column of the phosphorus oxychloride complexes as had been reported by A. E. Van Arkel and J. H. De Boer.

Since several abnormalities appeared in investigations from both groups, and since rather accurate information was desirable, it was chosen to supplement the data with an independently determined set of figures.

A one inch diameter packed column, seven feet high was erected and topped with a specially designed dividing head as shown in Figure III. A packed column was chosen to furnish comparative data as well as to obtain the information for the previous checking. This column was heated with electric heating mantles covered with glass fabric and the heating mantles for the two liter flask which served as a still were covered with a quartz cloth. The dividing head was heated with infrared lamps to prevent the complex from freezing. These heating lamps were used to control the rate of tops product removal, which in turn influenced the reflux ratio, in the column. Variacs were used to control the power input to the heating

Figure 3. Batch Distillation Column.

TABLE IV - BATCH DISTILLATION DATA

Bottoms		Tops	
Hf/Zr X 100	Mol % Hf Complex in Mixture	Hf/Zr X 100	Mol % Hf Complex in Mixture
Column at Equilibrium			
2.4	1.21	14.0	6.67
300 gram fraction removed			
2.2	1.11	15.5	7.34

mantles on the column, with the temperatures measured with iron-constantan thermocouples placed, at intervals, between the heating elements and the glass columns. Berl saddle packing, one quarter inch nominal diameter, was selected because of its large surface area and low frictional resistance. Before attaching the still pot to the column, a slow stream of nitrogen was allowed to flow through the column for fifteen minutes to remove all of the air and moisture.

A 2200 gram batch of complex was prepared as described previously and which filled the two liter boiling flask somewhat more than 50 per cent. It was attempted to bring the column and still to operating temperature as evenly as possible to avoid the thermal strains. It was recognized that the temperature of boiling, 360° C., was approaching the danger point of glass, and extreme care would have to be exercised. In spite of all the precautions, considerable breakage occurred during the work, possibly because a 360° C. temperature in the flask necessitated an outer surface temperature at least twenty to twenty-five degrees higher.

Standard taper joints were used in the original distillation apparatus, but these were unsatisfactory for two reasons:

- (1) Leaks, which apparently were unavoidable, and
- (2) Difficulties in taking the joints apart, after long exposure to the complex and heat. Various methods for sealing the joints were tried in an attempt to prevent leaks, and to permit disassembly at a later date but none were completely

satisfactory. The difficulty of taking these joints apart is attributed to (1) reaction of the complex with sulfuric acid to produce zirconium sulfate, and (2) the reaction of the complex with moisture to produce what appeared to be a ceramic material. When the latter was heated sufficiently to permit softening of the seal material, the glass around these sections became brittle. The complex could be observed working its way into the joint and forming a white deposit, which appeared to be a reaction compound, causing the major difficulty in separating the joints. This same type of formation occurred whether or not sulfuric acid was present and seemed to be similar to the hydrolysis products.

The difficulties encountered with standard taper joints led to the substitution of ball and socket joints wherever standard taper joints failed. This substitution did not alleviate all of the trouble with joints, but helped considerably. Taking the ball and socket joints apart became fairly easy when the joint was in a position as to permit heating below the socket section. The heating apparently caused sufficient expansion to break the seal formed by the complex and its reaction products. Heating the joint itself did not effect a separation, as both parts expanded equally. In the use of ball and socket joints a fine valve grinding compound was tried, for additional seating purposes, and was found to be quite good. It was necessary however, to prevent this valve grinding compound from entering the column, as the oil in the valve grinding compound, with the

complex, produced a black flaky solid.

In the initial operation of the column, it was noticed that a quantity of colorless liquid rose in the column and refluxed first in the dividing head. Fumes from the condenser indicated that this material was phosphorus oxychloride. The phosphorus oxychloride gradually became less and as the last of this material was removed through the condenser a white curdy material was deposited on the walls. It was supposed that a portion of this curdy material was from impurities such as a titanium complex, or from hydrolysis products of the zirconium material itself. All of these phenomena normally took place before any significant amount of complex was found in the dividing head. As the complex in the still approached boiling conditions, more of this curdy solid material appeared and continued to form even though the temperature of the column was at 360° C. As the dark fumes of complex rose in the column, the white solid was seemingly dissolved, reevaporated, and pushed up the column ahead of the refluxing liquid, until it reached the condenser. The refluxing liquid showed a graduated color change, over the length of the column. The complex was a dark green to black liquid in the still pot, but in higher sections of the column the liquid became amber, fading to pale yellow, and eventually to a clear liquid at the top. The color was probably from iron impurities in the zirconium tetrachloride remaining in the lower portion of the still and removed by fractionation as the complex moved up the column. Once a fairly stable thermal state had been reached, by regulating power input to the heating

mantles, a period of three hours was considered necessary for the system to reach equilibrium. Accordingly, the column was operated at total reflux during all of this time. Total reflux was accomplished by allowing the complex in the tops product take off arm to freeze and by keeping the condenser and return line to the column open with infra-red heating lamps.

At the end of three hours a sample was taken off the condenser by melting the complex in the take off arm and collecting a specimen of freshly condensing vapors. By means of a siphon arrangement in a side opening of the still pot a sample of the bottoms product was withdrawn by application of a partial vacuum.

After the samples were taken, a fraction was removed slowly from the dividing head at an approximate rate of 2.5 grams per minute. This fraction normally had a weight of about three hundred grams. The rate of removal was very slow, as indicated and it was assumed that equilibrium had been maintained in the column. Therefore, within a short time another series of samples were taken for analysis. Data on the first operations, with analysis are shown in Table IV and plotted on Figure II.

Upon the removal of the still pot from the batch column, after the first equilibrium test run it was observed that a solid mass had been formed in the bottom of the still pot. This layer of solid next to the glass, cut down the heat transfer, and caused a dangerous rise in temperature. The formation can and did cause the glass to become over

heated. On occasions this overheating of the glass actually resulted in the bottoms being melted from the flask. The weight of the formation was too large to be considered as arising from impurities only, and was supposed to be some decomposition product due to heating of the complex, although it had not been expected.

Experimental Distillations

Due to operating difficulties, it was found that with the equipment available it was not feasible to attempt a truly continuous operation. However, it was desirable to produce zirconium of low hafnium concentration, and this led to the adoption of a modified technique.

The complex was prepared in a manner similar to that previously described, in gallon size stainless steel beakers. Tops were fashioned for these beakers in order to facilitate the distillation of the freshly prepared complex and to remove the non-volatile portions.

The first experimental column was a simple stripper, with a feed inlet on the top plate and a dividing head as on the previously batch column (shown in Figure IV).

Freshly prepared and distilled complex was charged into the hot column through the feed inlet by siphoning molten complex from an auxiliary flask. Heating the feed flask produced sufficient pressure over the complex to force it through the feed line and into the column. The bottoms product take off was through a siphon from the still pot and extending into a receiver, which was connected to a vacuum line. When it was desired to remove the bottoms product, a controlled

Figure 4. Stripped Column.

vacuum on the receiver drew over the required material.

In order to prevent a continuous flow of vapors and/or liquid in the auxiliary lines, molten complex was frozen in them when the desired amounts had passed. This freezing of the complex in these glass lines often caused breakage and interruption of operations. However, no completely satisfactory method of control was found to replace this rather crude procedure.

Complex was charged into the column at a rate of one thousand grams in thirty minutes and was intermittent as a period varying from 30 minutes to 2 hours was permitted between recharging. Although a completely continuous operation was desired this was the slowest rate at which it was possible to charge, the column with the equipment available and therefore an intermittent operation was obtained. The top product was removed continuously at a varying rate, averaging approximately three grams per minute. The bottoms was taken off in batches and in an amount roughly equivalent to the quantity of tops removed. The total of the tops and bottoms corresponded to the preceding feed weight when figured on a relatively long time interval. A quantity of complex amounting to approximately five hundred cubic centimeters or one thousand grams, remained in the column and pot at the end of each cycle of operations. The operation was repeated after the removal of the bottoms fraction.

The feed inlet for this column was a part of the dividing head and probably because of the thermal strains placed on the glass during periods of feeding and the freezing

of the feed line, the apparatus did not function satisfactorily. The samples that were obtained gave analyses that showed the desired separation was not being accomplished. In order to remove the mechanical difficulties of feeding, and to give better separation, it was decided to make the column taller and place the feed at an intermediate point.

A new column was designed, and is illustrated in Figure V. This last modification was the one on which the remainder of the experimental work was performed. The column provided the maximum height of vapor travel which was possible to obtain as it then approached the ceiling. The column height, exclusive of the still pot and the condenser was nine feet. The feed inlet was placed two feet below the condenser and seven feet above the still pot. This column was operated similarly to that previously used with one exception. The section of the column above the feed line was operated as a partial condenser. By controlling the power input in the insulation of this section it was possible to control the amount of vapor which reached the dividing head. A partial control was thus maintained over the reflux ratio as in this way the amount of product take off was regulated. It was impossible to maintain the tops product take off at a constant rate however, as can be seen in the time log.

