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INVESTIGATIONS OF RHENIUM
1. A SURVEY OF THE LITERATURE
to
FLIGHT RESEARCH LABORATORY
WRIGHT AIR DEVELOPMENT CENTER
WRIGHT-PATTERSON AIR FORCE BASE
OHIO
November 7, 1952

by
C. T. Sims and E. N. Wyler

Contract No. AF 33(616)-232
Expenditure Order No. R-463-7 BR-1
For the Period June 23 to September 22, 1952
Flight Research Laboratory  
Wright Air Development Center  
Wright-Patterson Air Force Base  
Ohio

Attention WCRL

Dear Sir:

Enclosed are 11 copies, including one reproducible copy, of a technical report covering the first quarter of work done during the period June 23 to September 22, 1952, under Contract No. AF 33(616)-232 on "Investigations of Rhenium". Copies have also been sent directly to those on the attached distribution list.

This report covers an extensive survey of the literature on rhenium. So far as we are aware, it contains or summarizes all of the known technological information on the metal. Also of considerable interest to the reader will be the section on the projected as well as the known uses of rhenium.

It is the conviction of the research groups at Battelle concerned with rhenium that this metal is close to the stage where its great potentialities may be realized. We are now in the process of conducting experimental work toward this objective.

Yours very truly,

R. I. Jaffee

cc: 1st Lieut. John G. Humphreys  
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INTRODUCTION AND SCOPE

The first phase of the research program being conducted under Contract No. AF 33(616)-432, designed to investigate the physical and metallurgical properties of rhenium, is presented as this literature survey. To provide a sound basis for future experimental work, the survey includes all available data on rhenium, compiled and edited so as to present a complete but compact picture of the metal as it is now known.

This information, accumulating in the literature for the past twenty-seven years, has been classified into such major fields of interest as the history of rhenium, its occurrence, recovery and production, and its physical, chemical, electronic, and metallurgical properties. In addition, since a basic aim of this project is to evaluate, and arouse interest in, the prospective applications of rhenium, a quite complete section on the past, present, and future uses of the metal has been included. All of the references on rhenium, even those of only very remote value, have been listed in two distinct classifications: those which apply directly to the text, and those which have not been utilized in the text.
In general, it was found that information on the chemical properties of rhenium was abundant. Extensive work has been done on compound formation and analysis. However, physical-constant data were extremely scarce and usually only one source of information was available for these properties that were found. The physical metallurgy of rhenium is virtually an unexplored field and offers ample experimental opportunities.

**DISCOVERY AND HISTORY**

In the year 1869, the Russian chemist Mendeleev published his now famous periodic table. Numerous blanks appeared in the original chart, and Mendeleev predicted that these blanks would be filled with then unknown elements; he also predicted the properties these elements would have, and assigned atomic numbers and provisional names. In Group VIIb, headed by manganese, there were two unfilled spaces belonging to Element 43 and Element 75. To these, he assigned the provisional names of eka-manganese and dvi-manganese, respectively.

Despite near completion of the table by the 1920's, these two elements were still undiscovered. In 1925, the situation changed markedly, with almost simultaneous claims of discovery of Element 75 by three separate groups of workers.

W. Noddack, I. Tacke, and O. Berg, German chemists, were the first claimants. From the predicted properties of Mendeleev, the natural occurrence of elements, and studies of the properties of manganese, they reasoned that the missing elements would be associated with platinum and would also occur in certain other ores, principally columbite. By chemical concentration of columbite, sperrylite, gadolinite, and fergusonite, they produced a product, which on X-ray analysis yielded spectral lines indicating the presence of eka- and dvi-manganese. They named the elements masurium (At. No. 43) and rhenium (At. No. 75), and also predicted their abundance in the earth's crust to be $10^{-13}$ and $10^{-12}$ parts, respectively. The name "rhenium" was in honor of the German Rhineland.

Meanwhile, F. Loring and J. Druce in England, while examining pyrolusite and crude manganese compounds, concentrated a new substance. A few months after the German claim, Druce reported this substance as dvi-manganese, and presented chemical and X-ray evidence as proof. Loring predicted it would form a series of oxides, of which the highest would be of the type $M_2O_7$.

Also in 1925, V. Dolejšek and J. Heyrovsky detected an impurity in the electrolysis of manganese sulfate solutions with the then unique dropping mercury cathode and automatically registering polarograph.
Years later, however, Heyrovský(6) admitted that the polarographic steps at -1.0 and -1.2 volts found in polarograms of commercial manganese solutions, which were the basis for his rhenium claim, must have been due to other elements.

Shortly after Dolejšek and Heyrovský's "discovery", they commenced criticizing the work of Noddack, Tacke, and Berg, claiming the Germans' X-ray lines were due only to thallium and zinc. The Noddacks* and Berg defended themselves(7, 8) and presented more evidence. Druce(9, 10, 11) and Dolejšek and Heyrovský(12, 13, 14) also presented chemical and X-ray evidence to add to the polemic situation. Russian investigators(15, 16) studied numerous platinum ores and vigorously denied the presence of rhenium therein. To further complicate the situation, Prandtl(17) and Herszfinkel(18) in 1927 denied that any of the foregoing scientists had found Element 75. Their main reasons were that other elements, principally zinc and thallium, were being mistaken for dvi-manganese in X-ray photographs.

Whether the Noddacks had actually found Element 75 in 1925 may still be problematical, but it is certain that by 1926 and 1927 it had been separated and concentrated by them, for work on its properties had commenced.(19) The name they had given it, rhenium (Rhinemetal), soon came into general use, and today Noddack, Tacke, and Berg are recognized as the discoverers of rhenium.(20) Element 43, now called technicium, was never produced by the Noddacks in any quantity and they are not credited with its discovery. Their early work was well summed up by Von Hevesy(21) who presented the following table of Roentgen spectra as their proof:

<table>
<thead>
<tr>
<th>Element 75</th>
<th>$L_{a1}$</th>
<th>$L_{a2}$</th>
<th>$L_{b1}$</th>
<th>$L_{b2}$</th>
<th>$L_{b3}$</th>
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<tr>
<td>Observed</td>
<td>1429.9</td>
<td>1440.7</td>
<td>1235.0</td>
<td>1204.8</td>
<td>1216.0</td>
</tr>
<tr>
<td>Calculated</td>
<td>1430.6</td>
<td>1440.6</td>
<td>1235.5</td>
<td>1204.1</td>
<td>1216.9</td>
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Von Hevesy explained that even though the $L_{a1}$ line coincided with the Zn $K_{a3}$ line, it appeared too strongly to belong to zinc. The $L_{b1}$ line coincided with that of W $L_{b0}$, but it was far too intense to be the tungsten line. $L_{b2}$ and $L_{b3}$ match up with Tl $L_{a1}$ and Tl $L_{a2}$, but are of the expected rhenium, not thallium, intensity. The line $L_{a2}$ is characteristic of rhenium alone.

On the other hand, the work of Dolejšek and Heyrovský, as well as that of Druce, was severely taken to task by Hurd(22) some years later. Hurd and co-workers at the University of Wisconsin experimented extensively with manganese and pyrolusite ores, using procedures developed by the Europeans. Hurd emphatically denied the presence of rhenium in detectable amounts, and after testing ore to which rhenium standards were

---

*Walter Noddack married Elis Tacke in 1930, thus the disappearance of the name Tacke from the text.
previously added, he stated that the claim had been based on incomplete precipitations, complete reductions, and tremendous absorptions. It was about this time that Heyrovsky published his aforementioned refutation of a rhenium discovery claim, and Heyrovsky's findings prompted Druce to publish a statement to the effect that he really hadn't been trying to claim discovery all along. Druce has continued very active in the field. He has written many reviews in the past twenty years, and has culminated this work with the book, Rhenium, in 1948. This is the only modern authoritative text on rhenium, and covers the chemistry field exceedingly well. It is noteworthy, however, that Druce appears to be prejudiced against the Noddacks, and seems to continuously attempt to cloud their now substantiated claim for discovery, both in his papers and in the book. This prejudice must be borne in mind when reading Druce.

OCCURRENCE, ABUNDANCE, AND PRODUCTION

Originally, the Noddacks estimated the rhenium content of the earth's crust at $10^{-12}$ parts. This value was later revised upward to about $4 \times 10^{-9}$ parts after analysis of numerous minerals. Thus, rhenium is about 1000 times more rare than molybdenum, and 10 times more rare than iridium. Analysis of meteorites, to find the "natural" abundance of rhenium at first gave theoretically low results. Further analysis of meteorites showed the early results to be faulty; Goldberg and Brown found from $0.28 \times 10^{-6}$ to $1.45 \times 10^{-6}$ part of rhenium present, values with good theoretical agreement. A possibility exists that rhenium is also present in the sun, but if so, its concentration is minute. Fraunhofer lines show the strong Re 4889.38 A line missing.

Numerous practical sources of rhenium have been uncovered. The basis for this information was also laid by I. and W. Noddack who analyzed over 1800 minerals. Figure 1 shows the locations from which samples were procured and analyzed in the Scandinavian Peninsula. Others have also searched for rhenium. The richest known sources are presented in Table 1, in a roughly chronological order of their study. It is immediately evident that early production of rhenium was from sparse sources of the metal indeed. Recent findings have uncovered relatively rich sources of rhenium; some concentrates, particularly molybdenite, contain nearly 25 per cent. Kromman has suggested that rhenium probably accumulates in carbon-rich rocks also containing sulfur.

Despite no widespread production of rhenium in the United States, these new sources account partially for the reduction in price of rhenium since the early days of German production. In 1930 the price was about $37.00 per pound, although Kroll listed the "prevailing price" as $47.25
Figure 1. Scandinavian mineral sources investigated for rhenium content
Noddack and Noddack (37)

Batelle's Memorial Institute
<table>
<thead>
<tr>
<th>Source</th>
<th>Geographical Location</th>
<th>Mineral Composition</th>
<th>Uranium Content</th>
<th>Analysts and/or Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alunite</td>
<td>Norway</td>
<td>(Zr, Hf)SiO₂</td>
<td>0.6 ppm</td>
<td>I. and W. Noddack(32)</td>
</tr>
<tr>
<td>Thorivellite</td>
<td>Norway</td>
<td>Y₂Si₂O₇</td>
<td>0.6 ppm</td>
<td>I. and W. Noddack(32)</td>
</tr>
<tr>
<td>Columbite</td>
<td>Norway</td>
<td>(Fe, Mn)Nb₂O₆</td>
<td>0.2 ppm</td>
<td>I. and W. Noddack(32)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Norway</td>
<td>MoS₂</td>
<td>210 ppm</td>
<td>I. and W. Noddack(32)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Japan</td>
<td>MoS₂</td>
<td>100 ppm</td>
<td>I. and W. Noddack(32)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Siberia</td>
<td>MoS₂</td>
<td>0.6 ppm</td>
<td>I. and W. Noddack(32)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Colorado</td>
<td>MoS₂</td>
<td>1.8 ppm</td>
<td>I. and W. Noddack(32)</td>
</tr>
<tr>
<td>Platinum Ores</td>
<td>Ural</td>
<td>-</td>
<td>0.8 ppm</td>
<td>I. and W. Noddack(32)</td>
</tr>
<tr>
<td>Gadolinite</td>
<td>Finland</td>
<td>-</td>
<td>&gt;21.0 ppm</td>
<td>Aarnovaara(38)</td>
</tr>
<tr>
<td>Potash Waste</td>
<td>Germany</td>
<td>-</td>
<td>-</td>
<td>Anon.(33)</td>
</tr>
<tr>
<td>Copper Slate</td>
<td>Mansfield, German</td>
<td>CuS, MoS₂</td>
<td>5.0 ppm</td>
<td>Anon.(40)</td>
</tr>
<tr>
<td>Manganese Ore</td>
<td>Arkansas</td>
<td>-</td>
<td>10.0 ppm</td>
<td>Tyler(41)</td>
</tr>
<tr>
<td>Copper Ore</td>
<td>Arizona</td>
<td>CuS (?)</td>
<td>-</td>
<td>Tyler(42)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Domestic U. S.</td>
<td>MoS₂</td>
<td>50,000 ppm</td>
<td>Tyler(43)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Lainelau, Sweden</td>
<td>MoS₂</td>
<td>250,000 ppm</td>
<td>Aminoff(43, 44)</td>
</tr>
<tr>
<td>Anode Sludge</td>
<td>Norway</td>
<td>-</td>
<td>-</td>
<td>Druce(45)</td>
</tr>
<tr>
<td>Gold Extraction Slag</td>
<td>Zmeinogorsk, Siberia</td>
<td>MoS₂</td>
<td>-</td>
<td>Druce(46)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Northern Wisconsin</td>
<td>MoS₂</td>
<td>-</td>
<td>Works(46)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Unknown</td>
<td>MoS₂</td>
<td>320,000 ppm</td>
<td>Geilmann(47)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Stavenger, Norway</td>
<td>MoS₂</td>
<td>310,000 ppm</td>
<td>Geilmann(47)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Africa</td>
<td>MoS₂</td>
<td>280,000 ppm</td>
<td>Geilmann(47)</td>
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<tr>
<td>Molybdenite</td>
<td>Arendel, Norway</td>
<td>MoS₂</td>
<td>140,000 ppm</td>
<td>Geilmann(47)</td>
</tr>
<tr>
<td>Wolfenite</td>
<td>Unknown</td>
<td>PbMoO₄</td>
<td>Low</td>
<td>Geilmann(47)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Kounrad, Kazakh</td>
<td>MoS₂</td>
<td>15,000 ppm</td>
<td>Stepanov(48, 49, 59)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Tymenyuz, Kazakh</td>
<td>MoS₂</td>
<td>120 ppm</td>
<td>Stepanov(48, 49, 59)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Chikoy, Kazakh</td>
<td>MoS₂</td>
<td>120 ppm</td>
<td>Stepanov(48, 49, 59)</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Australia</td>
<td>MoS₂</td>
<td>110 ppm</td>
<td>Morgan and Davies(51)</td>
</tr>
<tr>
<td>Glimmerscheifen</td>
<td>Norway</td>
<td>-</td>
<td>Poor</td>
<td>FIAT #697(52)</td>
</tr>
<tr>
<td>Flue Dust</td>
<td>Miami, Arizona</td>
<td>MoS₂</td>
<td>10-15,000 ppm</td>
<td>Melaven(39)</td>
</tr>
<tr>
<td>Flue Dust</td>
<td>Miami, Arizona</td>
<td>MoS₂</td>
<td>3-5,000 ppm</td>
<td>Melaven(39)</td>
</tr>
<tr>
<td></td>
<td>Kennecott Copper Company</td>
<td>-</td>
<td>220 ppm</td>
<td>Melaven(39)</td>
</tr>
<tr>
<td></td>
<td>Brigham, Utah (Kennecott)</td>
<td>-</td>
<td>-</td>
<td>N. Y. Times(53)</td>
</tr>
</tbody>
</table>

*It must be noted that the values presented are analyses of both natural ores and of concentrates.

*Shown by Melaven(33) to be worthless.
per pound. This latter price is a low, a result of war economy. The present-day price of rhenium in the United States is around $350 per pound. In Germany it is 11-14 DM per gram, one-third the price of iridium.

Melavén has investigated over 100 domestic sources of rhenium. He has indicated that fly dust from copper ores containing molybdenite, collected by the Miami Copper Company of Miami, Arizona, is one of the few sources of rhenium containing a sufficiently high valuables content to be economically extractable.

The world production of rhenium has been very erratic. Figure 2 gives a rough approximation of production, and shows how discovery and utilization of the Mansfeld deposits spurred early high production. German production in the period 1939-1945 is unknown. A reasonable assumption is that it was level or rose slowly from the late thirties' output until the closing days of World War II, when all Germans turned to work more directly concerned with the hostilities. German patents indicate rhenium was still available in the early 1940's. Now, France and England are producing rhenium, but their source of concentrate is the United States.