The time log of this series of operations with the analysis of the samples is shown in Table V. The column was operated for three days without a complete shutting down, even

though difficulties were encountered with glass breakage. The bottoms product from this continuous operation was contaminated with large quantities of undesirable compounds, which apparently were in the original material as well as the non-distillables which formed during operations.

In order to rid the complex of these impurities a cleansing distillation was carried out in a thirty plate Oldershaw column. As was observed in the packed column the complex on the lower plates was amber, and the color faded to pale yellow and to a clear watery material at the top. By controlling the heat on the still pot, the clear white liquid was distilled over leaving all colored material as a residue.

Analyses of samples were made spectrographically by a method developed by C. Feldman (31). The chemical preparation of the samples for spectrographic analysis was proposed by D. M. Gruen and J. J. Katz (53).

TABLE V - TIME LOG FOR PACKED COLUMN OPERATION

Date	Time	Feed Wgt. gm.	Feed Label	Feed Analysis Hf/Zr x 100	Bottoms Wgt. Gm.	Bottoms Label	Bottoms Analysis Hf/Zr x 100	Tops Wgt.	Tops Label	Tops Analysis Hf/Zr x 100	Rat of Tops Removal 9m/min.
8/22/49	10:00)	1000	M-5	4.2							
A.M.	10:30)										
P.M.	1:00				341	B-1	2.44	566	T-1	4.22	3.15
	1:15)	1000	M-5	4.2							
	1:45)										
	2:30				312	B-2	2.35	566	T-2	4.55	6.28
	2:45)	1000	M-1	3.0							
	3:15)										
	4:00				170	B-3	2.00				
	4:15)	1400	M-2	4.1							
	4:45)										
	5:15				1360	B-4	2.4	1160	T-3	3.77	7.03
		B-4 ran thru column without any hold up time									
	5:30)	1200	M-3	4.78							
	6:00)										
	7:45	No bottoms available for removal									
	7:45)	1000	M-4	4.06							
	8:15)										
	10:15				481	B-5	1.42	865	T-4	2.7	2.88
	10:30)	1000	M-6	4.6							
	11:00)										
8/23/49	1:00				500	B-6	1.59	600	T-5	3.4	3.63
A.M.	1:15)	1000	M-7	3.73							
	1:45)										
	3:30				100	B-7	1.32	600	T-6	3.24	4.00
	3:45)	1000	M-11	2.75							
	4:15)										
	7:15				500	B-8	1.27	350	T-7	4.2	1.79
	7:30	Bottoms take off line broken, column at total reflux									
	9:30	Column Repaired									
	9:45)	1300	B-4	2.4							
	10:15)										

TABLE V (Cont.) - TIME LOG FOR PACKED COLUMN OPERATION

Date	Time	Feed Wgt. gm.	Feed Label	Feed Analysis Hf/Zr X 100	Bottoms Wgt. Gm.	Bottoms Label	Bottoms Analysis Hf/Zr X 100	Tops Wgt. gm.	Tops Label	Tops Analysis Hf/Zr X 100	Rate of Tops Re- moval gm/min.
P.M.	3:00	Column operation started again									
	5:30										
	5:45	)1400	M-8	1.31							
	6:15	)									
	7:30				500	B-10	1.77	500	T-9	4.38	
	7:45	)1400	M-9	1.74							
	8:15	)									
		Feed line broken, column refluxing, no tops removal									
8/24/49	1:00	Column repaired, tops fraction coming off									
A.M.	4:20				1100	B-10A		500	T-10	10.1	
	4:45	Bottoms take off arm broken, column at total reflux									
	9:30	Column Repaired									
	9:45	)1100	B-10A								
	10:15	)									
P.M.	7:00				182	B-11	1.6	686	T-11	3.35	
	7:15	)1400	M-10								
	7:45	)									
	11:00				1000	B-12	1.52	400	T-12	3.6	
	11:15	Column operation terminated

Figure 5. Production Column.

PHYSIOLOGICAL OBSERVATIONS

The safety precautions necessary in dealing with zirconium tetrachloride and phosphorus oxychloride have been published and since the work here deals primarily with the complex salts, they will not be dealt with here.

The complex formed from these two compounds is both dangerous and unpleasant to work with because of the decomposition products which result from the reaction of the complex with moisture even in the atmosphere, and which produces primarily hydrochloric acid with possibly some chlorine and phosphine.

Inhaled vapors and fumes cause severe coughing, sore throat, and congestion of the lungs, resulting in a "wheezing". These effects do not appear to linger or spread to other parts of the body, and the results of a minor exposure may be thrown off by the body in a few days. In like manner, the fumes irritate the mucous membranes of the eyes, creating tears and smarting. This irritation of the eyes persists for some hours after exposure, and boric acid solution should not be used to halt this irritation. Plain water appears to bring some relief, but is not satisfactory.

Fumes and vapors of the complex produce stinging and irritation of the skin, but if they are not hot, washing with water quickly removes the unpleasantness. If the vapors are hot, a burn results but if exposure to hot fumes or vapors is not excessive, only itching and scaling of the skin will occur.

By observing the proper precautions for hydrochloric acid, phosphorus oxychloride, and for burns, the harm from exposure to the fumes and vapors can be reduced to a minimum.

There have been no cases of zirconium or hafnium poisoning reported in the literature, the toxicity of each is considered very low, and the effect is not cumulative (32).

SUMMARY AND CONCLUSIONS

The preparation of zirconium, hafnium complex mixtures was found to be comparatively simple, and the melting and boiling points of the complexes compared favorably with those reported by other investigators. The phosphorus oxychloride complex however does not have a true melting point, softening at 80° C. and beginning to flow at 130° C., and in this respect, act as a tar or viscous solution. It was observed that the phosphorus oxychloride complexes were sufficiently stable to undergo fractional distillation and preliminary investigations indicate that the same is true for the phosphorus pentachloride complexes. Results indicate neither the formulae $2\text{MCl}_4 \cdot \text{POCl}_3$ and $2\text{MCl}_4 \cdot \text{PCl}_5$ as proposed by Van Arkel and De Boer nor $1.5 \text{MCl}_4 \cdot \text{POCl}_3$ and $1.5\text{MCl}_4 \cdot \text{PCl}_5$ as proposed by Gruen and Katz are exact for it has been observed that upon successive heating and cooling some gaseous decomposition material was removed from the mixture. This, and the presence of a heavy non-distillable substance in the bottom residue indicate that the complex, if an actual compound, is not completely stable.

The results of the batch distillation investigation parallel those of Gruen and Katz and those of Foote Mineral Company. If corresponding tops fraction and bottoms residue values are chosen from the data of Gruen and Katz and Foote Mineral Company, an average number of theoretical plates of approximately 18 is obtained from Figure I when using Oldershaw columns containing fifty actual plates on one such plate spacing, therefore the plate efficiency is approximately 36 per cent. An H.E.T.P. of five inches was obtained for a

one inch diameter column with 1/4 inch berl saddles with an actual height of packing of 80 inches. This 5 inches H.E.T.P. compares with reported values of 1 inch to 8 inch obtained by other investigators, with various types of packing on similar sized columns. (2)(34)(35). It has been shown that a column working with this material must have positive controls and should be constructed of material able to withstand considerable heat. The operations during this investigation indicate that a continuous distillation procedure for the separation of hafnium from zirconium is quite feasible.

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PART II

AN ENGINEERING APPRAISAL OF ALUMINUM STRUCTURAL MATERIALS

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ABSTRACT

Aluminum tubing was tested to determine the characteristic column strengths, bursting strengths, collapsing pressures, and resistance to fluid flow.

Results of column testing established formulae showing relationship between ultimate unit load, yield point of material, and slenderness ratio. The long column formula or Euler formula was assumed to hold true above the critical slenderness value. Yield points of materials were obtained by plotting the results of compression tests or stress-strain curves.

The bursting strengths of aluminum tubes were obtained by means of a high pressure pump. These values agree quite closely with the Barlow formula.

The results of collapsing pressure tests although agreeing well within themselves do not check closely with Timoshenko's formula.

The fluid flow investigation resulted in friction factors differing slightly for the 2 inch and 4 inch pipe. In general the data were well within the range of accepted values for commercial pipe and smooth tubes, the data for the 2 inch pipe approaching that for smooth tubes and the data for 4 inch pipe approaching values for commercial pipe.

INTRODUCTION

The work presented in this report was conducted at the University of Louisville Institute of Industrial Research under a contract with the Reynolds Metals Company of Louisville, Kentucky. A desire by the Reynolds Metals Company to contribute to the knowledge of aluminum column design, collapsing and bursting of aluminum tubing, and fluid flow characteristics of aluminum pipe prompted the undertaking.

Empirical formulae for the design of concrete, steel, and wood columns are well established. However, similar expressions for aluminum columns are not so well known primarily because of the relatively recent advent of aluminum and its alloys as structural materials. Likewise, in the field of fluid transportation little information is available on bursting and collapsing pressures or the frictional resistance of aluminum tubing to flowing fluids.

The increased use of aluminum in structures as well as in the transportation of fluids has emphasized the need for the design data and mathematical relations established and confirmed in these studies.

Three major phases of the investigation are presented and separately discussed:

Column Testing of Aluminum Alloy Extruded Shapes.

Bursting and Collapsing of Aluminum Alloy Tubing.

Fluid Flow Characteristics of Aluminum Alloy Pipe.

HISTORICAL

At the beginning of the 19th Century aluminum was a laboratory curiosity having no commercial significance. It remained so until the latter part of the Century when Martin Hall developed his now famous electrolytic process for the separation of metallic aluminum from its oxide ore.

This development brought aluminum into commercial production, but because of its softness and lightness several decades went by with comparatively few uses. Some of these uses were as kitchen utensils and for decorative purposes.

However, in 1898 an Austrian named Schwartz constructed an airship with aluminum structural members. It was destroyed on its first landing, but it was only two years later that Zeppelin launched his first rigid airship, which was built of structural aluminum. The structural members were Al-Zn alloy, non-heat treated, but by the standards of that day they functioned satisfactorily.

It was not until 1909 that the first successful heat treatable alloy was developed. This was the alloy which has come to be known as duralumin and was developed by Alfred Wilm. The explanation of this heat treating effect by P. D. Merica led to a new metallurgical principle, which later became important in other metallurgical fields.

Commercial introduction of heat treatable alloys awaited the end of World War I. With their development the guaranteed yield strength of aluminum alloys more than doubled in 20 years. This led to alloys of 60,000 psi tensile strength and 20% elongation, which is comparable with structural steel.

Prior to World War II practically all of the structural aluminum produced was utilized by the aircraft industry. Only a small percentage went to other types of structures most of which were experimental. However, the war brought on increased production and greater knowledge which led to lower prices and placed aluminum in competition with all structural materials.

Aluminum alloys of high corrosive resistance, which retain their strength have led to new uses and almost unlimited opportunities. The first section of aluminum pipe lines have been laid, since World War II, in the oil fields of Louisiana and experimental work is under way to use it in oil well casings. These are only two of the numerous use to which aluminum structural alloys are being adapted.

**COLUMN TESTING OF ALUMINUM ALLOY EXTRUDED
SHAPES**

THEORETICAL

Any object which undergoes axial loading is known as a compression member. These compression members will bend even with axial loads. When a compression member is so slender that the allowable end load must be reduced because of the bending stresses, it is termed a column.

It has been the object of the column evaluation work to determine a mathematical expression for the loading characteristics of columns as defined above.

Columns may be divided into two classes: long columns and short columns. Long columns have been examined mathematically and a rigorous equation developed by Euler as early as 1757. They are defined as columns which fail because of lack of stiffness, inelasticity, and the ultimate load being reached before the average stress has passed its proportional limit.

One form of Euler's Equation is:

$$P/A = \frac{R^2 E}{(L/r)^2}$$

Where:

P = total load in pounds.

A = area in square inches.

E = modulus of elasticity.

L = length in inches (effective).

r = radius of gyration in inches.

This equation is applicable to all columns as long as the proportional limit is not exceeded by the load on the column. This report, however, is not primarily concerned with the long or

Euler columns, as they are sometimes called, but is concerned with the short column.

Short columns may be defined as those in which stresses throughout the column have exceeded the proportional limit of the material long before the ultimate load is reached. This action brings about a considerable amount of inelastic action during the process of loading. While the theory of long columns has been known for several hundred years, it was not until the present century that short columns were handled on a rational basis, by Considere, Engesser, and others. The mathematical treatment, however, does not lend itself to practical design and, therefore, many empirical equations have been devised for materials in the short column range.

Aluminum members have the greatest use where light weight is advantageous, particularly in the aircraft industry, and in this field, equations following the experimental results comparatively closely are essential. Accordingly, many complicated equations have been devised. With the decrease in the cost of aluminum it is tending to come into competition with many other structural materials emphasizing the need of simple design formulae. The two types of equations that are most frequently used in the short column range are the parabolic and straight line forms as shown below.

Straight Line Equation:

$$P/A = D - B (L/r)$$

Parabolic Equation:

$$P/A = D - C (L/r)^2$$

Where:

$D = P/A$ intercept where $L/r = 0$

B and $C =$ Empirically determined constants

These equations must follow experimental results and they must either meet or intersect the Euler Equation. The point of meeting or intersection is known as the critical point, or the critical slenderness-ratio. For a slenderness-ratio above that point, the columns are long or Euler columns, for values below the critical, the columns are short.

The slenderness ratio is dependent upon (a) physical dimensions, and (b) the method of fixing the ends or the end conditions. The end-fixity has been incorporated into the slenderness ratio with the factor K converting the slenderness-ratio to an effective slenderness ratio $(K)(L/r)$. It has been shown that for columns of round or pinned-end conditions, the value of K is 1, i.e. the entire column bends when loaded. For fixed ends, $K = 0.5$ which means that only one half of the total length undergoes bending when loaded. When one end is fixed and one end is pinned or round, $K = 0.7$.

EXPERIMENTAL

The column testing was conducted on a Baldwin Southwark Testing Machine equipped with a Tate Emery load indicator. The dial has three scales; (1) 0 to 40,000 lbs.; (2) 0 to 160,000 lbs.; (3) 0 to 400,000 lbs. The rate of loading of test specimens was 2000 lbs./min., except for a few specimens of small cross sectional area which were loaded as constantly and as slowly as possible.

To obtain a pinned end, a spherical nosed hardened circular steel plate was used. This assembly was not frictionless, but results in preliminary testing justified its use. To obtain a fixed end, a series of brass bushings were used to fit tightly to the specimen and clamped into a steel ring bolted to a large steel plate. For fixed ends for the channel and angle columns steel blocks clamped into position were used.

The columns were placed in the machine and by means of a level and tripod to support the specimens, under a slight load they were adjusted to a vertical position. The tripod was removed before actual testing was started. The loading was then begun and continued until failure, as indicated by a reversal of the direction of travel of the loading needle. Where possible, three specimens were tested for each length and end condition.

It was apparent that the ultimate strength of the material would be helpful in stabilizing graphical representations of the data in the register of low values of L/r . This value was determined by the use of strain gage data in plotting a

stress-strain curve. Such data were obtained from tests made with a Riehle Testing Machine, Mechanical Type, 100,000 lb. capacity, in the materials testing laboratory of the University of Louisville, Civil Engineering Department. These data are shown in Table I and Figures 1 through 5.

The columns as tested included the materials and shapes as shown in Table II and specified by the Reynolds Metals Company.

Test results for each alloy and each shape were plotted as a straight line for all values of the slenderness ratio above and below the critical and are shown in Tables III through XIV and Figures 6 through 14.

TABLE I - STRESS-STRAIN DATA

Sample	Run No.	Reading	$\frac{L}{r}$	Unit Stress (psi)	Unit Strain
3S-0 0.065 in. x 1.00 in. Tubing*	1	1	12	2,630	0.000133
		2		5,260	.000166
		3		7,900	.002560
		4		10,550	.009400
	2	1	12	2,630	0.00010
		2		5,260	.000166
		3		7,900	.002660
		4		10,550	.00957
R361-0 0.194 in. x 1.58 in. Tubing	1	1	10	1,250	0.0000666
		2		2,500	.000200
		3		3,750	.000400
		4		6,250	.0021
		5		8,750	.00717
		6		9,600	.0085
	2	1	10	1,250	0.000066
		2		2,500	.00020
		3		3,750	.000466
		4		5,000	.000866
		5		6,250	.002040
		6		10,000	.00953
R361-T4 0.238 in. x 1.718 in. Tubing	1	1	10	5,440	0.000567
		2		10,890	.00110
		3		16,330	.00173
		4		21,780	.00323
		5		27,220	.00833
	2	1	10	5,440	0.000567
		2		10,890	.001133
		3		16,330	.00170
		4		21,780	.00323
		5		26,020	.01000
R361-T6 0.238 in. x 1.625 in. Tubing	1	1	10	4,980	0.00534
		2		9,960	.0011
		3		14,940	.001633
		4		19,900	.002233
		5		24,900	.0028
		6		29,875	.00343
		7		34,850	.00444
		8		39,060	.01000

* Shape dimensions are expressed as inches wall thickness x inches outside diameter.

TABLE I - STRESS-STRAIN DATA (Cont'd)

Sample	Run No.	Read- ing	$\frac{L}{r}$	Unit Stress (psi)	Unit Strain
R361-T6	2	1	10	4,980	0.000534
0.238 in.x		2		9,960	.0011
1.625 in.		3		14,940	.001633
Tubing		4		19,900	.00220
		5		24,900	.002766
		6		29,875	.003366
		7		34,850	.0044
		8		39,060	.01000
63S - T	1	1	10	4,540	0.000466
0.3125 in.x		2		9,080	.000833
1.875 in.		3		13,620	.001266
Tubing		4		18,160	.001700
		5		22,700	.002166
		6		27,240	.002900
		7		31,780	.00567
		8		33,720	.01000
	2	1	10	4,540	0.000433
		2		9,080	.000867
		3		13,620	.001300
		4		18,160	.001767
		5		22,700	.00260
		6		27,240	.002933
		7		31,780	.00490
		8		33,720	.01000

Figure 1. Stress-Strain Diagram for 3S-0 Aluminum Tubing

Figure 2. Stress-Strain Diagram for R361-0 Aluminum Tubing.