Mansfeld, Germany, is in the Russian Zone. The Russians have been interested in rhenium for years as witnessed by their extensive work on catalytic properties. It must, therefore, be assumed that production of rhenium at Mansfeld continues under Soviet domination. The Noddacks estimated present world production of rhenium as 2 to 3 tons per year. Since Britain and France, as well as the United States, are all producing rhenium at a low rate, their total production (estimated by the writer as about 500 pounds per year) subtracted from the Noddacks' 2 to 3 tons indicates the Russians have a healthy production indeed.

All rhenium used in the United States came from German sources until comparatively recently. When it was shut off by the war, Professor Melavén commenced production at the University of Tennessee in small quantities, and when his process was patented in 1947, production increased. Melavén has produced a total of 300 pounds of metal since 1947, so his present production is assumed to be about 60 to 80 pounds per year. He estimates that expansion of his facilities would permit production of approximately 50 pounds of metal per week if a good concentrate were continuously available for processing. The concentrate should be available, for some figures indicate that U. S. production potential is of the order of 20,000 to 30,000 pounds per year.

Present world production centers may thus be considered to be:

1. Mansfeld, Germany (Russian dominated)
2. Balkhash, Kazakh (Russia)
3. France
It is extremely important to compare the above list with the table previously presented listing world sources of rhenium (page 6). The comparison shows a striking fact. As far as can be ascertained from available information, although Swedish, Norwegian, and Yugoslavian ores or concentrates contain the highest percentages of rhenium, none of these sources are presently being worked. From present estimates of potential production, the United States probably has the best resources and best potential production.

EXTRACTION

Numerous methods have been published and/or patented for the separation, concentration, and ultimate recovery of rhenium salts or metal from the ores in which it occurs. Some of these processes seem to be too complicated for other than a laboratory production, while others, such as that of Feit(56), are aimed directly at full-scale industrial recovery. All of these methods depend upon certain of the characteristic properties of rhenium and its compounds. Some of these properties are listed below.

A. Insolubility of rhenium disulfide.
B. High volatility of rhenium heptoxide.
C. High solubility of rhenium heptoxide.
D. Temperature dependence of the solubility of potassium perrhenate.

Whatever the initial steps in the recovery process, the last step involves conversion of some rhenium compound into metallic rhenium either as a powder or in a consolidated form. These reduction processes are discussed at the end of this section, following presentation of the methods for separation of rhenium salts.

The Noddack Processes

The first process developed by the Noddacks(57) was that used in their original detection of rhenium. Starting with platinum ores, they dissolved the ore in aqua regia, evaporated the solution, and then ignited the residue. The aqua regia insolubles were chlorinated and reduced. This product was mixed with the solution residue, and both were heated in oxygen and hydrogen to sublime the resultant rhenium heptoxide. A solution of the heptoxide was purified and then precipitated with hydrogen sulfide. Purification and X-ray examination for characteristic rhenium lines followed.
FIGURE 2. KNOWN PRODUCTION OF RHENIUM

Note: Soviet production is not known and not indicated above. It may be on the order of tons per year (see text).

Rhenium Produced Per Year, pounds

1928 1932 1936 1940 1944 1948 1952

German production
U.S. production
Approximate
The Unidas, in effectivelyd strength, and their claim as discoverer of
obana by holding, chlorine from molybdenite. The general method
depend on the solubility of high oxides in reduced acid, and also on
water-soluble salts of the type K₂Re₂O₇. In their process (59, 60, 61),
molybdenite was dissolved in nitric acid and the molybdenum separated by
precipitation as ammonium phosphomolybdate. This process was repeated
many times until the bulk of the molybdenum was removed. The rhenium
was then coprecipitated with nickel, copper, cobalt, platinum, van-
dium, and usually residual molybdenum, all as sulfides. Nickel, cobalt,
copper, and iron were next separated by a hydrogen reduction. Re-
solution, reprecipitation, and reduction occurred. Rhenium was converted to the
oxide and sublimed. Water solution of the oxide and purification followed.
The final reduction produced the metal. The process was long and compli-
cated, as many of the steps had to be done over and over. This process is
probably not suitable to large-scale commercial production.

One patent (62) suggested a practical selective crystallization method,
whereby acid solutions of rhenium salts were evaporated with other metal
salts. If the first settling salts were removed, the liquid was then found to
be enriched in rhenium. Another method (63) was suggested for separation
of rhenium from residues (probably from the Mansfeld copper schist). So-
lution in nitric acid was followed by chlorination and then acid precipitation
of the sulfide. The precipitate was cleaned extensively and finally converted
to a solution of perrhenate ion. Potassium perrhenate is insoluble in po-
tassium hydroxide solution, so by this action crystalline potassium perrhenate
was separated.

The Feit Process

The Feit process (56, 64, 65) was probably the most important develop-
ment in rhenium recovery until very recent years. It was used for German
production of rhenium from a complex sulfide slime, the by-product from
refinement of Mansfeld copper schist. The method was cheap and relatively
simple. Slime was extracted with water, to which was added ammonium
sulfate. Copper, nickel, and zinc were precipitated as double ammonium
sulfates. These were removed and more ammonium sulfate precipitated
complex compounds of molybdenum, vanadium, and phosphorous. The
addition of potassium chloride to the filtrate formed crystals of crude
potassium perrhenate. Several recrystallizations produced a pure product.
Reduction of the perrhenate at red heat produced impure rhenium metal,
which was purified by leachings with water.

Feit also extracted rhenium from molybdenum pigs. (24) In one method,
the pulverized pigs were treated with cold sulfuric acid in a manner which
produced an enriched precipitate of potassium perrhenate. In a second
method, the oven pigs were melted with sodium sulfate so that rhenium and
In the reduction processes, Seitz\(^{(66,67)}\) found that if rhenium compounds, ready to be reduced at high temperatures with hydrogen, were mixed with a substance that did not allow fusion of the compound at the reduction temperature, reduction would be considerably facilitated. Iron or hematite, mixed with the reducible rhenium compound, will prevent agglomeration in this manner.

Seitz's processes have probably been considerably modified\(^{(68)}\), but their use continued in Germany at least until 1946.\(^{(52)}\)

The Driggs Process

The first American patent on commercial production was obtained by F. Driggs.\(^{(69)}\) His procedure was based on the theory that if reducing agents such as sulfur and phosphorus were removed from a rhenium source, oxidation of the rhenium to higher oxides would be simplified. The higher oxide, \(\text{Re}_2\text{O}_7\), was then volatilized, recovered, purified, and reduced to the metal. Most of the action occurred in a roasting step, where niter cake (\(\text{NaHSO}_4\)) was added to insure formation of \(\text{Re}_2\text{O}_7\). The process is shown in a flow sheet (Figure 3).

Russian Processes

The first Russian work on recovery was a laboratory method developed by Kronman, Bibikova, and Aksenov\(^{(70)}\) in 1933. Molybdenite was dissolved in nitric acid, the solution diluted, and molybdenum trioxide filtered out. The filtrate was distilled with carbon dioxide and then hydrochloric acid to remove interfering elements. Sulfides of rhenium and molybdenum were precipitated with hydrogen sulfide from acid solution. The rhenium sulfide was freed from molybdenum with hydroxyquinoline. Rhenium was again precipitated, but by nitron as nitron perrhenate. Nitron is a common reagent for this task.

Industrial production evidently began when the Balkhash works in Kazakh, refining molybdenum ores, were investigated for the presence of rhenium. Rhenium was being lost through the stack during roasting of molybdenite.\(^{(71)}\) In 1936, wool bags placed in the stack to trap the flue dust were found to retain some rhenium. Finally, in 1946, it was realised that rhenium was present in considerably higher quantities than previously estimated, and Stepanov\(^{(49)}\) recommended commencement of a rhenium-extraction plant. Experiments must have been conducted, for shortly it was reported\(^{(50)}\) that flue gases containing rhenium passed through an
FIGURE 3. DRIGGS PROCESS FOR THE RECOVERY OF RHENIUM
asbestos filter, retained over 50 per cent of the metal. If the flue gases were washed in a scrubber, 6 to 10 per cent of the rhenium was saved. A combination scrubber and electrofilter retained 86 to 90 per cent. It is probable that the Russians are now producing rhenium at this plant.

The Tennessee Process

Rhenium was supplied to the United States by the A. D. McKay Company of New York, prior to World War II. This was a German product, and when war intervened, further procurement was blocked. The University of Tennessee had been conducting research on rhenium and, with their supply cut off, began experimentation to produce rhenium from domestic sources. Melaven and Bacon(72) then patented a process for rhenium recovery from flue dust. The process is currently being used there(33), and the rhenium is sold commercially.

A flow sheet (Figure 4) illustrates this process. Rhenium-bearing flue dust, product of a roasting operation, is received at the University. It contains molybdenum and rhenium oxides and molybdenum sulfide. The concentrate is mixed with water and filtered. The soluble rhenium heptoxide is thus removed from the other more insoluble factions. The filtrate is pumped to a mixing vat and solid potassium chloride added. This precipitates crude perrhenate which is subsequently purified. The process is straightforward and simple.

French Processes

Several patents appeared in 1950-51 on French work with rhenium. All deal with the separation of rhenium from molybdenite and involve interesting processes. The first of these(73) required dissolution of the molybdenite in acid or alkaline aqueous solution and adjustment of the pH to 8 or 9. Then a solution of $\text{MR}_n^+$ was added, where:

- $M = \text{N, P, As, or Sb}$
- $R = \text{hydrocarbon radical, such as phenyl}$

A chloroform solution of tetraphenylnitrosonium chloride is an example. The chloroform solvated the perrhenate and the aqueous solution was removed. Then 12N hydrochloric acid was added (alone, or with reducing agents, or 0. 1N perchlorate solution) to the chloroform solution. Rhenium passed into the aqueous layer, which was distilled until the rhenium started to come over. The residual solution was processed to yield rhenium metal.

Bertolus(74, 75) developed a process which separated rhenium from molybdenum by fractional volatilization of the oxides. Copper sulfide ore
Re bearing flue dust or Re bearing material recovered from flue gases

Water

Mixer

Counter-current extraction filtration, or decantation

Water solution of rhenium compounds

Cool

Filter

Residue

Mixing vat

Filter or decant

Mother liquor

Evaporate

Residue

Return to roaster

KCl solid or solution

Crude KReO₄

Purity

FIGURE 4. TENNESSEE PROCESS FOR THE RECOVERY OF RHENIUM

A-4004

BATTLE MEMORIAL INSTITUTE
was selectively floated to give a product rich in molybdenite, containing 1:3000 to 1:5000 parts of rhenium. The molybdenite was then roasted in air at 500 to 600 °C. When sulfur in the concentrate started to oxidize, the reaction became exothermic, but was held down to about 500 to 600 °C by cooling the oxidizing gases. After sulfur removal was complete, K₂O₂ was formed. This was allowed to volatilize, but the temperature was kept below 700 °C to prevent volatilization of the molybdenum oxide. The gases were mixed with cool air and sent to a multicycle precipitator at 250 to 300 °C. A counter-current water washer removed most of the rhenium. The balance, as entrained droplets of solution, was removed in another cyclone precipitator. This process is simple and continuous; it is probably responsible for present French production of rhenium.

Ion-Exchange Separation

Very recently, Fisher and Meloche (76) have reported on the ion-exchange technique as applied to the separation of rhenium from molybdenite. They stated that in 1947 Alexander, at the University of Wisconsin, separated rhenium and molybdenum as perrhenate and molybdate, using the anion-exchange resin Amberlite 1R-4B at a pH of 4.8. The column was elutriated of the molybdate with buffered sodium hydroxide.

Fisher and Meloche continued this work, but decided to use Amberlite 1RA-400, an exchange resin with greater basicity than the 1R-4B. A solution of perrhenate and molybdate (ratio 1:3000) plus 10 per cent sodium hydroxide was passed through an exchange column containing the Amberlite 1RA-400. One hundred ± 0.5 per cent of the molybdate was recovered in the effluent. The perrhenate remained in the resin. The column was washed with water, dilute hydrochloric acid, and finally 7-8 N acid. This removed 99 ± 3 per cent of the available perrhenate in a concentrated state which was easily converted to a useful crystalline compound.

The process is excellent, but obviously expensive and definitely time consuming. Thirty hours actual running time were required. Ion exchange, however, is a growing field, and this process achieves a truly complete separation of these difficult-to-separate components. Further development may make this process economically feasible.

Miscellaneous Methods

It was early suggested (77) that a low-temperature roast of copper schist residues containing molybdenite would allow leaching out of the rhenium as potassium perrhenate. This is somewhat analogous to the process disclosed in Melvank's patent.
Much of the Russian work has involved the use of special distillants such as carbon dioxide and hydrochloric acid. Originally utilized to remove impurities, a hydrochloric acid distillation was later used to distill off rhenium heptachloride from nitric or sulfuric acid baths.

As will be noted in the analytical chemistry section of this report, it has been known for some time that if precipitation of rhenium sulfide from an alkaline solution could be effected, separation from molybdenum would be relatively simple. Molybdenum sulfide is fully soluble in alkaline solution as is usually rhenium sulfide. However, Voigt(79) found that if an alkaline solution containing molybdenum and rhenium sulfides (saturated with hydrogen sulfide) were cooled below -5°C, rhenium sulfide would precipitate leaving the molybdenum in solution. This was applied to recovery of rhenium from a furnace pig.

Hixson and MacR(80) used organic solvents to recover metal values, such as rhenium, from their compounds by interrelated cycles. The rhenium-rich ore or tailings were dissolved in acid. The metal valence was adjusted to allow future solubility in some organic solvent, but the rhenium radical was kept in combination with the elements originally present; i.e., still in aqueous solution. The impure aqueous solution was extracted by a hydrophobic selective organic solvent, and the solvent solution was then re-extracted with water.

Rhenium present in smelting residues and zinc dust, in Japan, (81) can be leached out with water after a sulfuric acid treatment. Also, per-rhenic acid in sulfuric acid solution(82) may be separated from molybdic acid by adsorption on Norit (vegetable char) which adsorbs molybdic acid more slowly than per-rhenic acid. Evidently this method has not been attempted commercially.

REDUCTION TO METAL

Numerous methods have been reported for the reduction of rhenium compounds to metal. The methods nearly always yield the metal in a powdered form.

Reduction of Heated Oxides by Hydrogen

The most common oxide, rhenium heptoxide, can be reduced by hydrogen(83), but with some difficulty as the heptoxide is so highly volatile. The initial reduction temperature is slightly above 100°C, where the reduction occurs in several stages. The yellowish heptoxide changes to
green, blue, then black oxides before the grayish metal powder appears.

Mears(84) notes that when the black rhenium dioxide state is reached, reduction temperature should be raised to above 500 °C to obtain the metal powder.

Reduction of Heated Sulfides by Hydrogen

Powell(83) recommends reduction of the heptasulfide as the best hydrogen reduction method. A hot acid solution of potassium perrhenate is saturated with hydrogen sulfide, producing the heptasulfide. This is introduced into the reduction tube wet to prevent oxidation. The heptasulfide is nonvolatile and reduces easily in hydrogen at a red heat, although some sulfur is retained in the metal. This is removed by continued high-temperature reduction.

Reduction of Heated Halides and Oxyhalides by Hydrogen

According to Druce(84), hot hydrogen will reduce rhenium halides at about 250 to 300 °C according to the equation:

$$2\text{ReCl}_3 + 3\text{H}_2 = 2\text{Re} + 6\text{HCl}$$

The inference is that the oxyhalides may also be reduced in this manner, although no further details are presented.

Reduction of Heated Perrhenates by Hydrogen

The most common methods for preparation of rhenium powder are by the reduction of either potassium or ammonium perrhenate.