Figure 3. Stress-Strain Diagram for R361-T4 Aluminum Tubing

Figure 4. Stress-Strain Diagram for R361-T6 Aluminum Tubing.

Figure 5. Stress-Strain Diagram for 63S-T Aluminum Tubing.

TABLE II - MATERIALS AND SIZES OF COLUMNS TESTED

ALLOY	SIZE	SHAPE
3S - O	0.065 in. x 1.00 in.	Tube
3S - H14	0.061 in. x 1.315 in.	"
3S - H14	0.125 in. x 1.5625 in.	"
R361 - O	0.194 in. x 1.58 in.	"
R361 - O	0.254 in. x 1.75 in.	"
R361 - T4	0.238 in. x 1.718 in.	"
R361 - T4	0.064 in. x 1.00 in.	"
R361 - T6	0.238 in. x 1.625 in.	"
63S - T	0.3125 in. x 1.875 in.	"
R361 - T	0.437 in. x 6.00 in.	Channel
R361 - T	1-1/4 in. x 1-1/4 in. x 3/16 in.	Angle
R361 - T	2-1/2 in. x 2-1/2 in. x 1/4 in.	"

TABLE III - COLUMN DATA

3S - 0 Tubing, 0.065 in. x 1.00 in.

Area = 0.19 Sq. Inches

End Condition	Spec. No.	Loading Rate, lb. per min.	$\frac{L}{r}$	Unit Load at Failure psi	Ave. Unit Load psi
Pinned	1 PS 1	2000	174.5	3,420	
"	1 PS 2			3,170	
"	1 PS 3			2,760	3115
"	1 PI 1	2000	194	2,100	
"	1 PI 2			2,370	2235
"	1 PSX 1	2000	96.4	3,950	
"	1 PSX 2			3,950	3950
"	1 PL 1	2000	214	1,710	
"	1 PL 2			1,570	
"	1 PL 3			1,570	1616

TABLE IV - COLUMN DATA

3S - H14 0.061 in. x 1.3125 inches

Area = 0.241 Sq. Inches

End Condition	Spec. No.	Loading Rate, lb. per min.	$\frac{L}{r}$	Unit Load at Failure psi	Ave. Unit Load psi
Pinned	3 PSX 1	2000	54	19,100	
"	3 PSX 2			19,400	19,250
"	3 PS 1	2000	97.5	12,650	
"	3 PS 2			13,300	
"	3 PS 3			12,250	12,670
"	3 PI 1	2000	108	10,400	
"	3 PI 2			10,600	
"	3 PI 3			10,800	10,600
"	3 PL 1	2000	118.5	9,550	
"	3 PL 2			10,200	
"	3 PL 3			8,100	9,280
One Fixed and One Pinned	3 OSX 1	2000	76.8	18,250	
	3 OSX 2	$\frac{KL}{r} =$	53.7	17,850	
	3 OSX 3			19,100	18,400
"	3 OI 1	2000	162.5	9,990	
"	3 OI 2	$\frac{KL}{r} =$	113.8	11,000	
"	3 OI 3			10,800	10,580
Fixed	3 FSX 1	2000	122	15,950	
"	3 FSX 2	$\frac{KL}{r} =$	61	16,800	
"	3 FSX 3			18,700	17,150

No Ultimate Strength of Material Found

TABLE V - COLUMN DATA

3S - H14 0.125 In. x 1.5625 Inches

Area $\pm$ 0.562 Sq. Inches

End Condition	Spec. No.	Loading Rate, lb. per min.	$\frac{L}{r}$	Unit Load at Failure psi	Ave. Unit Load psi
Pinned	4 PSX 1	2000	55	18,600	
"	4 PSX 2			17,900	18,250
"	4 PS 1	2000	97	10,650	
"	4 PS 2			11,350	
"	4 PS 3			10,625	10,875
"	4 PI 1	2000	108	9,800	
"	4 PI 2			9,800	
"	4 PI 3			9,950	9,815
"	4 PL 1	2000	118.5	8,800	
"	4 PL 2			8,850	
"	4 PL 3			8,825	8,835
One Fixed and one Pinned	4 OSX 1	2000	82.4	19,050	
	4 OSX 2	$\frac{KL}{r} =$	57.6	18,900	
	4 OSX 3	r		19,200	19,050
Fixed	4 FSX 1	2000	118	19,400	
"	4 FSX 2	$\frac{KL}{r} =$	59	19,800	
"	4 FSX 3	r		19,200	19,500

No ultimate strength of material found.

TABLE VI - COLUMN DATA

R361 - 0 0.194 In. x 1.58 Inches

Area = 0.80 Sq. Inches

End Condition	Spec. No.	Loading Rate, lb. per min.	$\frac{L}{r}$	Unit Load at Failure psi	Ave. Unit Load psi
Pinned	5 PSX 1	2000	92.5	4000	
"	5 PSX 2			4940	
"	5 PSX 3			5000	4640
One Fixed	5 OSX 1	2000	140.0	4500	
and One	5 OSX 2	$\frac{KL}{r} =$	98	4440	
Pinned	5 OSX 3	r		4130	4360
Ultimate Strength				10000	

TABLE VII - COLUMN DATA

R361 - 0, 0.254 In. x 1.75 In.

Area = 1.195 Sq. In.

End Condition	Spec. No.	Loading Rate, lb. per min.	$\frac{L}{r}$	Unit Load at Failure psi	Ave. Unit Load psi
Pinned	6 PSX 1	2000	85.0	4,700	
"	6 PSX 2			4,900	4,830
"	6 PS 1	2000	170.5	2,300	
"	6 PS 2			2,200	
"	6 PS 3			2,560	2,350
"	6 PI 1	2000	190	1,840	
"	6 PI 2			2,210	
"	6 PI 3			1,300	1,780
"	6 PL 1	2000	209	1,840	
"	6 PL 2			1,840	
"	6 PL 3			1,760	1,810

TABLE VIII - COLUMN DATA

R361 - T4 0.238 In. x 1.718 In.

Area = 1.102 Sq. In.

End Condition	Spec. No.	Loading Rate, lb. per min.	$\frac{L}{r}$	Unit Load at Failure psi	Ave. Unit Load psi
Pinned	8 PSX 1	2000	46.1	22,800	
"	8 PSX 2			21,600	
"	8 PSX 3			22,000	22,300
"	8 PS 1	2000	103.2	10,800	
"	8 PS 2			9,650	
"	8 PS 3			10,950	10,460
"	8 PI 1	2000	114.2	8,900	
"	8 PI 2			9,400	
"	8 PI 3			8,600	8,960
"	8 PL 1	2000	126.1	7,475	
"	8 PL 2			7,210	
"	8 PL 3			7,850	7,510
One Fixed and One Pinned	8 OSX 1	2000	87.3	18,600	
	8 OSX 2	$\frac{KL}{r} =$	61.1	18,300	
	8 OSX 3	r		18,850	18,600
Fixed	8 FSX 1	2000	124.5	17,300	
"	8 FSX 2	$\frac{KL}{r} =$	62.3	17,550	
"	8 FSX 3	r		16,900	17,250
"	8 OI 1	2000	144.9	7,600	
"	8 OI 2	$\frac{KL}{r} =$	101.5	8,030	
"	8 OI 3	r		8,529	8,050
"	8 OL 1	2000	180.3	6,805	
"	8 OL 2	$\frac{KL}{r} =$	126	6,720	6,760
		r			

Ultimate Strength

26,500

TABLE IX - COLUMN DATA

R361 - T4 0.064 In. x 1.00 Inches

Area = 0.189 Sq. In.

End Condition	Spec. No.	Loading Rate, lb. per min.	$\frac{L}{r}$	Unit Load at Failure psi	Ave. Unit Load psi
Fixed	7 FS 1	2000	186	10,600	
"	7 FS 2	$\frac{KL}{r} =$	93.2	13,200	
"	7 FS 3			9,800	11,200
Ultimate Strength				26,500	

TABLE X - COLUMN DATA

R361 - T6 0.238 In. x 1.625 In.

Area = 1.205 Sq. Inches

End Condition	Spec. No.	Loading Rate, lb. per min.	$\frac{L}{r}$	Unit Load at Failure psi	Ave. Unit Load psi
Pinned	9 PS 1	2000	73.2	24,600	
"	9 PS 2			23,950	
"	9 PS 3			23,700	24,080
"	9 PI 1	2000	81.2	21,200	
"	9 PI 2			21,200	
"	9 PI 3			22,400	21,600
"	9 PL 1	2000	89.5	17,100	
"	9 PL 2			16,700	
"	9 PL 3			15,800	16,530
One Fixed and One Pinned	9 OSX 1	2000	65.2	31,500	
	9 OSX 2	$\frac{KL}{r} =$	45.6	31,700	
	9 OSX 3			31,400	31,510
Fixed	9 FSX 1	2000	93.2	30,900	
"	9 FSX 2	$\frac{KL}{r} =$	46.5	30,000	
"	9 FSX 3			29,000	29,970
"	9 FS 1	2000	156	13,850	
"	9 FS 2	$\frac{KL}{r} =$	78.1	13,550	
"	9 FS 3			13,550	13,650
"	9 FI 1	2000	174.5	10,450	
"	9 FI 2	$\frac{KL}{r} =$	87.2	10,300	
"	9 FI 3			10,700	14,480
"	9 FL 1	2000	191.5	8,630	
"	9 FL 2	$\frac{KL}{r} =$	95.8	8,840	8,720
	Ultimate Strength			39,500	

TABLE XI - COLUMN DATA

63S - T 0.3125 In. x 1.875 Inches

Area = 1.542 Sq. Inches

End Condition	Spec. No.	Loading Rate, lb. per min.	$\frac{L}{r}$	Unit Load at Failure psi	Ave. Unit Load psi
Pinned	11 PSX 1	2000	55	26,000	
"	11 PSX 2			25,600	
"	11 PSX 3			27,200	26,260
"	11 PS 1	2000	96.5	13,350	
"	11 PS 2			14,550	
"	11 PS 3			14,050	13,980
"	11 PI 1	2000	107	12,600	
"	11 PI 2			12,750	
"	11 PI 3			12,000	12,450
"	11 PL 1	2000	117.5	9,140	
"	11 PL 2			10,600	
"	11 PL 3			9,260	9,700
One Fixed and One Pinned	11 OSX 1	2000	80.2	24,400	
	11 OSX 2	$\frac{KL}{r} =$	56.2	24,600	
	11 OSX 3			25,000	24,700
Fixed	11 FSX 1	2000	120	23,100	
"	11 FSX 2	$\frac{KL}{r} =$	60	22,450	22,770
	Ultimate Strength			33,500	

TABLE XII - COLUMN DATA

R361 - T 6 In. x 0.437 In. Channel

Area = 3.82 Square In.

End Condition	Spec. No.	Loading Rate, lb. per min.	$\frac{L}{r}$	Unit Load at Failure psi	Ave. Unit Load psi
Pinned	12 PS 1	8000	34.2	27,200	
"	12 PS 2			34,800	31,000
"	12 PI 1	8000	80.8	20,900	
"	12 PI 2			20,000	
"	12 PI 3			19,100	19,700
"	12 PL 1	8000	89.4	16,500	
"	12 PL 2			17,400	
"	12 PL 3			19,200	17,700
One Fixed and One Pinned	12 OS 1	8000	57.7	31,400	
	12 OS 2	$\frac{KL}{r} =$	40.4	34,000	32,100
"	12 OI 1	8000	115.5	24,400	
"	12 OI 2	$\frac{KL}{r} =$	80.8	24,200	
"	12 OI 3			21,000	23,200
Fixed	12 FS 1	8000	92.8	32,100	
"	12 FS 2	$\frac{KL}{r} =$	46.4	32,600	
"	12 FS 3			34,400	33,000
"	12 FI 1	8000	174	12,650	
"	12 FI 2	$\frac{KL}{r} =$	87.1	12,300	12,480

TABLE XIII - COLUMN DATA

R361 - T $1\frac{1}{4}$ In. x $1\frac{1}{4}$ In. x $3/16$ In. Angle

Area = 0.43 Sq. Inches

End Condition	Spec. No.	Loading Rate, lb. per min.	$\frac{L}{r}$	Unit Load at Failure psi	Ave. Unit Load psi
Pinned	13 PS 1	2000	40.6	31,200	
Ends	13 PS 2			30,400	
"	13 PS 3			30,500	30,700
"	13 PI 1	2000	81.2	17,850	
"	13 PI 2			16,250	
"	13 PI 3			16,220	16,770
"	13 PL 1	2000	89.5	15,100	
"	13 PL 2			16,750	
"	13 PL 3			16,700	16,180
One Fixed	13 OS 1	2000	52	28,100	
and One	13 OS 2	$\frac{KL}{r} =$	36.4	28,600	
Pinned	13 OS 3			29,200	28,600

TABLE XIV - COLUMN DATA

R361-T $2\frac{1}{2}$ In. x $2\frac{1}{2}$ in. x $\frac{1}{4}$ In. Angle

Area = 1.19 Sq. Inches

End Condition	Spec. No.	Loading Rate, lb. per min.	$\frac{L}{r}$	Unit Load at Failure psi	Ave. Unit Load Psi
Pinned	14 PS 1	2000	57.5	26,300	
"	14 PS 2			31,500	
"	14 PS 3			28,850	28,880
"	14 PI 1	2000	81.2	21,000	
"	14 PI 2			17,700	
"	14 PI 3			16,100	18,260
"	14 PSX 1	2000	40.4	32,200	
"	14 PSX 2			33,600	
"	14 PSX 3			31,800	32,530
One Fixed and One Pinned	14 OSX 1	2000	58.7	29,100	
	14 OSX 2	$\frac{KL}{r} =$	41.1	27,700	
	14 OSX 3			27,400	28,070
"	14 OI 1	2000	122.5	15,750	
"	14 OI 2	$\frac{KL}{r} =$	85.6	15,800	
"	14 OI 3			14,400	15,320
Fixed	14 FSX 1	2000	93.8	28,850	
"	14 FSX 2	$\frac{KL}{r} =$	46.8	28,900	
"	14 FSX 3			27,100	28,280
"	14 FS 1	2000	158	14,800	
"	14 FS 2	$\frac{KL}{r} =$	79	14,800	
"	14 FS 3			14,850	14,820
"	14 FI 1	2000	174.5	12,450	
"	14 FI 2	$\frac{KL}{r} =$	87.2	13,200	
"	14 FI 3			13,000	12,880
"	14 FL 1	2000	190	10,600	
"	14 FL 2	$\frac{KL}{r} =$	95	10,100	10,250

Figure 6. Unit Load vs. Slenderness Ratio for 3S-0 Tubing Columns,
0.065" x 1.00"; $K = 1, 0.7, 0.5$

○ Pinned Ends.

Figure 7. Unit Load vs. Slenderness Ratio for 3S-H14 Tubing Columns, 0.061" x 1.3125"; K = 1, 0.7, 0.5

○ Pinned Ends, ◐ One Pinned and One Fixed, ● Fixed Ends.

Figure 8. Unit Load vs. Slenderness Ratio for 3S-H14 Tubing Columns, 0.125" x 1.5625"; $K = 1, 0.7, 0.5$

○ Pinned Ends, ◐ One Pinned & One Fixed End, ● Fixed Ends.

Figure 9. Unit Load vs. Slenderness Ratio for R361-0 Tubing Columns, 0.254" x 1.75"; $K = 1, 0.7, 0.5$.

○ Pinned Ends, ○ One Pinned & One Fixed End, ○ 0.194" x 1.75" Fixed Ends.

Figure 10. Unit Load Vs. Slenderness Ratio for R361-T4 Tubing Columns, 0.238" x 1.718"; $K = 1, 0.7, 0.5$.

○ Pinned Ends, ◐ One Pinned & One Fixed End, ● Fixed Ends,
 ○ 0.064" x 1.00" Fixed Ends.

Figure 11. Unit Load vs. Slenderness Ratio for R361-T6 Tubing Columns, 0.238" x 1.625"; $K = 1, 0.7, 0.5$.

○ Pinned Ends, ◐ One Fixed & One Pinned End, ● Fixed Ends.

Figure 12. Unit Load vs. Slenderness Ratio for 63S-T Tubing Columns, 0.3125" x 1.875".

○ Pinned End, ◐ One Pinned & One Fixed End, ● Fixed Ends.

Figure 13. Unit Load vs. Slenderness Ratio for R361-T Channel Columns, 6" x 0.437; $K = 1, 0.7, 0.5$

○ Pinned Ends, ◐ One Pinned & One Fixed End, ● Fixed Ends.

Figure 14. Unit Load vs. Slenderness Ratio for R361-T Angle Columns
 $K = 1, 0.7, 0.5$

$1\frac{1}{2}'' \times 1\frac{1}{2}'' \times \frac{3}{16}''$
 ○ Pinned Ends
 ● Fixed Ends

$2\frac{1}{2}'' \times 2\frac{1}{2}'' \times \frac{1}{4}''$
 ○ Pinned Ends
 ● One Pinned & One Fixed End
 ● Fixed Ends

CONCLUSIONS

On the basis of curves as plotted, the equations in Table XV are suggested as being as nearly correct as is warranted by the small number of columns tested. It is quite likely that with a larger number of test columns greater accuracy could be obtained.