Potassium perrhenate is reduced with hydrogen(83) at a fairly low temperature. The potassium is converted to potassium hydroxide which is removed by leaching with water. Repeated reductions and leachings are usually carried out for two or three cycles. Melaven(33) reduces the potassium perrhenate at 300 °C under 3000 psi in a silver-lined bomb. The reaction(84) is:

$$2\text{KReO}_4 + 7\text{H}_2 = 2\text{KOH} + 2\text{Re} + 6\text{H}_2\text{O}$$

Unfortunately, complete leaching of the hydroxide is difficult if not impossible, and potassium perrhenate-prepared metal usually possesses some occluded \(\text{K}_2\text{O}\) (around 0.5 per cent).
Ammonium perhenate can also be reduced to the metal in a similar manner, and is thought to produce a pure and also more active product. Melaven first produces the metal from potassium perhenate (as above), then oxidizes it to rhenium heptoxide. The heptoxide is solubilized in water and ammonium perhenate prepared by putting gaseous ammonia through the solution. This is then reduced in the metal powder.

Another perhenate commonly used because of its analytical value is nitron perhenate. This organic salt has the advantage that it can readily be reduced to recover the rhenium content. After an analysis, the precipitate is heated in a current of hydrogen where it melts and breaks down. Alcohol extraction removes the organic components and the resultant mass is again hydrogen reduced to produce a pure product.

Electrolysis of Aqueous Solutions

Several authors, principally Höleman, Fink and Deren, and Netherton and Hoit have electrolyzed acid, alkaline, and neutral baths to give precipitates or plates of rhenium metal. Their work is discussed below under Electrodeposition.

Thermal Dissociation

The first vapor deposition of rhenium was accomplished by the Noddacks who heated a 0.02-mm platinum wire electrically in an atmosphere of rhenium chloride (valence not mentioned) at 1200 to 1400 C. The chloride dissociated on the hot wire surface and deposited rhenium on the wire. Agte, Moers, et al. used the same process, but deposited rhenium on a 0.03-mm tungsten wire at higher than 1800 C.

Chlorine freed by these reactions will reassociate with a source of rhenium in the system and act as a carrier, continually depositing rhenium on the wire, until all the rhenium is exhausted. Eventually, a rhenium rod or wire with a tungsten (or platinum) core is prepared. This process is important in the manufacture of lamp filaments, for which several patents have been drawn.

The Thermite Reaction

The thermite reaction, so well known with iron oxide and aluminum powder, can also be performed with rhenium dioxide and aluminum.
The reaction is:

\[ 3\text{Re}_2\text{O}_7 + 4\text{Al} = 2\text{Al}_2\text{O}_3 + 3\text{Re} \]

This reaction produces rhenium, which, of course, must then be separated from the aluminum oxide, a step which probably precludes this reduction method from ever acquiring any commercial importance.

**CONSOLIDATION AND FABRICATION**

Except for the vapor-deposition processes, all of the above reduction methods result in a rhenium product in powder form. The powder must be consolidated into a useful massive state; even the vapor-deposited metal should be further consolidated before a sound structure is realized. The following procedures might be used for this purpose.

**Electric-Arc Melting**

It is believed that rhenium powder or sections cut from a crystal bar can be fused by arc melting with inert electrodes in a water-cooled copper crucible or hearth. This melting method is being used extensively for producing ingots of molybdenum, titanium, and zirconium. If it can be applied to the production of rhenium ingots suitable for fabrication, it would simplify the consolidation problem considerably.

**Sintering**

Rhenium powder has been pressed into bars and electrically sintered in hydrogen at 1000°C by the Noddacks. (37)

A more complete description of sintering processes is given in Agte's paper. (91, 94) Powder from the Siemens and Halske Company, possessing a high volume and deep-black color, was pressed at 2000 kg/cm² into a 3 x 3 x 40-mm rod. Presintering was carried out in dry hydrogen in a tube furnace where the rod was heated only to 500°C. It achieved sufficient strength so that a hole for melting point determination could be bored with a steel drill without crumbling of the bar. The rod was then sintered at 1000°C in hydrogen where it became very hard and dense, possessing a platinum-like glaze. No information on sintering time or current was reported.
Methods for sintering of rhenium alloys have been mentioned in patent literature by Kurtz and Williams (95, 96), who recommend a sintering range of 1500 to 1850 C under dry hydrogen.

Workability

Agte, et al. (91, 94), found that rhenium sintered at "moderate" temperatures is brittle at room temperatures. However, if sintering is carried out close to the melting point, a certain cold ductility is exhibited in a compression test (liberal translation of "Zerkleinerungsversuch" gives "crushing" test, which may mean size reduction in a device such as a machinist's vise). High-temperature-sintered rhenium can be worked at "high temperatures". Forging can be accomplished (in several stages) at about 800 C, and forging and rolling can be carried out at "high temperatures".

The sintered material behaves differently than vapor-deposited rods, which were described as very soft and pliable, akin to copper. These were coiled, bent, drawn, rolled, etc., but only in small steps. The strength increases during these manipulations.

Bridgman (97) reported that rhenium sheared quietly when subjected simultaneously to high shearing stress and high hydrostatic pressure. Many substances explode under this treatment.

PHYSICAL PROPERTIES

The physical properties of rhenium have been grouped under three major headings: Physical Constants, Spectra of Rhenium, and Nuclear Properties.

Physical Constants

Atomic Weight

Rhenium's position in the periodic table between the Elements tungsten (at. weight 183.92) and osmium (190.2), obviously places its weight between these two values. Loring (98) first suggested an approximation of 187 for the atomic weight, and then Washburn (99) calculated 187.4, a value later shown to be slightly high. From the specific heat (100), the atomic weight is calculated to be 187 by Dulong and Petit's law (see Specific Heat).
The first experimental determination was by the Noddack(101), who reduced rhenium disulfide in hydrogen, to obtain a value of 186.71 ± 0.15. Schäfer(102) repeated this and obtained 188.7 ± 0.25, but these values were also high due to incomplete reduction of the rhenium disulfide.

Hönigschmidt and Zachariasen(103) converted silver rhenate into silver bromide by a painstaking procedure. The perhenate was prepared in a very pure state several times by three different procedures. The products were fused, and the reaction completed; weight calculations gave a result of 186.31 ± 0.02. This was accepted by the German Atomic Weight Commission in 1931(104), and has not been challenged since, although Aston(105) calculated 186.22 from the correct proportions of the two naturally occurring isotopes, Re185 and Re187. The value 186.31 ± 0.02 is the accepted one.

Crystal Structure

Rhenium was found to possess a hexagonal close-packed structure by both Goldschmidt(106, 107) and Agte(91, 94). They disagreed on lattice constants, so other investigators also made measurements. Results of these measurements and the calculations of atomic radius and volume are shown in Table 2. The values of atomic radii fall approximately between those of tungsten and osmium, as would be expected from the periodic position of rhenium. The lattice constants calculated by Moeller and by Stenzel and Weertz seem to be based on purer material than that of Agte or Goldschmidt, as molybdenum would interfere with this type of data more than potassium. Furthermore, the two values agree quite closely, so the results of Stenzel and Weertz are recommended as probably the more accurate.

### Table 2. Lattice Constants, Atomic Radius, and Atomic Volume of the Rhenium Atom

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Year</th>
<th>a (Å)</th>
<th>c (Å)</th>
<th>c/a</th>
<th>Atomic Radius, A</th>
<th>Atomic Volume, A³</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goldschmidt</td>
<td>1929</td>
<td>2.752</td>
<td>4.448</td>
<td>1.616</td>
<td>1.371</td>
<td>8.89*</td>
<td>0.3% Mo</td>
</tr>
<tr>
<td>Agte, et al.</td>
<td>1981</td>
<td>2.755</td>
<td>4.448</td>
<td>1.616</td>
<td>1.382</td>
<td>8.89*</td>
<td>0.3% Mo</td>
</tr>
<tr>
<td>Moeller(108)</td>
<td>1931</td>
<td>2.752</td>
<td>4.448</td>
<td>1.616</td>
<td>1.378*</td>
<td>8.89*</td>
<td>0.5% K₂O</td>
</tr>
<tr>
<td>Stenzel and Weertz(109)</td>
<td>1933</td>
<td>2.753</td>
<td>4.448</td>
<td>1.614</td>
<td>1.3777*</td>
<td>8.89*</td>
<td></td>
</tr>
<tr>
<td>Blitz and Meisel(110)</td>
<td>1931</td>
<td>2.753</td>
<td>4.448</td>
<td>1.614</td>
<td>1.3777*</td>
<td>8.89*</td>
<td></td>
</tr>
</tbody>
</table>

The lattice constants (a) are accurate to ±0.001 Å except those found by Stenzel and Weertz, which are claimed to be accurate to ±0.01 Å.

*Calculated by the writer

**At absolute zero
The crystal structures of a few rhenium compounds have been reported, the type and dimensions of which are recorded in Table 9 in the Chemical Properties section of this report.

Density

Using the atomic weight found by the Noddack (101), Goldschmidt (106, 107) calculated the density of metallic rhenium as 21.33 (containing 0.3 per cent molybdenum). This was corrected to 21.40 ± 0.06 for pure rhenium. However, it is known (103) that Noddack's atomic weight is a false basis for calculation; as a result, Agte (91, 94) calculated 20.53 from the presently accepted atomic weight of 186.31. Experimentally, he found a value of 20.9 for annealed rod. Agte's calculated value is accepted today.

The densities of numerous rhenium compounds are recorded in Table 9 of the Chemical Properties section.

Melting Point

The melting point of rhenium has, more than any other, stirred the imagination of scientists. Rhenium has a very high melting point, second only to tungsten. Agte and co-workers (91, 94) used the drilled-hole method (in an argon atmosphere) to find a value of 3440 ± 60 K. Their rhenium was procured from I. and W. Noddack, and contained only 0.01 per cent impurities. Shortly thereafter, Jaeger and Rosenbohm (100) reported 3160 C. Within the limits of accuracy at such high temperatures, the values are identical. 3440 K is the most commonly used value in the literature. Melting points for tungsten and rhenium on three temperature scales may be tabulated:

<table>
<thead>
<tr>
<th>Metal</th>
<th>C</th>
<th>K</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten</td>
<td>3380</td>
<td>3653</td>
<td>6110</td>
</tr>
<tr>
<td>Rhenium</td>
<td>3170 ± 60</td>
<td>3440 ± 65</td>
<td>5740 ± 110</td>
</tr>
</tbody>
</table>

Boiling Point

The boiling point of very high melting metals is difficult to determine, but Richardson (112) estimated by spectroscopic techniques that carbon-saturated rhenium (rhenium takes up little carbon) boils at approximately 5900 C. Tungsten boils somewhere in this neighborhood; one source (113) listed 5930 C. Thus, the boiling point of rhenium is one of the highest known.
The parabolic of rhenium was determined (111) from three different rhenium compounds:

\[ \text{ReO}_2\text{Cl}_3 = 78.9 \]
\[ \text{Re}_2\text{O}_7 = 68.9 \]
\[ \text{ReO}_3\text{Cl} = 76.4 \]

The most significant of these three values is 76.4 because the authors found that \( \text{ReO}_2\text{Cl}_3 \) was colorless, mobile, and easily purified, and possessed a freely moving meniscus. The value for \( \text{ReO}_2\text{Cl}_3 \) is considered inaccurate, because it gave a poorly defined meniscus, even though 78.9 is close to that predicated on the basis of the parachors of tungsten and osmium.

**Specific Heat**

The specific heat was measured by Jaeger and Rosenbohm (100) in a metal calorimeter, from 0 to 1200 C. The value at t degrees may be calculated from the equation:

\[ C_p = 0.03256 + 0.625 \times 10^{-5} t \text{ cal/g/C}. \]

A mean value for 0 to 20 C is given as 0.03262 cal/g/C.

According to a basic relationship revealed by Dulong and Petit, the product of the saturation value of the specific heat and the atomic weight for a metal is 3R, where R is the gas constant (2 cal per deg). This value is not adhered to by all metals, particularly at elevated temperatures. For rhenium, 3R is surpassed at -66 C. A value of 0.0346 (101, 115) cal/g/C has also been reported, but Jaeger and Rosenbohm's work appears to be the most complete and accurate.

**Linear Thermal Expansion**

The linear thermal expansion of close-packed hexagonal rhenium was determined by Agte, et al. (91, 94). Measurements were taken at room temperature and 1917 C by X-ray methods. There was no variation with temperature and the c-axis expansion was 2.6 times that of the a-axis. The results were:

\[ \beta [001] = 12.45 \times 10^{-6} \pm 6\% \]
\[ \beta [100] = 4.67 \times 10^{-6} \pm 6\% \]
Since the linear expansion of glass is about $3.0 \times 10^{-6}$, (116) it should be possible to stick selenium to it.

**Specific Electrical Resistance**

The basic room-temperature resistivity of rhenium has been measured by Agte, et al. (91, 92), to be $21.1 \times 10^{-6}$ ohm-cm (± 15 per cent), for both vapor-deposited and drawn wire. The wires were 100 per cent dense and contained impurities. This is the value accepted today. The temperature coefficient of resistance over the range 0 to 100 C is the constant value $3.11 \times 10^{-3}$. Other values of the resistivity, $\rho$, and the temperature coefficient of resistance determined by Agte and also by Meissner and Voigt (117) are found in Table 3. The temperature range covered is from -271.64 to 2710 C. The resistivity of rhenium is approximately four times that of tungsten at room temperature and 1.7 that of tungsten at 2500 C. This value falls between those for lead and strontium.

### Table 3. The Specific Electrical Resistance of Rhenium at Various Temperatures

<table>
<thead>
<tr>
<th>Temperature, C</th>
<th>Resistivity, $\rho$, ohm-cm</th>
<th>Temperature Coefficient of Resistivity From 20 C, C$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>After Meissner and Voigt</td>
<td>After Agte, et al.</td>
</tr>
<tr>
<td>-271.64</td>
<td>$2.06 \times 10^{-6}$</td>
<td>--</td>
</tr>
<tr>
<td>-268.78</td>
<td>$2.08 \times 10^{-6}$</td>
<td>--</td>
</tr>
<tr>
<td>-252.35</td>
<td>$2.08 \times 10^{-6}$</td>
<td>--</td>
</tr>
<tr>
<td>-194.71</td>
<td>$4.68 \times 10^{-6}$</td>
<td>--</td>
</tr>
<tr>
<td>-190</td>
<td>--</td>
<td>$4.94 \times 10^{-6}$</td>
</tr>
<tr>
<td>-184.77</td>
<td>$5.39 \times 10^{-6}$</td>
<td>--</td>
</tr>
<tr>
<td>-30</td>
<td>--</td>
<td>$15.4 \times 10^{-6}$</td>
</tr>
<tr>
<td>0</td>
<td>--</td>
<td>$19.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>0.16</td>
<td>$18.9 \times 10^{-6}$</td>
<td>--</td>
</tr>
<tr>
<td>20</td>
<td>--</td>
<td>$21.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>100</td>
<td>--</td>
<td>$26.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>2130</td>
<td>--</td>
<td>$125 \times 10^{-6}$</td>
</tr>
<tr>
<td>2420</td>
<td>--</td>
<td>$130 \times 10^{-6}$</td>
</tr>
<tr>
<td>2710</td>
<td>--</td>
<td>$134 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

*Compiled from data of Agte, et al. (91, 92), and Meissner and Voigt (117). Other compilations may be found in Maitz (120) and Nodack (37).*
No research appears to have been completed on this property, and it must be considered unknown.

Spectral Emissivity

The first data on spectral emissivity were calculated by Becker and Koers(118) using values of the black-body melting temperature found by Aghe, et al.,(91,94) and themselves, from the following equation:

$$\ln \frac{C_2}{\lambda} = \frac{1}{T_w} - \frac{1}{T_s},$$

where:

- $T_w$ = true temperature,
- $T_s$ = brightness temperature,
- $\lambda = 0.650$ micron,
- $C_2 = 14,330$, a universal constant for radiation processes.