No equation is given for 3S - O tubing because the spread of test results does not warrant one. A single equation is given for material of the same general shape, for example two sizes of tubing. But equations of different value are given for the same material where the shape is different, for example the angles and channels. This treatment was employed not only because it agreed with test data but because it is generally accepted that the shaping does influence the slope of the equation by effecting the actual physical properties of the metal.

TABLE XV
COLUMN FORMULAS

MATERIAL	FORMULA
3S-H14	$P/A = 27,000-155 K(L/r)$
R361-O	$P/A = 8,000-34 K(L/r)$
R361-T4	$P/A = 27,750-167.5 K(L/r)$
R361-T6	$P/A = 42,000-253 K(L/r)$
63S-T	$P/A = 35,500-220 K(L/r)$
R361-T	$P/A = 44,000-290 K(L/r)$
R361-T	$P/A = 44,000-340 K(L/r)$

**BURSTING AND COLLAPSING PRESSURES
OF ALUMINUM TUBES**

THEORETICAL

It has been observed previously that the cost of aluminum in recent years has declined because of increased output and advances in the technological field. This decrease in cost has brought aluminum into competition with many of the so-called standard materials. The bursting and collapsing strength has become important in fluid transportation, since aluminum has high resistance to corrosion and can be extruded as a smooth bore tube. It also finds uses in oil well drilling and pumping. It is here that the collapsing data are very essential. The bursting data are essential because fluids are usually transported under pressure, to increase the rate of flow and reduce costs.

Bursting Theory

The bursting of thick cylinders is shown by Lamé's Solution to follow the equation:

$$\text{Max } S = P \frac{r_2^2 - r_1^2}{r_2^2 - r_1^2}$$

Where:

S = Circumferential Unit stress, lbs/sq. in.

P = Internal fluid pressure, lbs/sq. in.

r_1 = Internal radius of cylinder, inches

r_2 = External radius of cylinder, inches.

Lamé's solution makes two assumptions: (1) that the thick cylinder is composed of a series of thin cylinders each of which has an equal distribution of stresses throughout its thickness and

(2) that the strains of all the longitudinal fibers are equal; that is, the tube maintains its geometric shape. This last assumption does not hold at the closed ends of a cylinder where a distinct change in geometric shape can take place under the influence of internal pressure.

The well known Barlow formula for bursting pressures may be applied to thick cylinders. In this formula it is assumed that the wall thickness and the diameter do not change during the period the specimen is undergoing stress, an assumption which is not exact.

Barlow's formula is:

$$P = \frac{st}{r_2}$$

Where:

P = internal pressure, lbs./sq. in.

t = wall thickness, inches

r_2 = external radius, inches

s = unit stress, inside fiber, lbs/sq. in.

Collapsing Theory

Tubes collapse because of the application of a load which will exceed the elastic limit of the material, or they may fail before the elastic limit is reached due to insufficient flexural rigidity of a cross-sectional circular ring. Failure occurring for the second reason is often far below the elastic limit. This flexural rigidity is insufficient because of two physical deformations, (1) wall becoming thinner in a particular section, (2) slight elliptical shape instead of circular. The elliptical deformation is the more important of the two. For

the case of a circular ring collapsing because of an elliptical formation the following equation has been derived by Timoshenko:

$$q_{cr} = \frac{3 EI}{r^3}$$

Where:

q_{cr} = critical pressure, lbs/unit length

E = modulus of elasticity

I = moment of inertia

r = radius of gyration

The theory of collapsing of tubes follows from this equation, since a tube may be considered as sub-divided into a number of rings. If from a tube a cross section of unit length is cut its moment of inertia is:

$$I = \frac{1 \cdot h^3}{12}$$

and E becomes $\frac{E}{1 - \mu^2}$, where μ is Poisson's Ratio. The above

equation now becomes: $P_{cr} = \frac{Eh^3}{4(1 - \mu^2)R^3}$. This equation holds

Where: h = wall thickness, inches, P_{cr} = Critical, psi,

R = radius of center line of cylinder, inches,

for tubes as long as the proportional limit has not been reached.

In the work herein reported the specimens did not approach the proportional limit in test results, indicating that the specimens failed because of elliptical deformation. A check was made of wall thicknesses to determine whether or not this factor could have contributed to their failure. No deviations of sufficient proportions were found.

Beyond the elastic limit, or after the proportional limit has been reached, the above equation gives values which

are too high. The following equation may be used to represent the critical results:

$$P_{cr} = \frac{h}{R} \frac{1 - 4 \frac{\delta_{yp}}{E} \frac{R^2}{h^2}}{\frac{\delta_{yp}}{E} \frac{R^2}{h^2}}$$

Where:

δ_{yp} = yield point in compression

This discussion has not included the effect which an end closure on a tube would have. It is known that the stresses in a short specimen are altered by the support afforded by the end closures. It is also known that a short specimen will collapse with a series of waves along the circumference. The length usually taken as being a long specimen for these conditions has an $L/r = 20$. The lengths used in these tests gave L/r values from 21 to 12. However, none of the failures corresponded to the short specimen type. All of them failed by a collapse from one side and there was no indication of a series of waves along the circumference. Therefore, it is believed that no correction for this short specimen factor is necessary. However, the end closures would have a tendency to increase the critical pressures.

EXPERIMENTAL

The specimens for bursting were cut six feet long to minimize the influence of the end closures on the strength of the tube. The end closures were made in three parts. A tapered plug was driven into the end of the specimen to enlarge it. A block with a tapered center hole was fitted around the end of the specimen with the tapered plug in position. Into the end of the block and facing the tapered plug a screw was placed to bear against the plug, thereby providing a tight fit. This arrangement was sufficient to prevent the plug from sliding from the tube under pressure, and the tapered grip was adequate to prevent the block from sliding off the specimen, and to prevent leakage. A positive displacement, radial piston pump delivering 3 gal. of hydraulic fluid per minute was used to develop pressure. The fluid was passed into the tube through the end closures. The bursting failure was observed on a pressure gage.

Each specimen for collapsing tests was cut 30" long and the ends machined square in order that they would fit tightly into aluminum blocks used as end closures. These end closures were blocks into which were machined grooves for the various size specimens to fit. The two end closures were joined by a tie rod passing axially through the specimen. The specimen after being thus closed was placed inside a steel tank, of welded construction, with a top which was bolted onto a heavy flange. The same pump used in the bursting tests was used to develop pressure within the tank and around the specimen. A pressure gage indicated when the specimen had collapsed.

CONCLUSIONS

Bursting test results were consistent, with duplicate data on two of the 4 in. diameter specimens and on two of the 5 in. diameter specimens. Three three inch specimens gave results within 10%. The calculations shown in Table XVI give satisfactory results with agreement, between the Barlow and Lamé formulae. Accordingly, it is believed that these results indicate that the Barlow and Lamé are reliable formulae for use in design of aluminum fluid flow system, for internal pressure.

The experimental collapsing values of the unit pressure upon failure of the 3 inch tube were identical for two tests and the unit pressure failure of the 5 inch tube were the same for two tests. Two of the three tests on the 4 inch tube gave the same unit pressure at failure and the third value was very close to these two. It was difficult to locate any great amount of reference material on collapsing tests. Timoshenko's formula for critical unit pressure probably is a satisfactory reference. The experimental unit pressure at failure were determined and these values were compared with the critical unit pressure as computed by Timoshenko's formula. In the case of the 4" tubes the experimental value was approximately 10% greater than the theoretical value and in the case of the 3 and 5 inch tubes the experimental values were approximately 50% greater than the theoretical value. The data are shown in Table XVII. (There is no explanation of the wide range of test results.)

TABLE XVI - BURSTING TEST DATA AND RESULTS

Size In.	Wall Thick- ness Inches	Internal Unit Pres- sure at Failure (psi)	Unit Stress in Material at Failure by Barlow Formula (psi)	Unit Stress in Material at Failure by Lame Formula (psi)
3	0.05	1175	35,250	34,100
3	0.05	1075	32,250	31,200
3	0.05	1265	37,950	36,600
	Ave.	1170	Ave. 35,100	34,000
4	0.063	1100	35,000	34,100
4	0.063	1100	35,000	34,100
5	0.063	1000	39,600	39,400
5	0.063	1000	39,600	39,400

Barlow's Formula: $p = \frac{st}{r_2}$

p = internal pressure (psi)

t = wall thickness (inches)

r_2 = external radius, inches

s = unit stress, inside fiber (psi)

Lame's formula: $\text{Max } S = p \frac{r_2^2 - r_1^2}{r_2^2 - r_1^2}$

S = circumferential unit stress

p = internal fluid pressure (psi)

r_2 = external radius (inches)

r_1 = internal radius (inches)

TABLE XVII - COLLAPSING TEST DATA AND RESULTS

Size In.	Wall Thickness (Inches)	Unit Pressure at Failure (psi)	L/R	Computed P_{cr} from Timoshenko's Formula (psi)
3	0.05	175	21.3	111
3	0.05	175	21.3	111
4	0.125	800	16	725
4	0.125	825	16	725
4	0.125	825	16	725
5	0.08	150	12	98
5	0.08	150	12	98

Timoshenko's Formula, eg. 187, p. 219

Strength of Materials, Part II

$$P_{cr} = \frac{Eh^3}{4(1-\mu^2)R^3}$$

P_{cr} = critical unit pressure, psi

E = modulus of elasticity = 10,600,000 psi

μ = Poisson's ratio = 0.33

h = wall thickness, inches

R = radius of center line of cylinder, inches

**FLUID FLOW CHARACTERISTICS OF ALUMINUM
ALLOY PIPE**

THEORETICAL

Power costs have always added considerably to the cost of the process of transporting fluids. Considerable work has been done in attempting to reduce this cost through a study of the factors involved. The friction between the moving fluid and the channel wall has been the power consumption factor which has given the trouble. For the older or commonly used materials this problem has been solved in terms of a friction factor. The use of aluminum in the field of fluid transportation brings with it the need for determination of this friction factor for aluminum tubing.