The value of $A_\lambda$ was found to be 0.42.

Levi and Esperson(119) reported a value of $A_\lambda = 0.366$. The black-body temperature versus brightness temperature of a rhenium surface (rhenium plated on tungsten) is shown in Figure 5, compared with tungsten and molybdenum.

Magnetic Constants

Rhenium was found to have a paramagnetism independent of temperature, in the early 1930's. Numerous papers were published, of which a brief summation of the reported values follows:

<table>
<thead>
<tr>
<th>Date</th>
<th>Investigators</th>
<th>Coefficient of Magnetism, $X_\lambda$, Cm units</th>
<th>Temperature Range, $C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1931</td>
<td>Albrecht and Wedekind(121)</td>
<td>$+0.048 \times 10^{-6}$</td>
<td>--</td>
</tr>
<tr>
<td>1933</td>
<td>Perakis, Capatos and Kytikades(122,123)</td>
<td>$+0.046 \times 10^{-6}$</td>
<td>$00. -23. -79$</td>
</tr>
<tr>
<td>1934</td>
<td>Perakis and Capatos(124)</td>
<td>$+0.047 \times 10^{-6}$</td>
<td>--</td>
</tr>
<tr>
<td>1936</td>
<td>Perakis and Capatos(128)</td>
<td>$+0.369 \times 10^{-6}$</td>
<td>$-90$ to 28</td>
</tr>
<tr>
<td>1938</td>
<td>Perakis and Capatos(126)</td>
<td>$+0.366 \times 10^{-6}$</td>
<td>--</td>
</tr>
</tbody>
</table>
FIGURE 5. BLACKBODY TEMPERATURE PLOTTED AGAINST BRIGHTNESS TEMPERATURE FOR MOLYBDENUM, RHENIUM, AND TUNGSTEN

Levi and Esperson[119]
Perakis and Capatos have done the only extensive work in this field, so it must be assumed that their latest values are the most correct. They also determined several values for the temperature-independent paramagnetism of Re⁺⁷:

\[ \chi = 0.04 \times 10^{-6} \]  
\[ \chi = 0.044 \times 10^{-6} \]  
\[ \chi = 0.049 \times 10^{-6} \]

Thus, it can be seen that the specific susceptibility for Re⁺⁷ is one-eighth that of the pure metal, assuming the last value is most correct. Re⁺⁴ has a variable paramagnetism. Numerous values have been calculated for rhenium compounds, the more important of which have been recorded in Table 9.

The magnetic moment of isotopes ⁷⁵Re¹⁸⁵ and ⁷⁵Re¹⁸⁷ was first calculated to be 3.3 nuclear magnetons for both, but more recent work by Alder and Yu has produced these results:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Magnetic Moment, nuclear magnetons</th>
</tr>
</thead>
<tbody>
<tr>
<td>⁷⁵Re¹⁸⁵</td>
<td>3.1433 ± 0.006</td>
</tr>
<tr>
<td>⁷⁵Re¹⁸⁷</td>
<td>3.1755 ± 0.006</td>
</tr>
</tbody>
</table>

This all supports the thesis that, for atomic nuclei with an odd number of protons and an even number of neutrons, the moment is from 4.6 to 0.1. Perakis, Karantassis, and Capatos found the moment of Re⁺⁷ to be 3.83 Bohr magnetons, which agreed closely with 3.87 Bohr magnetons determined experimentally. From this was derived the above conclusion that Re⁺⁴ has a variable paramagnetism.

Position in the Electromotive Series

The electrode potential of rhenium versus the normal calomel electrode in 2N sulfuric acid is 0.6 volt. This places rhenium between copper and thallium in the electromotive series, a mildly noble position.

Spectra of Rhenium

The Optical Spectrum

Measurements on the arc spectrum of rhenium commenced about 1931 when several investigators became interested in this phenomenon. Using rhenium nitrate, Schöber measured the arc
Spectra from 7200 to 6700 

line of the durely on silver electrodes was the medium. A few of the more important of these lines are recorded in Table 4. It is noteworthy that Meggers reported that at least 25 per cent of the lines showed hyperfine structure. For instance, the strongest line, 4889.15 Å, has six components, and the reported wavelength of this line is an average of the wavelengths of these six components. This type of structure is shown in Figure 6, where the wavelengths of the six components are also recorded. 560 of the lines showed an intensity greater than 20 on a 1-to-2000 scale. These were classified as a combination of 115 levels, belonging to quartet, sextet, and octet systems. Meggers found the ionization potential to be 7.85 volts.

TABLE 4. MAJOR LINES IN THE OPTICAL SPECTRUM OF Rhenium

<table>
<thead>
<tr>
<th>Wavelength, Angstroms</th>
<th>Relative Intensity</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>3460.47</td>
<td>600</td>
<td>Raie ultime</td>
</tr>
<tr>
<td>3464.46</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>4513.31</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>4889.15*</td>
<td>2000</td>
<td>Strongest, blue</td>
</tr>
<tr>
<td>5270.98*</td>
<td>400</td>
<td>Green</td>
</tr>
<tr>
<td>5275.57*</td>
<td>1000</td>
<td>Green</td>
</tr>
<tr>
<td>5834.31</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Meggers later explored the infrared region to 11,000 Å, and other investigators supplemented his work. King observed furnace spectra of tungsten and rhenium and concluded that all of the rhenium lines originated in the lowest energy levels of the atom. These arc spectra are useful for quantitative analysis. Although rhenium content must be less than 1 per cent, Piña de Rubies determined the numbers of rays corresponding to rhenium contents of 5 x 10^{-5}, 10^{-6}, 10^{-7}, and 10^{-6}. Rhenium in materials such as calcite and molybdenite concentrates can be determined from 0.002 to 0.1 per cent by using the intensity of lines 3451.88, 4460.47, and 3464.72 Å. Manganese interferes, up to 16 to 20 per cent, but molybdenum does not.
Englemann (145) studied spectral distribution curves, and from these calculated photoelectric thresholds.

<table>
<thead>
<tr>
<th>Material</th>
<th>Wavelength</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhenium block</td>
<td>2677 Å</td>
<td>Not in vacuum</td>
</tr>
<tr>
<td>Precipitated Re</td>
<td>2671 Å</td>
<td>Not in vacuum</td>
</tr>
<tr>
<td>Rhenium wire</td>
<td>2830 Å</td>
<td>Partial vacuum</td>
</tr>
<tr>
<td>Rhenium</td>
<td>2799 Å</td>
<td>Calculated by Fowler theory</td>
</tr>
<tr>
<td>Rhenium</td>
<td>2480 Å</td>
<td>Probably best value for completely outgassed condition</td>
</tr>
<tr>
<td>Rhenium</td>
<td>2487 Å</td>
<td>Corresponds to exit energy</td>
</tr>
</tbody>
</table>

Thus, the optical spectrum of rhenium has been determined from about 2000 to 11,000 Angstroms.
X-rays were instrumental in the isolation of rhenium (1, 2, 3, 5, 14), and as a result information on the spectrum of rhenium was available at an early date. The principal X-ray lines are reported in Table 5. The work of early investigators was checked by Cauchois (149, 150, 151), who has done extensive work in this field determining some of the less common rhenium lines. (151, 152) Other studies on new or minor X-ray lines have been completed by Lindberg (153, 154) and Renfro (148) (M-series), Inglestam (155) (K-series), and Klinkenberg (156). Klinkenberg notes that the 6s electron is more tightly bound than the 5d electron.

TABLE 5. PRINCIPAL X-RAY SPECTRUM LINES OF RHENIUM

<table>
<thead>
<tr>
<th>Line</th>
<th>Doljek 1926(14)</th>
<th>Berg and Tacke 1926(101)</th>
<th>Weimertof 1926(146)</th>
<th>Renfro 1928(147, 148)</th>
<th>Cauchois 1936-7(149, 150)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lα</td>
<td>1430</td>
<td>1429.9</td>
<td>1429.97</td>
<td>1429.9</td>
<td>1429.97</td>
</tr>
<tr>
<td>Lα2</td>
<td>-</td>
<td>1440.7</td>
<td>1441.0</td>
<td>1440.7</td>
<td>1440.96</td>
</tr>
<tr>
<td>Lβ1</td>
<td>1253.3</td>
<td>1236.2</td>
<td>1236.03</td>
<td>1235.9</td>
<td>1236.92</td>
</tr>
<tr>
<td>Lβ2</td>
<td>1204.3</td>
<td>1204.8</td>
<td>1204.08</td>
<td>1203.8</td>
<td>1204.15</td>
</tr>
<tr>
<td>Lβ3</td>
<td>-</td>
<td>(1216)</td>
<td>-</td>
<td>1217.6</td>
<td>1217.81</td>
</tr>
<tr>
<td>Lβ4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1256.3</td>
<td>1256.60</td>
</tr>
<tr>
<td>Lγ6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1174.7</td>
<td>1174.80</td>
</tr>
<tr>
<td>Lβ6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1248.1</td>
<td>1248.46</td>
</tr>
<tr>
<td>Lβ7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1183.3</td>
<td>1183.71</td>
</tr>
<tr>
<td>Lβ8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1190.0</td>
<td>-</td>
</tr>
<tr>
<td>Lβ9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1162.4</td>
<td>1162.48</td>
</tr>
<tr>
<td>Lβ10</td>
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<td>-</td>
<td>1034.3</td>
<td>1034.92</td>
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Voth (157) determined the relationship between Kα, Kα', Kβ, and Kγ to be as follows:
Three methods were used: the transition method of Kühner, the double-filter method of Russ, and the triple-filter method of Wollan.

The K-absorption limit for rhenium was listed as 173.5 Å by von Platen(158) and Wemmerlöf(37). This was recently revised to 172.66 Å by Manescu(159). Several physicists have found the L-absorption limits; their work is summarized:

<table>
<thead>
<tr>
<th></th>
<th>Rehrts(148)</th>
<th>Sandstrom(149, 150)</th>
<th>Grushin(149)</th>
<th>Manescu(161)</th>
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Manescu(161) also studied and recorded the absorption edges for the double hydrate of rhenium dioxide and for potassium perrhenate. A high-transmission region, \( \alpha \), and a low-transmission region, \( \beta \), were found.

**Nuclear Properties**

**Nuclear Moment**

The nuclear moment of both naturally occurring isotopes of rhenium, \( ^{75}\text{Re}^{185} \) and \( ^{75}\text{Re}^{187} \), is \( \frac{5}{2} \). (105, 162) It was noted in the Optical Spectrum section that many of the rhenium lines are hyperfine. The hyperfine lines, if resolved, show "Flag" patterns caused by a diminishing of intensities from one side to the other. Since this "Flag" effect is regular, both isotopes must have the same moment, \( \frac{5}{2} \). (163, 164, 165) This is characteristic of atoms with two isotopes, of odd atomic number, and odd atomic weight(166), and was verified by Schmidt, who also found that \( \mu = 3.3 \). Kernmagnetons for \( ^{75}\text{Re}^{185, 187} \). Schüller and Korshing(167) found that an addition of 2 neutrons to the nucleus (Re\(^{185} \rightarrow \text{Re}^{187}\)) increased the ratio of the magnetic moment to the atomic number by 1,0108. This additional(168) produced only a small change in the magnetic moment (about 1 per cent), which is characteristic of other elements similar to rhenium, such as thallium and copper. Because of the production of a minimum change, the heavier isotope has the greater magnetic moment. These authors also found marked deviation from the interval rule in the term fine structure which allowed calculation of the quadrupole moment, \( +2.6 \times 10^{-24} \) for the LS coupling (verified by Solomon(169)). This implies a lengthened nucleus. Introduction of the two neutrons also alters the quadrupole moment (a few per cent) but in the opposite direction from the magnetic moment. The isotope displacements were about \( 60 \times 10^{-3} \) cm\(^{-1} \), with \( ^{75}\text{Re}^{187} \), toward the red. Rittenberg(170) has summarized the information as follows:
Naturally Occurring Isotopes. It has been noted above that rhenium has two naturally occurring isotopes, $^{187}\text{Re}$ and $^{185}\text{Re}$. These occur in the ratio of 1:1,62 (105, 161) and the packing fraction is $-1 \pm 2$, identical with osmium.

Of the two isotopes, $^{187}\text{Re}$ is the more interesting. It is radioactive and gives off a $\beta$-particle. (42, 171, 172) Its half-life was found to be $(4 \pm 1) \times 10^{12}$ years by Naidrett and Libby (171); this data was confirmed and broadened by Sugermann and Richter (173) who stated that the half-lives of $^{187}\text{Re}$ cluster into two groups, $4 \times 10^{12}$ and $6.5 \times 10^{12}$ years. The $\beta$-range is 3.5 mg of aluminum/sq cm, giving an upper energy limit of about 43 ev. $^{187}\text{Re}$ also possesses a short-lived isomer, a comparatively rare occurrence among atomic nuclei. The isomer, $^{187}\text{Re}$, was found by DeBenedetti and McGowan (174, 175) who assigned it a half-life of $0.65 \times 10^{-6}$ second with an energy of 0.62 mev. They later (176) estimated the half-life to be $(2.9 \pm 0.6) \times 10^{-7}$ second. Its existence was confirmed by Bunyan, et al. (177), who found a half-life of $(5.26 \pm 0.12) \times 10^{-7}$ second.

The isotopes of rhenium are also produced, of course, as decay products of $^{185}\text{W}$ and $^{187}\text{W}$. In fact, a study of the disintegration of 24-hour $^{187}\text{W}$ led to the discovery of $^{187}\text{Re}$. (174) In general, $^{185}\text{W}$ yields a 0.55-mev $\beta$-particle when decaying to $^{187}\text{Re}$. (178) $^{187}\text{W}$ decays to $^{187}\text{Re}$ through emission of a 1.4-mev $\beta$-particle, or a complicated series of $\gamma$-ray emissions. (178, 179, 180)

Perlman and Friedlander (181) bombarded $^{187}\text{Re}$ with 100-mev and 50-mev $X$-rays. They found the $(\gamma, \gamma)$ yields, relative to $^{14}\text{N}$(n, $\gamma$)$^{15}\text{N}$ yield as unity, to be 82.5, 82.0.

Artificial Isotopes of Rhenium. Numerous radioactive isotopes of rhenium have been produced artificially. The first step in this direction was by Amaldi, D'Agostino, and Signer (182), who claimed neutron bombardment produced a 37-hour period. This has not been found since, but Fermi (183) with the above authors, found a half-life of about 18 to 20 hours. This was confirmed (184), and one of 35 hours was also found. Other investigators soon were working in this field, their work being summarized in Table 6.
It can be seen from the table that about seven artificial isotopes of rhenium are now known, 74Re, 75Re, 76Re, 77Re, 78Re, 75Re, 76Re, and probably 75Re and 76Re. Although not reported in the table, 75Re also has evidently been prepared and studied to a limited degree. Of all these, 75Re and 76Re are by far the most common, and when formed from rhenium occur in close proportion to the natural abundance of 75Re and 76Re.

In general, the preparation of the lower isotopes of rhenium (75Re, 76Re, and 77Re) has been by bombardment of tantalum, tungsten, or rhenium with 20 to 40-nev particles (175, 204, 212), 20-nev deuterons (197, 198, 213), or 10-nev protons (188, 195, 204, 213). For example, Gile, Gerrison, and Hamilton (179, 180) produced the following reactions from tungsten and tantalum:

\[
\begin{align*}
\text{Ta}^{181} (\alpha, n)\text{Re}^{184} & \quad \text{W}^{182} (d, n)\text{Re}^{183} \\
\text{Ta}^{181} (\alpha, 2n)\text{Re}^{183} & \quad \text{W}^{183} (d, 2n)\text{Re}^{183} \\
\text{Ta}^{181} (\alpha, 3n)\text{Re}^{182} & \quad \text{W}^{184} (d, n)\text{Re}^{184} \\
\text{W}^{184} (d, 2n)\text{Re}^{184} & \quad \text{W}^{182} (\alpha, pn)\text{Re}^{184}
\end{align*}
\]

The common isotopes such as 75Re and 76Re are produced by irradiation of rhenium with X-rays (198), or slow and fast neutrons (185, 214), irradiation of compounds (194), or irradiation of some other metal (191). The higher isotopes, 75Re or 76Re, are prepared by neutron or X-ray irradiation of rhenium or some other neighboring element (201, 202).

**Other Nuclear Properties**

Rhenium was found by Goldsmith and Rasetti (215) to exhibit resonance capture for neutrons of high energies (30 to 85 ev). The capture cross section for slow neutrons was calculated by Sinma and Yamasakt (216), who found a cross-section value of \( \sigma = 85 \times 10^{22} \text{ cm}^2 \) for 75Re and \( \sigma = 63 \times 10^{24} \text{ cm}^2 \) for 75Re. The thermal-neutron cross section reported by the AEC is 84 barns per atom (217). Seren, Friedlander, and Turkel (218) measured these properties of rhenium powder as listed on page 38. 75Re possessed a large capture cross section according to Cork (193) and also according to Hibdon and Meuhlhause (219), who did further work on this subject. Harris, et al. (220), measured the neutron-absorption cross section for rhenium in the neutron flux of the Argonne heavy-water reactor, and found the \( \sigma \) pile to equal 120 barns. Pomerance (220A) determined the thermal-neutron-capture cross section to be 84 barns. Meuhlhause (221) also measured the average number of \( \gamma \)-rays and \( \nu \)/neutron capture for rhenium. The value for (odd, even) \( \rightarrow \) (odd, odd) is 1.2.
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<th>Energy</th>
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## Radioactive Isotopes of Rhenium

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Satellite Memorial Institute
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<td>Steffen</td>
<td>207</td>
<td>1951</td>
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<td>Turner and Morgan</td>
<td>208</td>
<td>1951</td>
<td>120-140</td>
<td>0.1, 3.30</td>
<td>0.76</td>
<td>1.07</td>
<td>Particles</td>
<td>Particles</td>
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<td>Stover</td>
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<td>1951</td>
<td>12.7 hr</td>
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### Table of Radiations

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half Life</th>
<th>Energy, Mev</th>
<th>Type of Radiation</th>
<th>Energy, Mev</th>
<th>Type of Radiation</th>
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<th>Energy, Mev</th>
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<th>Half Life</th>
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<td>β</td>
<td>7.30</td>
<td>β</td>
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<td>0.96</td>
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<td>β</td>
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<td></td>
<td>90 hr</td>
<td>1.07</td>
<td>β</td>
<td>7.30</td>
<td>β</td>
<td>90 hr</td>
<td>1.07</td>
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<td>7.30</td>
<td>β</td>
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<td></td>
<td>0.93</td>
<td>β</td>
<td>16.9 hr</td>
<td>β</td>
<td></td>
<td>0.93</td>
<td>β</td>
<td>16.9 hr</td>
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<td>β</td>
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<td></td>
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<td>0.2, 0.7</td>
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<td>250-300 days*</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.2 days</td>
<td>0.2, 1.1</td>
<td>Particles</td>
<td>250-300 days*</td>
<td></td>
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</tr>
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<td></td>
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<tr>
<td>See note below**</td>
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</tr>
</tbody>
</table>

**McBrien (1948) states that the β-particles represent 90 per cent of Re-186 decay.

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* Indicates a decay period.

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Since the discovery of rhenium in 1925, a comparatively small amount of work has been done on the investigation of the physical properties of the metal. This appears to be a result, at least in part, of the unavailability of sufficient quantities of the metal in a high state of purity. It is highly probable that if sufficient use is found for rhenium, a suitable means of producing metal with the required purity would be developed. For most electron-tube applications it is desirable to have the construction materials of very high purity, or at least of a controlled-impurity content.

Rhenium is believed to have physical and electrical properties which might make it a desirable material for certain electron-tube applications.

**Emission Constants**

Only two sets of emission constants for rhenium have been found in the literature. The first measurement of the emission constants of rhenium was made by Alterthum\(^{(120)}\). These were determined for a surface of rhenium deposited on tungsten by vapor-phase decomposition of a rhenium halide. The values which were reported are a work function of 5.1 electron-volts when the Richardson constant is 200 amp cm\(^{-2}\) K\(^{-2}\). The second set of constants, as determined at the Philips Laboratories by Levi and Esperen, (see Figure 7) gives a work function of 4.74 electron-volts with a Richardson constant of 720 amp cm\(^{-2}\) K\(^{-2}\).\(^{(119)}\) The surface used was
FIGURE 7. A RICHARDSON PLOT OF D-C EMISSION DATA TAKEN FROM AN AVERAGE OF ELEVEN DIODES HAVING RHENIUM-PLATED TUNGSTEN EMITTERS LEVI AND ESPERSON (119)
formed by electropolishing rhenium on a tungsten wire in the same manner as described by Link and Barlow. The values were calculated from experimental measurements by employing the following relation:

\[ J = A T^2 e^{-\frac{\phi}{K T}} \]

where

- \( J \) is the measured emission current in amperes cm\(^{-2}\),
- \( A \) is the Richardson constant,
- \( T \) is the temperature, K,
- \( \phi \) is the work function,
- \( K \) is the Boltzmann constant.

Theoretically, the Richardson constant should be 120 amp cm\(^{-2}\) K\(^{-2}\). For most metals the experimental value for this constant is about 60 amp cm\(^{-2}\) K\(^{-2}\). When the value of this constant significantly exceeds the theoretical value of 120 amp cm\(^{-2}\) K\(^{-2}\), or, in the case of metals, 60 amp cm\(^{-2}\) K\(^{-2}\), there are usually impurities present on the surface of the material. For this reason it is believed that the emission constants which have been reported for rhenium are not those of the pure metal. The existing thermionic emission constants for rhenium indicate that additional measurements will be necessary in order to establish better values.

**Secondary-Electron Emission**

The secondary-electron emission of rhenium has been measured for bombarding energies of from 50 to 8000 electron-volts. The maximum yield of 1.3 occurs at an energy of about 900 electron volts. For comparison, the maximum yield for tungsten is 1.38. The most probable energy of secondary electrons from rhenium was found to be approximately 5 electron-volts.

**Photoelectric Threshold**

The photoelectric threshold for rhenium was determined in 1933 by Engelmann. Measurements were made on rhenium in both block and precipitated form in systems which were not evacuated. The photoelectric threshold reported for rhenium in block form was 2677 A. The photoelectric threshold for rhenium in the precipitated form was found to be 2671 A.
photoelectric threshold which was reported for a rhenium wire in a partial vacuum was found to be 2830 A. These three values were calculated from spectral-distribution curves.

When the Fowler theory was used to determine the photoelectric threshold of the rhenium wire in a vacuum, a value of 2799 ± 3 A was found. This threshold corresponds to a photoelectric work function of approximately 4.42 electron-volts. With the usual experimental procedures and techniques for evaluation of the data, photoelectric measurements of the work function are not so sensitive to surface impurities and are more nearly correct than thermionic measurements. By comparison of the above photoelectric value with the thermionic emission work function, experienced technologists would accept the photoelectric value as being most nearly correct. If this value is correct, the work function for rhenium is slightly lower than the work function for tungsten.

**Hall Effect**

Ascherman and Justi have reported work on the electrical conductivity, magnetic increase of resistance, Hall effect, and superconductivity of rhenium. (226) The Hall constant for rhenium is reported to be anomalous, having a value of +3150 x 10^-6 emu. The increase of resistance of rhenium in a magnetic field has the same characteristics as do other metals of uneven atomic number.

Rhenium becomes a superconductor at a temperature of 0.95 K.

**Ionization of Sodium and Cesium Vapor on Glowing Rhenium Surfaces**

The yields of ionized atoms in sodium and cesium vapor at a rhenium surface are 20 per cent and 50 per cent, respectively. (227) This compares with a value of 8.5 per cent for sodium vapor at a tungsten surface and 45 per cent for cesium vapor at a tungsten surface. The yield versus temperature relationship for cesium at the rhenium surface does not agree with Langmuir's theory since the absolute values of yields are below the theoretical amounts. For sodium vapor this relationship is that given by the Langmuir theory.

**Detector Effect of Rhenium Sulfide**

The detector effect of rhenium sulfide has been investigated by Tiede and Lichtenberg. (228) The investigators prepared samples of molybdenum,
tungsten, and rhenium sulfides for their tests. The detector effect was a measurable quantity for both molybdenum sulfide and tungsten sulfide, but for rhenium sulfide the effect was so small that it could not be measured with the equipment which was at hand.

**The Electronic Properties of Rhenium as Compared With Other Refractory Metals**

In order to facilitate evaluation of the possibility of using rhenium in electron tubes, Table 7 was assembled to compare the more pertinent properties which determine the performance of electron-tube components. As may be seen from the table, the spectral emissivity of rhenium is the lowest of those metals listed. This indicates that rhenium, without treatment, is the least applicable where heat dissipation by radiation is of prime importance. Rhenium has a higher electrical resistivity than any of the metals listed in the table. This would allow wire of larger cross section to be used for filament applications. The melting point of rhenium is second only to tungsten for the metals listed in the table. The secondary-emission yield is comparable to that of other metals listed. For most grid applications rhenium would have to be plated with gold or nickel because of its secondary-emission properties. Although the emission constants for rhenium have not been well established, it appears that rhenium might be a better emitter than tungsten. The information given in the table indicates that the boiling point of rhenium is comparable to that of tungsten. For most purposes it appears that rhenium might be superior to other refractory metals in electron-tube applications.

**METALLURGICAL PROPERTIES**

Information on the metallurgy of rhenium is extremely scarce. Only one measurement of the tensile strength and elongation has been carried out, and that on a very fine wire. A little more is known about rhenium alloys, but practically nothing about the alloy structures has been recorded.

**Mechanical Properties**

**Tensile Strength and Elongation**

Agte and co-workers\(^{(91, 94)}\) found the tensile strength of 0.25-mm-diameter vapor-deposited rhenium wire (with 0.03 mm tungsten core) to be 50.6 kg/mm\(^2\), or approximately 70,000 psi. The elongation of the wire in this determination was 24 per cent.
TABLE 7. COMPARISON OF PROPERTIES OF REFRACTORV METALLS
(All references after Kohl(229) except those indicated)

<table>
<thead>
<tr>
<th>Metal</th>
<th>Work Function, ( \phi ) electron-volts</th>
<th>Richardson Constant, ( A_1 ) ( \text{amp/cm}^2/K^2 )</th>
<th>Secondary Electron Emission Coefficient, ( \delta ) max</th>
<th>Electrical Resistivity, ohm-cm (20°C)</th>
<th>Melting Point, C</th>
<th>Boiling Point, C</th>
<th>Spectral Emissivity (0.665µ)</th>
<th>Emission Current, amp/cm² (2600 K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molybdenum</td>
<td>4.37</td>
<td>115</td>
<td>1.25(a)</td>
<td>4.8 ( \times 10^{-6} )</td>
<td>2630 ( \pm 50 )</td>
<td>4800</td>
<td>0.420(b)</td>
<td>2.74</td>
</tr>
<tr>
<td>Columbium</td>
<td>4.01</td>
<td>26</td>
<td>-</td>
<td>15.5 ( \times 10^{-6} )</td>
<td>2415 ( \pm 15 )</td>
<td>&gt;3000(b)</td>
<td>-</td>
<td>4.40</td>
</tr>
<tr>
<td>Tantalum</td>
<td>4.10</td>
<td>37</td>
<td>-</td>
<td>12.4 ( \times 10^{-6} )</td>
<td>2996 ( \pm 50 )</td>
<td>-</td>
<td>0.493</td>
<td>4.43</td>
</tr>
<tr>
<td>Tungsten</td>
<td>4.56</td>
<td>45</td>
<td>1.4(a)</td>
<td>5.5 ( \times 10^{-6} )</td>
<td>3410 ( \pm 20 )</td>
<td>5900</td>
<td>0.470(b)</td>
<td>1.44</td>
</tr>
<tr>
<td>Thorium</td>
<td>3.35(b)</td>
<td>60.2(b)</td>
<td>1.1(a)</td>
<td>18 ( \times 10^{-6} )(b)</td>
<td>1845(b)</td>
<td>&gt;3000(b)</td>
<td>0.360(b)</td>
<td>0.37(b) (1873 \text{ K observed melting point})</td>
</tr>
<tr>
<td>Rhenium</td>
<td>4.47</td>
<td>200</td>
<td>1.3</td>
<td>21.1 ( \times 10^{-6} )</td>
<td>5170 ( \pm 50 )</td>
<td>5900</td>
<td>0.355(d)</td>
<td>5.44</td>
</tr>
</tbody>
</table>

(a) After McKay(230).
(b) International Critical Tables(231).
(c) Calculated from photoelectric threshold determined by Fowler Plot (Englemann).
(d) \( \lambda = 0.650 \mu \) for rhenium.
(e) Emission current calculated for the two sets of constants.
Hardness

The Nadolski (15) first reported a hardness of 250 Brinell, but did not specify the state or purity of the rhenium metal. It was probably annealed. Fink and Deren (38) checked this with special measurements when they determined hardness values for electrodeposited rhenium. The hardness of the electrodeposited plate was also 250 Brinell, compared with 400 for chromium plate and 150 for cadmium plate.

In a study of the so-called "frictional strength" characteristics of rhenium-osmium alloys, Winkler (232) found Vickers values of 247 and 637 for pure rhenium in the annealed and cold-worked states, respectively. In these ranges of hardness readings, the Vickers value of 247 is practically identical to 250 Brinell. Winkler also reported readings of 465 Vickers for annealed tungsten and 183 for annealed osmium (see Table 8).

**TABLE 8. CHARACTERISTICS OF SOME OSMIUM-RHENIUM ALLOYS (After Winkler)**

<table>
<thead>
<tr>
<th>Alloy</th>
<th>a</th>
<th>c/μ</th>
<th>Abrasion Resistance</th>
<th>Scratch Hardness (annealed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-Os</td>
<td>2.725</td>
<td>1.583</td>
<td>100</td>
<td>79</td>
</tr>
<tr>
<td>75-25</td>
<td>2.728</td>
<td>1.586</td>
<td>53</td>
<td>78</td>
</tr>
<tr>
<td>50-50</td>
<td>2.740</td>
<td>1.595</td>
<td>28</td>
<td>59</td>
</tr>
<tr>
<td>25-75</td>
<td>2.750</td>
<td>1.602</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>100-Re</td>
<td>2.754</td>
<td>1.613</td>
<td>21</td>
<td>32</td>
</tr>
</tbody>
</table>

Recently, hardness readings on cross sections of hot-wire-deposited rhenium were taken in this laboratory. The average hardness of pure hot-wire rhenium was about 170 Vickers.

Frictional Properties

These properties govern wear resistance, according to Winkler (232), who evaluated several metals from scratch-hardness measurements (Table 8). The scratch hardness was listed as 32 for "soft" and 36 for "hard" rhenium. The former value can be compared with 34 for tungsten and 79 for osmium. From these scratch hardnesses, Winkler showed that "frictional strength" increased from tantalum (atomic number 73) through tungsten (74) and rhenium (75) to osmium (76) and then dropped off rapidly for iridium, platinum, and gold (77, 78, and 79, respectively). Rhenium, then, was second in "frictional strength" only to osmium.
Abrasion Resistance

In the above study, the abrasion resistance was determined to be 11 for tungsten, 21 for rhenium, and 100 for osmium (see Table 7).

It is noteworthy that rhenium, although second best to osmium in the types of properties just discussed, betters tungsten on almost every count.