The flow of fluids through tubing or pipes takes place in two different ways dependent upon the velocity of fluid the properties of the fluid and the dimensions of the pipe. At low velocities the flow occurs in a smooth even pattern, that is, it occurs in layers as demonstrated by Reynolds.* There is little mixing of the liquid in the channel. The velocity approaches zero at the wall surface and increases in approximately a parabolic manner as the center of the channel is approached. This type of flow is seldom encountered in engineering practice and the project is not concerned with this flow.

The second type of flow is that at relatively high velocities where the flow is turbulent and somewhat complete mixing of the fluid takes place. However, there is still a layer at the wall surface which approaches zero velocity. The speed at

* Osborne Reynolds, 19th Century Physicist.

which the velocity increases as the center of the channel is approached is much greater, than in laminar flow.

Reynolds devised a dimensionless factor, which has come to be known as Reynolds Number, to distinguish between the two types of flow. It may be defined,

$$Re = \frac{DV\rho}{\mu} = \frac{DG}{\mu}$$

Where:

D = diameter of pipe, ft.

V = velocity of fluid, ft/sec.

G = mass velocity, lb./(sq.ft. of pipe cross-section)
(sec.)

ρ = density, lb./ft³.

μ = viscosity of fluid, lb./sec. ft.

When the Reynolds Number is less than 2000 the flow of any fluid in any channel is of the slow or viscous type. In the range of 2000 to 2500 the flow may be either type and very little is known about this region. Above 2500 the flow is always turbulent and is the range usually encountered in engineering work.

A term known as the Fanning friction factor may be plotted versus the Reynolds Number. It is used to determine the friction between the fluid and the channel wall, and may be evaluated from a loss of pressure in the channel, the dimensions of the channel, the velocity of flow and the properties of the fluid. In mathematical form the relationship becomes:

$$f = \frac{FD}{(V^2/2g)4L}$$

Where:

F = friction head, ft. of the flowing fluid

f = Fanning friction factor

L = length of pipe, ft.

D = diameter of pipe, ft.

V = velocity of fluid, ft/sec.

g = acceleration of gravity, 32.2 ft/sec².

EXPERIMENTAL

The hydraulic test stand of the University of Louisville Civil Engineering Department was used for this phase of the work. The two sections of aluminum pipe were used, 2 and 4 inch diameters, each 20 ft. long. Manometer taps were placed five feet from the up stream end and one foot from the down stream end. The tubing was then placed in the stand and connected. The stand was equipped with a centrifugal pump to deliver a steady flow of water. The tests were started at the maximum pumping rate and decreased in subsequent runs. Weight rates and absolute pressures were recorded simultaneously. The flow of water was reduced by an outlet valve after each series of runs, to obtain pressure value at several flow rates. This procedure was continued to a flow rate at which the pump could not maintain its prime. The same technique was employed for the 4-inch diameter pipe.

CONCLUSIONS

The data shown in Table XVIII and Table XIX were calculated using the formulas cited above for Reynolds number and friction factor:

$$Re = \frac{D G}{\mu}$$

$$f = \frac{D}{4L} \cdot \frac{F}{V^2/2g}$$

Then using corresponding Reynolds numbers and friction factors these data were plotted on a reproduction of a portion of the Reynolds number-friction factor plot taken from Perry, Chemical Engineers Handbook, Second Edition, page 811 (10). On this plot the accepted curves for commercial pipes and smooth tubes are shown.

The data are very good, only three points falling outside the range between commercial pipes and smooth tubes. In general, the data for the 2-inch pipe tend to approach the curve for smooth tubes, whereas the data for the 4-inch pipe tend to approach the curve for commercial pipe. However, it is observed that substantially all the data fall within the range between commercial pipe and smooth tubes indicating that the 4-inch pipe was slightly smoother than commercial pipe and the 2-inch pipe slightly rougher than "smooth" tubing.

TABLE XVIII - FLOW DATA FOR TWO-INCH PIPE

Run No.	Discharge lb. H ₂ O/ 30 sec.	Friction Head ft. of H ₂ O	$v^2/2g$ Velocity Head ft. of H ₂ O	Re Reynolds Number	F Fanning Friction Factor
1	627.9	6.41	4.52	2.502X10 ⁵	0.00401
2	630.4	6.41	4.56	2.513	0.00398
3	632.1	6.41	4.58	2.519	0.00395
4	600.8	5.78	4.14	2.394	0.00395
5	596.6	5.78	4.08	2.378	0.00400
6	591.9	5.78	4.02	2.359	0.00407
7	573.0	5.25	4.76	2.284	0.00394
8	574.3	5.25	3.93	2.289	0.00377
9	574.3	5.25	3.93	2.289	0.00377
10	545.6	4.73	3.41	2.174	0.00393
11	546.0	4.73	3.42	2.176	0.00391
12	546.0	4.73	3.43	2.179	0.00390
13	512.6	4.20	3.01	2.043	0.00394
14	512.1	4.20	3.01	2.041	0.00395
15	510.9	4.20	2.99	2.036	0.00397
16	467.6	3.68	2.51	1.863X10 ⁵	0.00414
17	475.3	3.68	2.59	1.894	0.00401
18	473.6	3.68	2.57	1.887	0.00404
19	432.9	3.15	2.15	1.725	0.00443
20	434.6	3.15	2.17	1.732	0.00440
21	433.7	3.15	2.16	1.768	0.00413
22	393.9	2.63	1.78	1.530	0.00417
23	390.0	2.63	1.74	1.554	0.00426
24	390.4	2.63	1.75	1.556	0.00425
25	345.4	2.10	1.37	1.377	0.00434
26	342.4	2.10	1.36	1.364	0.00437
27	340.3	2.10	1.33	1.356	0.00447
28	287.1	1.58	0.95	1.144	0.00471
29	227.7	1.58	0.59	0.901	0.00748
30	281.1	1.58	0.91	1.120	0.00491

Length of Test Section: 14.0 ft.

Measured Diameter of Pipe: 1.90 in., I. D.

Water Temperature: 20° C.

TABLE XIX - FLOW DATA FOR A FOUR-INCH PIPE

Run No.	Discharge lb. H ₂ O/ 30 sec.	Friction Head ft. of H ₂ O	$v^2/2g$ Velocity Head ft. of H ₂ O	Re Reynolds Number	F Fanning Friction Factor
1	713.0	0.256	0.337	1.394X10 ⁵	0.00438
2	708.5	0.224	0.333	1.385	0.00387
3	717.5	0.287	0.342	1.403	0.00485
4	707.0	0.292	0.332	1.382	0.00507
5	695.0	0.268	0.320	1.359	0.00482
6	687.5	0.260	0.313	1.344	0.00493
7	685.0	0.253	0.311	1.339	0.00469
8	687.0	0.268	0.313	1.343	0.00493
9	686.0	0.253	0.312	1.341	0.00467
10	614.0	0.224	0.250	1.200	0.00516
11	615.0	0.224	0.251	1.202	0.00514
12	567.5	0.189	0.214	1.109	0.00509
13	570.0	0.189	0.215	1.114	0.00506
14	529.0	0.116	0.186	1.034	0.00514
15	523.0	0.166	0.182	1.022	0.00525
16	489.0	0.144	0.158	0.956	0.00525
17	582.0	0.146	0.244	1.138	0.00345

Length of Test Section: 14.0 ft.

Measured Diameter of Pipe: 3.875 in, I. D.

Water Temperature: 20° C.

Figure 15. Fanning Friction Factor vs. Reynolds Number*

* Curves Taken From Perry's Chemical Engineers Handbook.