Alloys of Rhenium

Tungsten

Becker and Moers(118) determined the melting points in the system tungsten-rhenium. The alloys were prepared as small rods by sintering techniques and installed as anodes in an electric-arc system. After primary ignition of the anode, the current was raised until melting of alloy anode was observed, at which time a large melted bend was allowed to form in the head of the anode. True temperature was calculated and the results combined with the melting point determination of Agte, et al. (91, 94). The resultant solidus curve is shown in Figure 8. It can be seen that the melting points of both pure metals were lowered by addition of the second component. However, a maximum occurred at about 60 per cent rhenium, which the authors assumed to be a new phase with a melting point of about 3010 C. The composition of this phase was equivalent to the formula W\textsubscript{2}Re\textsubscript{3}, and it formed a eutectic with tungsten and rhenium on both sides of the maximum. The melting points of these minima were 2890 C and 2820 C, respectively. Radiographic examination verified the presence of the new crystalline form, different from both tungsten and rhenium (Figure 9). It was also shown that W\textsubscript{2}Re\textsubscript{3} was slightly miscible in tungsten as the saturated solid solution of the new phase in tungsten caused a lattice constant decrease of 1.4 per cent for the tungsten. Solution in rhenium was not proven. A limited solubility for both tungsten and rhenium in the W\textsubscript{2}Re\textsubscript{3} phase seemed to exist.

Small amounts (0.5%) of rhenium added to pure tungsten markedly increased the electrical resistivity\((91, 94)\) according to the following figures:

<table>
<thead>
<tr>
<th>Wire Diameter</th>
<th>As Drawn</th>
<th>Recrystallized</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15 mm</td>
<td>11.5%</td>
<td>12.3%</td>
</tr>
<tr>
<td>0.02 mm</td>
<td>13.5%</td>
<td>14.5%</td>
</tr>
</tbody>
</table>

Iron

This is the only binary system other than tungsten which has been reasonably well studied. Eggert(233) found five phases in establishing the
**FIGURE 8. SOLIDUS CURVE OF THE TUNGSTEN-RHENIUM SYSTEM**
Becker and Moers

**FIGURE 9. SCHEMATIC DIAGRAM OF THE DEBYE-SCHERRER-ROENTGEN PHOTOGRAPH OF W, W₂Re₃ AND Re**
Becker and Moers

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equilibrium diagram up to 50 per cent rhenium (Figure 10). The phases are:

1. \( \epsilon \)-phase — This is probably \( \text{Fe}_3\text{Re}_2 \) and showed a low solubility for iron down to room temperature. It was very hard.

2. \( \eta \)-phase — A phase of wide solubility, apparently based on \( \text{Fe}_3\text{Re} \), formed at 1205 C.

3. \( \delta \)-iron — Decomposes eutectoidally to \( \gamma \)- and \( \eta \)-phases at 1540 C.

4. \( \gamma \)-iron — Face-centered gamma iron which dissolves up to 40 per cent rhenium at 1205 C.

5. \( \alpha \)-iron — Body-centered alpha which dissolves up to 29 per cent rhenium.

Carbon

In general, rhenium does not react readily with carbon, and one writer(234) reported that rhenium-methane reactions were too slight for observation. Another(235) stated that no carbides were formed with rhenium. However, Trzebiatowski(85) heated rhenium in methane and reported an increase in the carbon content in the temperature range 800 to 2200 C. One per cent carbon was taken interstitially into the rhenium lattice, causing an expansion to take place.

When rhenium powder was treated with carbon monoxide, a more noticeable reaction occurred. The carburization effect depended greatly on the activity of the rhenium powder, the most active being a fine-grained product prepared by reduction of ammonium perrhenate.

Large-grained rhenium powder took carbon into its lattice from carbon monoxide at 410 to 1100 C, which resulted in a greater lattice expansion than when rhenium was treated with methane. This expansion then receded to smaller values (e.g., the solubility decreased) than those resulting from methane treatment if the temperature was raised above 1100 C.

The active, small-grained rhenium formed a new phase when treated with monoxide at 470 C or at 600 C. One analysis reported by Trzebiatowski for a 600 C test showed 4.9 per cent carbon content, but the other part from the same specimen showed only 1.0 per cent carbon, normally the highest carbon content found. The new phase probably is rhenium carbidе or a mixture of carbides. This carbidе was unstable at high temperatures, and decomposed above 1600 C to form rhenium metal as one of its decomposition...
FIGURE 10. PHASE DIAGRAM OF THE IRON-RHENIUM SYSTEM
Eggers (233)
products. Thus, rhenium behaves toward carbon as an element inter-
mediary between tungsten and osmium. Osmium also does not form
temperature-resistant carbides.

Mercury

During the electrolysis of aqueous potassium perrhenate\(^{(236)}\), hy-
drated rhenium dioxide, \(\text{ReO}_2\cdot 2\text{H}_2\text{O}\), and an amalgam were deposited at
the mercury cathode, indicating that rhenium does amalgamate with mer-
cury. Druce\(^{(84)}\) also reported that rhenium formed amalgams.

Tin

X-ray studies\(^{(237)}\) have indicated that tin is not soluble in rhenium,
and rhenium is not soluble in tin.

Zirconium

Wallbaum\(^{(238)}\) reported on the lattice constants of the compound
\(\text{ZrRe}_2\).

Osmium

In his study on frictional strength, Winkler\(^{(232)}\) prepared a few
osmium-rhenium alloys which he subsequently tested for abrasion resist-
ance. The lattice constants of these alloys, given in Table 8, show com-
plete mutual solid solubility.

Miscellaneous Alloys

Numerous patents and papers have presented other binary, ternary,
and quaternary alloys containing rhenium. These alloys were most com-
monly developed for thermocouples or high-wear-resistant applications.

An early patent\(^{(239)}\) stated that rhenium will alloy with platinum,
rhodium, iridium, silver, or copper. It was recommended\(^{(240)}\) that a
3.15 per cent rhenium balance platinum versus platinum thermocouple
be used to replace the common Pt/PtRh couple. According to a Fiat
report\(^{(241)}\), the use of rhenium to replace all or part of the rhodium in
thermocouples in this manner evidently became fairly widespread in
Germany in the 1930's.
It was also found at this time that if rhenium was added to iridium in amounts up to 1% per cent, better wire-drawing properties were obtained. (242)

Several refractory alloys were patented by Hensel and Emmert (243, 244). These alloys were reported to be fine grained, with low electrode emissivity, and excellent properties for make-and-break contacts. Their compositions were:

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re</td>
<td>0.01-10</td>
<td>0.01-25</td>
<td>15-25</td>
</tr>
<tr>
<td>Mo</td>
<td>1-20</td>
<td>20-60</td>
<td>20-60</td>
</tr>
<tr>
<td>W</td>
<td>Bal</td>
<td>40-80</td>
<td>40-60</td>
</tr>
</tbody>
</table>

Hard, white alloys of 2 or more per cent rhenium with a balance of tungsten, molybdenum, chromium, tantalum, nickel, cobalt, or iron have also been patented (245), and are reportedly good for pen nibs. In addition, alloys for pen nibs containing rhenium as base metal (50 to 99.9 per cent) have been patented. (95, 96, 246) They are made by powder-metallurgy techniques and may be precipitation hardened. Three typical alloys of this latter type are: (52)

(1) 60Re 15Ni 10W 15Pt or Ru
(2) 90Re 6W 3Ta 1Ni or Co
(3) 75Re 20Pt 5Ni or Co

Alloy (2) above is the hardest of the three listed. Many of these developments were triggered by an osmium shortage in Germany.

An alloy of 95Pt-5Re was found useful for platinum-base electrodes, as it was claimed to possess better corrosion resistance than pure platinum. If true, this alloy is extremely resistant to corrosive attack, for platinum is considered the most corrosion-resistant metal in existence. Five per cent rhenium hardened platinum better than twice as much iridium. Rhenium, it should be noted, is cheaper than iridium. (24)

Corrosion Resistance

The following information on the corrosion resistance of rhenium is classified according to corrosive media.

Atmosphere

Rhenium oxidizes in air (91), and when heated to 1000 °C it oxidizes at the same rate as tungsten. When only 10 per cent oxygen is present in the ambient atmosphere, no attack occurs below 1600 °C, and above 1600 °C
it oxidizes about 1/3 as fast as tungsten. Water vapor or carbon dioxide present in atmospheres of hydrogen or nitrogen speed oxidation, but when the metal is heated in moist hydrogen at 2000°C, passivation occurs toward the moisture-ameliorated oxidation. When so passivated, it still oxidizes in dry air. Sintered rhenium, particularly, corrodes quite readily in air, and evidently suffers a more serious type of attack than has been noticed for plated or arc-melted rhenium. As would be expected, the corrosion product is the heptoxide which is readily hydrolyzed to perhenic acid, a corrosive media in its own right.

Codeposits of rhenium with nickel or iron(247, 248) were found to halt atmospheric tarnishing.

In general, rhenium is more resistant to oxidation than tungsten, and less so than osmium.

Hydrogen

Agte(91) stated that rhenium was not attacked by moist hydrogen at any temperature, although tungsten is susceptible.

Nitrogen

Moist nitrogen(91) attacked rhenium above 1900°C, and if carbon dioxide was used in place of moisture, the attack still continued. Passivation in moist hydrogen stopped this oxidation, even up to 2500°C.

Inert Atmospheres

Under argon, rhenium(91, 94) yields a slight white fog at about 1400°C, but at higher temperatures no fog and no blackening of a surrounding glass envelope occurred.

Acids

One of rhenium's more noted properties is its high resistance to corrosion by hydrochloric acid. Specimens tested in this media have remained unattacked and untarnished for days. However, nitric acid readily dissolves rhenium. Sulphuric acid has little or no effect, even at elevated temperatures. Codeposited nickel-rhenium platings(248) showed even more resistance to concentrated hydrochloric acid than did pure rhenium deposits, although the alloy plate did not stand up against 6N hydrochloric acid, and was also attacked by oxidizing acids.
Alkalies

Alkalies, particularly if fused and in the presence of oxidizing agents, will attack finely divided rhenium. Codeposited nickel(248) aided the resistance of plated rhenium to sodium and ammonium hydroxides.

CHEMICAL PROPERTIES

Introduction

The chemical properties of rhenium are quite well known. They are presented in a highly subdivided manner in this report, so a very brief summary of the more practical chemical properties is given here for the casual reader.

In general, rhenium behaves as an element between tungsten and osmium in the periodic table is expected to behave. It is practically inert to halogen acids, but is attacked by oxidizing acids, such as nitric. It forms a long series of oxides, evidencing its wide variety of valences, from Re to Re+7. The highest oxide, rhenium heptoxide, readily forms from the action of moist air on the metal. This oxide is volatile when heated, so unprotected rhenium cannot be used at high temperatures. The heptoxide is readily soluble in water to form a strong nonoxidizing acid, HReO₄.

Rhenium forms a wide variety of other inorganic and organic compounds, but does not form nitrides. Indications are that rhenium forms both carbides and amalgams.

The physical properties of many of the more common compounds will be found summarized in Table 9.

Valence States

Rhenium has now been found to possess all valence states from Re to Re+7. Since rhenium occurs in Group VII of the periodic table, the maximum valence of +7 is expected. Re+7 is also the strongest rhenium valence. According to Pauling(282), the single-bond radius of rhenium is 1.283 Å.

Rulfs and Elving(283), in a study of the oxidation levels of rhenium, stated that the tendency for rhenium to exist in the Re+1, Re+2, or Re+3 valence states is very low. They determined oxidation potentials in this range which were reported as follows:
<table>
<thead>
<tr>
<th>Oxidation State</th>
<th>Potential vs. Standard Calomel Electrode, volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re(^{-1}) to Re(^{+1})</td>
<td>-0.90</td>
</tr>
<tr>
<td>Re(^{+1}) to Re(^{+2})</td>
<td>-0.27</td>
</tr>
<tr>
<td>Re(^{+2}) to Re(^{+3})</td>
<td>-0.02</td>
</tr>
</tbody>
</table>

**Rhenium\(^{-1}\)**

This is the most recent valence of rhenium observed. In 1937 Lundell and Knowles (284) reduced permanganic acid in the Jones reductor and claimed formation of a Re\(^{-1}\) compound. According to Pauling (285) (1947), this is the only known occurrence of a metal with a negative oxidation number. Maun and Davidson (286) and Lingane (287) also prepared Re\(^{-1}\) by zinc reduction methods. These preparations of Re\(^{-1}\) all occurred in solution only and no compounds were separated, although still more recently, Rulfs and Elving (288) also asserted that some sort of compound must be formed. The following reactions are thought to occur:

\[
\text{Re}^{-1} + \text{gaseous oxygen} = \text{Re}^{+1}
\]
\[
\text{Re}^{-1} + \text{Cu}^{+2} = \text{Re}^{+1} + \text{Cu}
\]
\[
3\text{Re}^{-1} + \text{Re}^{+7} = 4\text{Re}^{+1}
\]
\[
\text{Re}^{+1} + \text{gaseous oxygen} = \text{Re}^{+4}
\]
\[
\text{Re}^{+1} + \text{Cu}^{+2} = \text{Re} \text{ (higher oxidation state)} + \text{Cu}^{+1}
\]
\[
\text{Re}^{+1} + \text{Re}^{+7} = 2\text{Re}^{+4}
\]

Pauling's (285) explanation of the situation is that rhenium possibly exists with an electronic structure similar to Pt\(^{+2}\), which is isoelectronic with Re\(^{-1}\). Re\(^{-1}\) may exist with 4 covalent bonds, with 4 groups arranged in a co-planar square around it. The four groups may be water molecules. If this is the case, hydridorhenic acid, HRe\(_n\), could be formed, although no one has yet isolated it.

**Rhenium\(^{+1}\) and Rhenium\(^{+2}\)**

Two low hydrated oxides of rhenium, Re\(_2\)O\(_3\)-2H\(_2\)O and ReO\(_2\)-H\(_2\)O, were prepared in an impure state by Young and Irvine (288). They reduced permanganic acid with zinc and cadmium, forming Re\(_2\)O\(_3\)-H\(_2\)O and ReO\(_2\)-H\(_2\)O, respectively. Both compounds were isolated.

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TABLE 9. KNOWN PHYSICAL PROPERTIES OF

<table>
<thead>
<tr>
<th>Compound</th>
<th>Name</th>
<th>Crystalline Form</th>
<th>Crystal Dimensions</th>
<th>Physical State</th>
<th>Density at 25°C, g/cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>ReO₂</td>
<td>Rhenium dioxide</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Solid</td>
</tr>
<tr>
<td>ReO₃</td>
<td>Rhenium trioxide</td>
<td>Cubic</td>
<td>3,734</td>
<td>Solid</td>
<td>11.4</td>
</tr>
<tr>
<td>Re₂O₇</td>
<td>Rhenium heptoxide</td>
<td>-</td>
<td>-</td>
<td>Solid</td>
<td>7.43</td>
</tr>
<tr>
<td>H₂ReO₄</td>
<td>Perrhenic acid</td>
<td>-</td>
<td>-</td>
<td>Liquid</td>
<td>2.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K₂ReO₄</td>
<td>Potassium perrhenate</td>
<td>Tetragonal</td>
<td>5.615 12.50</td>
<td>Solid</td>
<td>4.38</td>
</tr>
<tr>
<td>Na₂ReO₄</td>
<td>Sodium perrhenate</td>
<td>-</td>
<td>-</td>
<td>Solid</td>
<td>5.24</td>
</tr>
<tr>
<td>NH₄ReO₄</td>
<td>Ammonium perrhenate</td>
<td>-</td>
<td>-</td>
<td>Solid</td>
<td>3.53</td>
</tr>
<tr>
<td>Ag₂ReO₄</td>
<td>Silver perrhenate</td>
<td>-</td>
<td>-</td>
<td>Solid</td>
<td>6.96</td>
</tr>
<tr>
<td>Cs₂ReO₄</td>
<td>Cesium perrhenate</td>
<td>Orthorhombic</td>
<td>5.73 5.98 14.26</td>
<td>Solid</td>
<td>4.76</td>
</tr>
<tr>
<td>Rb₂ReO₄</td>
<td>Rubidium perrhenate</td>
<td>Tetragonal</td>
<td>5.80 13.14</td>
<td>Solid</td>
<td>4.73</td>
</tr>
<tr>
<td>TI₂ReO₄</td>
<td>Thallium perrhenate</td>
<td>Orthorhombic</td>
<td>5.63 5.80 13.33</td>
<td>Solid</td>
<td>6.89</td>
</tr>
<tr>
<td>ReF₆</td>
<td>Rhenium hexafluoride</td>
<td>-</td>
<td>-</td>
<td>Liquid</td>
<td>4.251</td>
</tr>
<tr>
<td>ReCl₃</td>
<td>Rhenium trichloride</td>
<td>Hexagonal</td>
<td>-</td>
<td>Solid</td>
<td>-</td>
</tr>
<tr>
<td>ReCl₅</td>
<td>Rhenium pentachloride</td>
<td>-</td>
<td>-</td>
<td>Solid</td>
<td>-</td>
</tr>
<tr>
<td>ReBr₃</td>
<td>Rhenium tribromide</td>
<td>-</td>
<td>-</td>
<td>Solid</td>
<td>-</td>
</tr>
<tr>
<td>ReS₂</td>
<td>Rhenium disulfide</td>
<td>-</td>
<td>-</td>
<td>Solid</td>
<td>7.5</td>
</tr>
<tr>
<td>Re₂S₇</td>
<td>Rhenium heptasulfide</td>
<td>Amorphous</td>
<td>-</td>
<td>Solid</td>
<td>4.866</td>
</tr>
<tr>
<td>K₂ReCl₆</td>
<td>Potassium rhenchloride</td>
<td>Octahedral</td>
<td>-</td>
<td>Solid</td>
<td>3.3415</td>
</tr>
<tr>
<td>ReO₃Cl</td>
<td>Rhenium trioxochloride</td>
<td>-</td>
<td>-</td>
<td>Liquid</td>
<td>-</td>
</tr>
<tr>
<td>ReO₂Cl₃</td>
<td>Rhenium dioxytrichloride</td>
<td>-</td>
<td>-</td>
<td>Solid</td>
<td>3.35935</td>
</tr>
<tr>
<td>ReOF₄</td>
<td>Rhenium oxytetrafluoride</td>
<td>-</td>
<td>-</td>
<td>Solid</td>
<td>4.032</td>
</tr>
<tr>
<td>Re(CO)₅</td>
<td>Rhenium pentacarbonyl</td>
<td>Pseudo-tetragonal</td>
<td>-</td>
<td>Solid</td>
<td>-</td>
</tr>
<tr>
<td>Re(CH₃)₃</td>
<td>Trimethylrhenium</td>
<td>-</td>
<td>-</td>
<td>Liquid</td>
<td>1.0</td>
</tr>
<tr>
<td>K₃[ReO₂(CN)₄]</td>
<td>Potassium thoxyocyanide</td>
<td>Monoclinic</td>
<td>-</td>
<td>Solid</td>
<td>2.70440</td>
</tr>
</tbody>
</table>

Notes: d. = decomposed; s. = soluble; est. = estimated
## SOME SELECTED RHENIUM COMPOUNDS

<table>
<thead>
<tr>
<th>Melting Point</th>
<th>Boiling Point</th>
<th>Color</th>
<th>Magnetic Susceptibility at 20°C, CGS units $X \times 10^6$</th>
<th>Solubility Cold Water</th>
<th>Solubility Hot Water</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>d.</td>
<td>-</td>
<td>Brown</td>
<td>+101</td>
<td>-</td>
<td>-</td>
<td>128, 249</td>
</tr>
<tr>
<td>d.</td>
<td>-</td>
<td>Red</td>
<td>+94</td>
<td>-</td>
<td>-</td>
<td>128, 250, 251, 252, 253</td>
</tr>
<tr>
<td>297</td>
<td>363</td>
<td>Yellow</td>
<td>+90</td>
<td>Very soluble</td>
<td></td>
<td>35, 128, 251, 254</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>Colorless</td>
<td>-</td>
<td>Very soluble</td>
<td></td>
<td>255, 266</td>
</tr>
<tr>
<td>555</td>
<td>1370</td>
<td>White</td>
<td>+90</td>
<td>3.6, 22.240, 128, 257, 258, 259, 37, 260, 261</td>
<td></td>
<td></td>
</tr>
<tr>
<td>414</td>
<td>-</td>
<td>White</td>
<td>-</td>
<td>654, 110050.3</td>
<td>260, 262</td>
<td></td>
</tr>
<tr>
<td>580</td>
<td>-</td>
<td>White</td>
<td>-</td>
<td>17, s., d.</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>455</td>
<td>-</td>
<td>White</td>
<td>-</td>
<td>4.3, 27, 150</td>
<td>263, 264</td>
<td></td>
</tr>
<tr>
<td>618</td>
<td>-</td>
<td>White</td>
<td>-</td>
<td>2.44, 18, 15, 260, 3</td>
<td>260, 262</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>-</td>
<td>White</td>
<td>-</td>
<td>2.73, 24, 260, 3</td>
<td>260, 262</td>
<td></td>
</tr>
<tr>
<td>525</td>
<td>-</td>
<td>White</td>
<td>-</td>
<td>1.15, 5, 55, 50</td>
<td>259, 262, 264, 265</td>
<td></td>
</tr>
<tr>
<td>188</td>
<td>47.6</td>
<td>Yellow</td>
<td>-</td>
<td>s., d., s., d.</td>
<td>35, 266, 267, 268</td>
<td></td>
</tr>
<tr>
<td>Sublimes 500 to 550</td>
<td>-</td>
<td>Brown</td>
<td>+1225</td>
<td>s., d., s., d.</td>
<td>35, 128</td>
<td></td>
</tr>
<tr>
<td>- d.</td>
<td>-</td>
<td>Brown</td>
<td>+1225</td>
<td>s., d., s., d.</td>
<td>128, 269</td>
<td></td>
</tr>
<tr>
<td>Sublimes 450</td>
<td>-</td>
<td>Dk. green</td>
<td>+12</td>
<td>-</td>
<td>-</td>
<td>128, 270</td>
</tr>
<tr>
<td>- d&gt;1000</td>
<td>Black</td>
<td>+62</td>
<td>Insoluble</td>
<td>128, 271</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- d&gt;470</td>
<td>Black</td>
<td>-</td>
<td>Insoluble</td>
<td>272</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>Yellow green</td>
<td>-</td>
<td>Slight Insoluble</td>
<td>273, 274</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>171</td>
<td>Yellow</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>275</td>
</tr>
<tr>
<td>394.5</td>
<td>249</td>
<td>Red brown</td>
<td>-</td>
<td>s., d., s., d.</td>
<td>35, 276</td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>Colorless</td>
<td>-</td>
<td>Insoluble</td>
<td>35, 277</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>Colorless</td>
<td>-</td>
<td>Insoluble</td>
<td>278, 279</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>White</td>
<td>-</td>
<td>s., s.</td>
<td>280</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>s., s.</td>
<td>281</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Trivalent rhenium compounds are fairly common; Re$^{+3}$ was probably first prepared in solution by Manchot, Schmid, and Düsing (289). It was later verified by the separation of halides such as rhenium trichloride, ReCl$_3$, and rhenium tribromide, ReBr$_3$. ReCl$_3$ has been studied by Biltz, Geilmann, and Wrigge (290) and can be prepared by electrolytic reduction of potassium rhenochloride solutions (291, 292) or by reduction of perrhenic acid with a hot hydrochloric acid solution of chromium dichloride (293). Oxidation of Re$^{+3}$ solutions to higher valence states occurs very readily (291).

Re$^{+4}$ has been known since early in rhenium history. Turkiewicz (294) reduced potassium perrhenate with chromium and an iodine catalyst to give Re$^{+4}$. The reduction of potassium perrhenate by iodine alone proceeds in two stages:

\[
\text{Re}^{+7} + 2I^- = \text{Re}^{+5} + 2I
\]

\[
\text{Re}^{+5} + I^- = \text{Re}^{+4} + I
\]

Other methods for preparation involve reduction of perrhenic acid by the chlorides of Sn$^{+2}$, Cr$^{+2}$, Ti$^{+3}$, or V$^{+3}$ in hydrochloric acid solution (293, 295, 296). Re$^{+4}$ ion is responsible for the formation of the so-called "Burgundy Red" (161) and has an ionic diameter of 0.68 Å (297). Some of the more common tetravalent compounds are rhenium dioxide, rhenium disulfide, rhenium tetrafluoride, double halides (as K$_2$ReCl$_6$) etc.

Re$^{+7}$ reduces easily in hydrochloric acid to Re$^{+5}$ by electrolytic procedures. Re$^{+5}$ is usually an intermediate in the formation of Re$^{+4}$. It hydrolyzes easily (298) and is unstable in acid solutions, decomposing to Re$^{+4}$ and Re$^{+7}$ (293, 299). Jakob and Jezowska (300) prepared compounds of the type X$_2$ReOCl$_5$. The pentachloride, ReCl$_5$, and a few other pentavalent compounds exist, but Re$^{+5}$ is not so common as Re$^{+4}$ or Re$^{+7}$.

Re$^{+6}$ exists in compounds such as rhenium trioxide, rhenium hexafluoride, and the oxytetrahalides like ReOCl$_4$. The Noddacks (251, 301) reduced rhenium heptoxide with zinc to produce the trioxide in solution, and Biltz, et al. (252) later prepared it in a free state. Re$^{+6}$ has an ionic radius of 0.58 Å.
Rhenium +7

This is the highest and most common of all rhenium valences. Re +7 was present in the starting compounds from which virtually all of the compounds mentioned previously in this valence section were prepared. Hepta-valence is characteristic of Group VII and is evidenced by rhenium heptoxide, Re₂O₇, perrhenic acid, HReO₄, and the salts of perrhenic acid such as potassium and ammonium perrhenates, KReO₄ and NH₄ReO₄, respectively.

Oxides of Rhenium

If rhenium metal is fused with sodium hydroxide, there is no color change immediately noticed. However, if oxygen is added to a water solution of the fused material in greater and greater quantities, a series of color changes will occur in this order: dark brown, light brown, yellow, olive green, dark green, brown, bright red. These colors all correspond to varying oxidation states of rhenium, and of course, simultaneously represent the valences listed above.

About 9 or 10 rhenium oxides in these oxidation states have been reported, but the existence of several is quite doubtful. As might be expected, the higher oxides form acids in solution. Noddack originally noted the following oxides: Re₂O₅, ReO₃, Re₂O₃, ReO₂, Re₂O₅, and Re₂O₇. Others have reported Re₂O₃ (or ReO₄) and Re₃O₈. Rhenium heptoxide forms the very strong acid, HReO₄. The lower oxides should form basic solutions, but the dioxide does not. These oxides are generally quite stable (the highest are more so than the corresponding manganese oxides), which Noddack attributed to their moderate heats of formation. Neighboring elements, such as tungsten, manganese, or osmium possess higher heats of formation. A detailed discussion of the various oxides follows.

Rhenium Suboxide, Re₂O

Young and Irvine, as noted previously, definitely prepared Re₂O·H₂O in the Jones reductor, although Noddack reported it as early as 1933. The compound was black, insoluble in hydrochloric acid, and unattacked by alkaline chromate or acid ferric sulfate. It was soluble in nitric acid and bromine water.

Rhenium Monoxide, ReO

This was also first reported by Noddack, but later produced by Young and Irvine in the same manner as Re₂O·H₂O. Rhenium monoxide
appeared as the double hydrate, ReO$_2$·2H$_2$O, and possessed the same properties noted above for the suboxide.

Rhenium Sesquioxide, Re$_2$O$_3$

Impure black Re$_2$O$_3$ has been prepared with difficulty by Geilmann and Wrigge. (305)

$$2 \text{ReCl}_3 + 3\text{H}_2\text{O} \text{ (alkaline)} = \text{Re}_2\text{O}_3 + 6\text{HCl}$$

Air must be excluded, as the sesquioxide oxidizes readily to perrhenate. It decomposes to Re$^{+2}$, Re$^{+4}$, and Re$^{+7}$ in the presence of alkalies.

Rhenium Dioxide, ReO$_2$

Any high rhenium oxide may be reduced to ReO$_2$ if treated strongly. The Noddacks (251, 301) prepared it by heating sodium or potassium perrhenate with hydrogen. However, the simplest technique was that of Biltz (249), who heated the heptoxide and rhenium for a day at about 650 C:

$$3 \text{Re} + 2 \text{Re}_2\text{O}_7 = 7\text{ReO}_2$$

The dioxide is a dark brown or black solid which reduces easily to metal. (301) Oxidation to perrhenic acid also occurs readily. It will not fuse with barium oxide, but will do so with alkaline sodium and barium perrhenates, and sodium or potassium hydroxides. (302) In the absence of air, rhenites (as Na$_2$ReO$_3$) are formed, and with excess alkali, the hyporhenites (as Na$_3$ReO$_4$). With air, the perrhenates are formed.

Hydrogen chloride will cause formation of oxychlorides from the dioxide, and the dioxide will also precipitate quantitatively as the disulfide from acid solution when treated with hydrogen sulfide. (306) This is important analytically. The thermite reaction can be performed with ReO$_2$ to yield rhenium metal. (93) Decomposition of the dioxide occurs at elevated temperatures in vacuum as follows:

$$7\text{ReO}_2 = 2\text{Re}_2\text{O}_7 + 3\text{Re}$$

Treatment with sulfur dioxide causes formation of ReSO$_4$. (306)

Rhenium Pentoxide, Re$_2$O$_5$

Briscoe, et al. (307) reduced Re$_2$O$_7$ with rhenium metal in a sealed tube, producing a reddish substance claimed to be Re$_2$O$_5$:

$$4 \text{Re} + 5 \text{Re}_2\text{O}_7 = 7 \text{Re}_2\text{O}_5$$
Roth and Becker\(^308\) also formed this oxide as partial product from heating rhenium metal and paraffin oil in a combustion tube. \(\text{Re}_2\text{O}_5\) was insoluble in cold water, hydrochloric and sulfuric acids, and alkaline solutions, but was soluble in warm water and nitric acid. Chlorine probably converted the oxide to oxytetrachloride.