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APPENDIX

RECORDED EXPERIMENTAL DATA

COLUMN TESTING

Spec. No.	Column Cross Section Area - Square Inches	Load at Failure lbs.
I PS 1	0.19	650
I PS 2		600
I PS 3		525
I PI 1	0.19	400
I PI 2		450
I PSX 1	0.19	750
I PSX 2		750
I PL 1	0.19	325
I PL 2		300
I PL 3		300
3 PSX 1	0.241	4,600
3 PSX 2		4,650
3 PS 1	0.241	3,050
3 PS 2		3,200
3 PS 3		2,950
3 PI 1	0.24	2,500
3 PI 2		2,550
3 PI 3		2,600
3 PL 1	0.241	2,300
3 PL 2		2,450
3 PL 3		1,950
3 OI 1	0.241	2,650
3 OI 2		2,400
3 OI 3		2,600
3 FSX 1	0.241	3,850
3 FSX 2		4,050
3 FSX 3		4,500
4 PSX 1	0.562	10,450
4 PSX 2		10,050
4 PS 1	0.562	5,975
4 PS 2		6,350
4 PS 3		5,925
4 PI 1	0.562	5,500
4 PI 2		5,500
4 PI 3		5,575

RECORDED EXPERIMENTAL DATA

COLUMN TESTING
(Continued)

Spec. No.	Column Cross Section Area - Square Inches	Load at Failure psi
4 PL 1	0.562	4,950
4 PL 2		5,000
4 PL 3		4,975
4 OSX 1	0.562	10,700
4 OSX 2		10,600
4 OSX 3		10,800
4 FSX 1	0.562	10,900
4 FSX 2		11,200
4 FSX 3		10,750
5 PSX 1	0.80	4,000
5 PSX 2		3,200
5 PSX 3		3,950
6 PSX 1	1.195	5,700
6 PSX 2		5,850
6 PS 1	1.195	2,750
6 PS 2		2,625
6 PS 3		3,050
6 PI 1	1.195	2,200
6 PI 2		2,650
6 PI 3		1,550
6 PL 1	1.195	2,200
6 PL 2		2,200
6 PL 3		2,100
8 PSX 1	1.102	25,100
8 PSX 2		23,800
8 PSX 3		24,300
8 PS 1	1.102	11,900
8 PS 2		10,625
8 PS 3		12,025
8 PI 1	1.102	9,825
8 PI 2		10,350
8 PI 3		8,275
8 PL 1	1.102	8,250
8 PL 2		7,950
8 PL 3		8,625

RECORDED EXPERIMENTAL DATA

COLUMN TESTING
(Continued)

Spec. No.	Column Cross Section Area - Square Inches	Load at Failure psi
8 OSX 1	1.102	20,500
8 OSX 2		20,200
8 OSX 3		20,800
8 OI 1	1.102	8,375
8 OI 2		8,850
8 OI 3		9,400
8 OL 1	1.102	7,500
8 OL 2		7,400
8 FSX 1	1.102	19,100
8 FSX 2		19,400
8 FSX 3		18,700
7 FS 1	0.189	2,000
7 FS 2		1,850
7 FS 3		2,500
9 PS 1	1.205	29,725
9 PS 2		28,850
9 PS 3		27,500
9 PI 1	1.205	25,550
9 PI 2		25,850
9 PI 3		26,975
9 PL 1	1.205	20,650
9 PL 2		20,075
9 PL 3		19,000
9 OSX 1	1.205	38,000
9 OSX 2		38,200
9 OSX 3		37,900
9 FSX 1	1.205	37,200
9 FSX 2		36,150
9 FSX 3		35,000
9 FS 1	1.205	16,700
9 FS 2		16,300
9 FS 3		16,300
9 FI 1	1.205	12,600
9 FI 2		12,450
9 FI 3		12,900

RECORDED EXPERIMENTAL DATA

COLUMN TESTING
(Continued)

Spec. No.	Column Cross Section Area - Square Inches	Load at Failure psi
9 FI 1	1.205	10,400
9 FI 2		10,650
11 PSX 1	1.542	40,200
11 PSX 2		39,500
11 PS 1	1.542	20,600
11 PS 2		22,450
11 PS 3		21,700
11 PI 1	1.542	19,425
11 PI 2		19,675
11 PI 3		18,500
11 PL 1	1.542	14,100
11 PL 2		16,350
11 PL 3		14,300
11 OSX 1	1.542	37,800
11 OSX 2		38,000
11 OSX 3		38,550
11 FSX 1	1.542	35,650
11 FSX 2		34,650
12 PS 1	3.820	135,800
12 PS 2		104,000
12 PI 1	3.820	80,000
12 PI 2		76,500
12 PI 3		73,000
12 PL 1	3.820	63,000
12 PL 2		66,500
12 PL 3		71,500
12 OS 1	3.820	120,000
12 OS 2		130,000
12 OI 1	3.820	64,000
12 OI 2		63,250
12 OI 3		54,900

RECORDED EXPERIMENTAL DATA

COLUMN TESTING
(Continued)

Spec. No.	Column Cross Section Area - Square Inches	Load at Failure psi
12 FS 1	3.820	122,400
12 FS 2		124,500
12 FS 3		131,800
12 FI 1	3.820	48,400
12 FI 2		47,000
14 FS 1	1.190	17,600
14 FS 2		17,600
14 FS 3		17,700
14 FI 1	1.190	14,700
14 FI 2		15,750
14 FI 3		15,450
14 FL 1	1.190	12,600
14 FL 2		12,000

RECORDED EXPERIMENTAL DATA

Fluid Flow 2-Inch Pipe

Run No.	In. of Hg.	Tare Weight, Lbs.	Total Weight, Lbs.
1	6.1	264.0	996.5
2	6.1	244.0	979.5
3	6.1	253.5	991.0
4	5.5	209.0	905.0
5	5.5	253.0	943.0
6	5.0	208.0	876.5
7	5.0	254.0	924.0
8	5.0	253.5	923.0
9	4.5	201.5	838.0
10	4.5	252.0	889.0
11	4.5	245.0	883.0
12	4.0	210.0	808.0
13	4.0	252.5	850.0
14	4.0	253.5	849.0
15	3.5	204.0	774.0
16	3.5	219.5	774.0
17	3.5	231.0	783.5
18	3.0	213.0	717.0
19	3.0	241.0	748.0
20	3.0	245.0	751.0
21	2.5	244.0	703.5
22	2.5	243.0	698.0
23	2.5	261.5	717.0
24	2.0	205.5	608.5
25	2.0	236.0	635.5
26	2.0	256.0	653.0
27	1.5	230.0	565.0
28	1.5	263.0	587.0
29	1.5	251.0	579.0

Length of Test Section: 14.0 ft.

Measured Diameter of Pipe: 1.90 in.

Water Temperature: 20° C.

Time of Collection: 35 seconds.

RECORDED EXPERIMENTAL DATA

Fluid Flow 4-Inch Pipe

Run No.	In. of CCl ₄	Tare Weight, Lbs.	Total Weight, Lbs.
1	5.25	235.0	948
2	4.60	252.0	943
3	5.90	252.0	970
4	6.00	230.0	937
5	5.50	250.0	945
6	5.50	254.0	941
7	5.20	238.0	923
8	5.50	216.0	903
9	5.20	260.0	946
10	4.60	251.0	865
11	4.60	229.0	846
12	3.90	210.0	777
13	3.90	242.0	812
14	3.40	247.0	776
15	3.40	263.0	786
16	3.00	238.0	727
17	3.00	251.0	733

Length of Test: 14.0 ft.

Measured Diameter of Pipe: 3.875 in.

Water Temperature: 20° C.

Time of Collection: 30 seconds

COLUMN TESTING NOMENCLATURE

MATERIAL DESIGNATION

Lab. No.	Shape	Alloy	Dimensions
			Wall thickness - Outside Diam.
1	Tubing	3S-0	0.065 inches x 1.00 in.
2	"	3S-1/2H	0.065 in. x 1.00 in.
3	"	3S-H14	0.061 in. x 1.3125 in.
4	"	3S-H14	0.125 in. x 1.5625 in.
5	"	R361-0	0.194 in. x 1.500 in.
6	"	R361-0	0.254 in. x 1.75 in.
7	"	R361-T4	0.064 in. x 1.00 in.
8	"	R361-T4	0.238 in. x 1.718 in.
9	"	R361-T6	0.238 in. x 1.625 in.
10	"	63S-F	0.25 in. x 3.50 in.
11	"	R361-T	0.3125 in. x 1.875 in.
12	Channel	R361-T	0.437 in. x 6.0 in.
13	Angle	R361-T	1 $\frac{1}{4}$ in. x 1 $\frac{1}{4}$ in x 3/16 in.
14	"	R361-T	2 $\frac{1}{2}$ in. x 2 $\frac{1}{2}$ in. x $\frac{1}{4}$ in.
15	"	R361-T	4 in. x 4 in. x 3/16 in.

TYPE END CONDITION

P	Both Ends Pinned
F	" " Fixed
O	One End Pinned and One End Fixed

COLUMN TESTING NOMENCLATURE (Cont'd)

COLUMN LENGTH

L	Long Column (Critical Length - 10%)
I	Critical Length
S	Short Column (Critical Length - 10%)
SX	Short Column (Critical Length - 50%)

Typical Specimen designation:

4PL2: Sample is 3S-H 14, 1/8" X 1-5/16"

Both ends pinned

Long Column

Second specimen tested under
designated conditions.

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VI TA

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