**Tri-Rhenium Octoxide, \(\text{Re}_3\text{O}_8\)?**

This oxide was formed by the reaction:

\[
3 \text{Re}_2\text{O}_7 + 5\text{SO}_2 \text{ (or CO)} = 2 \text{Re}_3\text{O}_8 + 5\text{SO}_3
\]

as stated by the Noddacks\(^{251}\). However, they later surmised it to be compounds of \(\text{ReO}_2\) with \(\text{ReO}_3\) or \(\text{Re}_2\text{O}_7\), so its existence is somewhat questionable. It appeared as a black or violet compound to them, although others thought it was blue.\(^{30}\)

**Rhenium Trioxide, \(\text{ReO}_3\)**

Rhenium trioxide was also first noticed by the Noddacks\(^{297,301}\), who prepared it from perrhenic acid and zinc. It was unstable and impossible to isolate, but salts of \(\text{ReO}_4^{2-}\) were similar to manganates, forming bright yellow solutions. Heating caused decomposition to the heptoxide.\(^{251}\) Biltz\(^{252,309}\) formed it from rhenium metal powder and rhenium heptoxide by a long heating process at about 300°C. It was not originally claimed by him as \(\text{ReO}_3\), but evidence for this formula was good:

\[
3 \text{Re}_2\text{O}_7 + \text{Re} = 7 \text{ReO}_3
\]

Biltz\(^{249}\) later definitely claimed that he prepared the trioxide by heating weighed amounts of the dioxide and heptoxide for over a week:

\[
\text{ReO}_2 + \text{Re}_2\text{O}_7 = 3 \text{ReO}_3
\]

and then found it identical with "rhenium blue"\(^{310}\) found by earlier investigators\(^{30}\). It can also be prepared from the heptoxide and dioxane\(^{253,311}\):

\[
\text{Re}_2\text{O}_7 + x\text{C}_4\text{HgO}_2 = 2 \text{ReO}_3 + \text{decomposition products}
\]

It is a red cubic crystalline solid\(^{252,312}\) not affected by water or dilute caustic. Its heat of formation\(^{313}\) is 82.5 ± 8 kg-cal. The trioxide will liberate iodine from potassium iodide, but no chlorine from hydrochloric acid. In excess of potassium hydroxide and sodium oxide it will fuse to form perrhenates or perrhenites.
Rhenium Heptoxide, \( \text{Re}_2\text{O}_7 \)

This is the most common of the oxides, and is readily formed by exposure of the metal to moist air, or by heating. Oxidation of any of the lower oxides also produces the heptoxide. \( ^{(253)} \)

\[
4 \text{Re} + 7\text{O}_2 \rightarrow 2 \text{Re}_2\text{O}_7
\]

\[
4 \text{ReO}_2 + 3\text{O}_2 \rightarrow 2 \text{Re}_2\text{O}_7, \text{ etc.}
\]

It is a yellow, crystalline substance\( ^{(251)} \) and is readily soluble in water, hydrolyzing to form the strong acid, \( \text{HReO}_4 \). It is also soluble in alcohol and acetone, but not in ether. It can be reduced by hydrogen, carbon monoxide, sulfur dioxide, and other reducing agents to lower oxides or the metal. It is precipitable from solution with hydrogen sulfide as the heptasulfide.

The heptoxide has a density of 8.2 and melts at 297°C. It sublimes at 363°C\( ^{(128)} \), so is a completely unprotective coating for massive rhenium above 300°C. Roth and Becker\( ^{(313)} \) found the heat of formation to be 297.5 ± 2 kg·cal.

Rhenium Tetroxide, \( \text{Re}_2\text{O}_8 \) or \( \text{ReO}_4(?) \)

The Noddacks\( ^{(301)} \) originally assumed falsely that the highest oxide possible for rhenium was \( \text{Re}_2\text{O}_8 \), and isolated a white substance claimed to be this compound. Druce\( ^{(306)} \) also claimed such an oxide. However, its existence was soon questioned by Briscoe, Robinson, and Rudge\( ^{(314)} \) who tried to make it. They found that moisture lowered the melting point of the heptoxide to the value found by the Noddacks, and furthermore, the sublimate was white. A careful check proved the substance was only \( \text{Re}_2\text{O}_7 \), so the existence of \( \text{Re}_2\text{O}_8 \) (or \( \text{ReO}_4 \)) is highly improbable.

Acids and Their Salts

Acids of Rhenium

Perrhenic Acid, \( \text{HReO}_4 \). This is a stable, colorless acid. It is prepared in several simple ways, the most common of which is by the combination or solution of the very common heptoxide with water:\( ^{(301)} \)

\[
\text{Re}_2\text{O}_7 + \text{H}_2\text{O} \rightarrow 2 \text{HReO}_4.
\]
It can also be produced\(^{(255)}\) by the oxidation of rhenium metal with nitric acid:

\[
3 \text{Re} + 7\text{HNO}_3 \rightarrow 3 \text{HReO}_4 + 7\text{NO} + 2\text{H}_2\text{O}.
\]

In addition, oxidation of the lower rhenium oxides, such as \(\text{ReO}_2\)\(^{(315)}\), by hydrogen peroxide, chlorine water, and other oxidizing agents produces the acid:

\[
2 \text{ReO}_2 + 3\text{H}_2\text{O}_2 \rightarrow 2\text{HReO}_4 + 2\text{H}_2\text{O}.
\]

Druce\(^{(316)}\) suggested that oxidation of a sulfide, such as \(\text{Re}_2\text{S}_7\), to perrhenic acid would be a means of recovery of rhenium after analysis when the sulfide was formed.

Roth and Becker\(^{(317)}\) measured the conductivity of perrhenic acid, and found the mobility of \(\text{ReO}_4^-\) at 18°C was 44 ± 1. Thus, \(\text{HReO}_4\) is considered a strong acid, although it is not an oxidizing one. It neutralizes bases and its heat of neutralization with potassium hydroxide is 13.5 ± 0.1 kg-cal at infinite dilution. It is usually yellow in color when concentrated, unless very pure when it appears colorless. The densities of aqueous solutions of perrhenic acid were found by Feit\(^{(256)}\) and are reported in Table 10.

Perrhenic acid will dissolve zinc, iron, and manganese.\(^{(301)}\) It reacts with hydrates of aluminum, zinc, and iron to form perrhenates:

\[
\text{Fe} + 2\text{HReO}_4 = \text{Fe(ReO}_4)_2 + \text{H}_2 \\
\text{Fe(OH)}_3 + 3\text{HReO}_4 = \text{Fe(ReO}_4)_3 + 3\text{H}_2\text{O}.
\]

Although not usually an oxidizing agent, additions of various metals and acids cause the formation of oxides:\(^{(288,301)}\)

\[
2\text{HReO}_4 + \text{Zn} + \text{H}_2\text{SO}_4 \rightarrow 2\text{ReO}_3 + \text{ZnSO}_4 + 2\text{H}_2\text{O}.
\]

Perrhenic acid will react with hydrogen sulfide or ammonium polysulfide in acid solution to produce rhenium disulfide, \(\text{ReS}_2\).\(^{(301)}\) If the solution is dilute, the thioderivatives are apt to be first found.\(^{(318)}\) With hydrogen peroxide alone, it gives a red color, which Hagen and Sieverts\(^{(319)}\) claimed showed the presence of a "per-acid of rhenium heptoxide".

It can be seen, from the reactions of perrhenic acid with metals and bases, that many metal salts of the acid are formed. They are discussed below.

Other Acids, \(\text{H}_2\text{ReO}_4\) and \(\text{H}_3\text{ReO}_5\). Druce\(^{(255)}\) reported rhenic acid, \(\text{H}_2\text{ReO}_4\), as existing in a solution containing perrhenic acid after sulfur...
<table>
<thead>
<tr>
<th>Specific Gravity</th>
<th>Per Cent HReO$_4$</th>
<th>Grams HReO$_4$ per Liter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>1.025</td>
<td>2.93</td>
<td>30</td>
</tr>
<tr>
<td>1.05</td>
<td>5.71</td>
<td>60</td>
</tr>
<tr>
<td>1.075</td>
<td>8.37</td>
<td>90</td>
</tr>
<tr>
<td>1.10</td>
<td>10.91</td>
<td>120</td>
</tr>
<tr>
<td>1.15</td>
<td>15.65</td>
<td>180</td>
</tr>
<tr>
<td>1.20</td>
<td>20.00</td>
<td>240</td>
</tr>
<tr>
<td>1.25</td>
<td>24.40</td>
<td>305</td>
</tr>
<tr>
<td>1.30</td>
<td>28.46</td>
<td>370</td>
</tr>
<tr>
<td>1.35</td>
<td>31.85</td>
<td>430</td>
</tr>
<tr>
<td>1.40</td>
<td>35.00</td>
<td>490</td>
</tr>
<tr>
<td>1.45</td>
<td>37.93</td>
<td>550</td>
</tr>
<tr>
<td>1.50</td>
<td>40.67</td>
<td>610</td>
</tr>
<tr>
<td>1.55</td>
<td>43.23</td>
<td>670</td>
</tr>
<tr>
<td>1.60</td>
<td>45.94</td>
<td>735</td>
</tr>
<tr>
<td>1.65</td>
<td>48.18</td>
<td>795</td>
</tr>
<tr>
<td>1.70</td>
<td>50.29</td>
<td>855</td>
</tr>
<tr>
<td>1.75</td>
<td>52.57</td>
<td>920</td>
</tr>
<tr>
<td>1.80</td>
<td>54.44</td>
<td>980</td>
</tr>
<tr>
<td>1.85</td>
<td>56.22</td>
<td>1040</td>
</tr>
<tr>
<td>1.90</td>
<td>57.90</td>
<td>1100</td>
</tr>
<tr>
<td>1.95</td>
<td>59.49</td>
<td>1160</td>
</tr>
<tr>
<td>2.00</td>
<td>61.00</td>
<td>1220</td>
</tr>
<tr>
<td>2.05</td>
<td>62.44</td>
<td>1280</td>
</tr>
<tr>
<td>2.10</td>
<td>63.81</td>
<td>1340</td>
</tr>
<tr>
<td>2.15</td>
<td>65.12</td>
<td>1400</td>
</tr>
</tbody>
</table>
dioxide was passed through it. The Noddacks(302) claimed the formation of meso-perrhenic acid, $H_2ReO_5$, and some of its salts from a reaction between barium perrhenate and sodium hydroxide. They stated that it was weaker than carbonic acid.

**Salts of Perrhenic Acid**

The $ReO_4^{-}$ ion derived from perrhenic acid forms many salts with metals, positive radicals, and organics. A discussion of all of these with the exception of organics follows. It might be noted that Fonteyne(320) found that the rhenate ion is octahedral in solution, but has a slightly deformed tetrahedral structure in the crystalline state. The valency forces increase when proceeding from the tetrahedral to the octahedral state.

Potassium perrhenate, $KReO_4$. This salt is the result of neutralization of potassium hydroxide with perrhenic acid,

$$KOH + HReO_4 = KReO_4 + H_2O,$$

or potassium chloride and the acid will react:

$$KCl + HReO_4 = KReO_4 + HCl.$$

Potassium perrhenate is the most important salt of perrhenic acid and is an article of commerce.

According to Vorlander and Dalichau(259) (through Druce(321)) the melting point is 552-3 C and boiling point about 1370 C. The melting point was later determined as 513 C by Kleese and Hölemann(261), but revised to 555 C by Smith and Long(260). The heat of formation is 263 kg-cal and a saturated aqueous solution at 18 C is 0.0329N. The density is 4.38 and the heat of solution, according to Roth and Becker(317), is 13.80 ± 3 kg-cal at 21.7 C, but Smith and Long reported a value of 7.68 kcal/mole.

Hölemann and Kleese(261) and Pushin and Kovack(322) have determined the water solubility of this salt at various temperatures. Druce(321) has combined this with unpublished data (see Table 11). Smith(323) also determined the solubility, and his data is combined with the above in Table 11. His plot, including the data of Pushin and Kovack and Hölemann and Kleese is shown in Figure 11. Good agreement was found except for a 6 per cent variation at zero C. Pushin and Kovack also found a eutectic of 0.343 per cent perrhenate at 0.066 C, and noted that the freezing point lowering was 1.5 times the theoretical.

In general, it may be noted that the solubility of potassium perrhenate in cold water is low, and is further lowered by the presence of potassium ion. This is helpful in chemical analysis or recovery. Smith(323) studied
### TABLE 11. THE SOLUBILITY OF POTASSIUM PERRHENATE
*(After Hölemann and Kleese, Pushin and Kovack, Druce, and Smith)*

<table>
<thead>
<tr>
<th>Temp, °C</th>
<th>$\text{KReO}_4$, g/100 cc of water</th>
<th>Temp, °C</th>
<th>Per Cent $\text{KReO}_4$, per 100 cc of solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.36*</td>
<td>109</td>
<td>12.6</td>
</tr>
<tr>
<td>2.01</td>
<td>0.4945</td>
<td>112</td>
<td>14.0</td>
</tr>
<tr>
<td>8.30</td>
<td>0.5207</td>
<td>154</td>
<td>26.3</td>
</tr>
<tr>
<td>10.20</td>
<td>0.5777</td>
<td>194</td>
<td>39.7</td>
</tr>
<tr>
<td>16.90</td>
<td>0.8350</td>
<td>220</td>
<td>50.7</td>
</tr>
<tr>
<td>23.80</td>
<td>1.1580</td>
<td>239</td>
<td>59.9</td>
</tr>
<tr>
<td>30.00</td>
<td>1.47*</td>
<td>290</td>
<td>71.9</td>
</tr>
<tr>
<td>30.90</td>
<td>1.5410</td>
<td>335</td>
<td>84.6</td>
</tr>
<tr>
<td>35.00</td>
<td>1.7920</td>
<td>401</td>
<td>89.3</td>
</tr>
<tr>
<td>38.95</td>
<td>2.016</td>
<td>445</td>
<td>94.4</td>
</tr>
<tr>
<td>40.00</td>
<td>2.22*</td>
<td>470</td>
<td>96.8</td>
</tr>
<tr>
<td>44.85</td>
<td>2.525</td>
<td>498</td>
<td>98.4</td>
</tr>
<tr>
<td>49.78</td>
<td>3.21*</td>
<td>518</td>
<td>100.0 (mp)</td>
</tr>
<tr>
<td>50.45</td>
<td>3.129</td>
<td></td>
<td></td>
</tr>
<tr>
<td>65.80</td>
<td>5.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>86.15</td>
<td>7.522</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100.30</td>
<td>9.484</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Per 100 g water.
FIGURE 11. TEMPERATURE - SOLUBILITY CURVE OF POTASSIUM PERRHENATE AND WATER
Pushin and Kovack\(^{(582)}\),
Höleman and Kleese\(^{(581)}\),
and W.T. Smith\(^{(583)}\)
A systematic study on perchlorate-potassium chloride-water, and found that mild chloride was needed to cause effective precipitation if the temperature was depressed to about zero C. Increasing the temperature decreased the equatorial efficiency.

The electrolytic conductivity of potassium perrhenate solutions at infinite dilution has been determined as follows. (324)

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Molar Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>115.5</td>
</tr>
<tr>
<td>25</td>
<td>125.7</td>
</tr>
<tr>
<td>30</td>
<td>141.8</td>
</tr>
<tr>
<td>40</td>
<td>169</td>
</tr>
</tbody>
</table>

Per cent dissociation of 0.02M and 0.01M solutions were also determined. (324)

Potassium perrhenate can be reduced by zinc, calcium, sodium amalgam, hydrazine hydrate, magnesium, etc. (325, 326) It will not be reduced by sulfur dioxide or hydrocarbons.

Careful reduction with zinc and cold hydrochloric acid (326) will yield step-by-step color changes: yellow, yellow green, bluish violet, brownish black, and nearly colorless. This reduction can be stopped at any time and the appropriate oxide separated. In concentrated sulfuric acid solution, Hölemann (327) found that ferrous, stannous, or titano-sulfates will reduce potassium perrhenate to Re$^5+$ compounds, while chromous sulfate will reduce it to Re$^4+$ compounds. Electrolytic reduction with zinc chloride in the presence of thiocyanates also produced Re$^5+$. (328) In neutral solution (327), electrolysis liberated rhenium and hydrated rhenium dioxide at the cathode. (235)

Numerous other compounds can be prepared, using potassium perrhenate as a starting material.

Ammonium Perrhenate, $\text{NH}_4\text{ReO}_4$. This also is an important rhenium salt. In fact, it is more satisfactory than the potassium perrhenate for reduction to very pure rhenium metal as the potassium-produced metal often contains potassium oxide or other impurities difficult to remove. (33) The salt is prepared by neutralization of perrhenic acid with ammonium hydroxide:

$$\text{HReO}_4 + \text{NH}_4\text{OH} \rightarrow \text{NH}_4\text{ReO}_4 + \text{H}_2\text{O}.$$  

Early determinations gave its solubility in water to be 120 g/l (301), but this has been recently revised to about 17 g/l at zero °C. (260) The temperature of the 120 g/l value is unknown, but it must have been over.

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The density of ammonium perrhenate is 3.53 and the heat of solution 6.21 kcal/mole. It decomposes upon heating at about 165°C, but it is heated in hydrogen, first the black oxide and then metal powder are produced:

\[
\begin{align*}
\text{NH}_4\text{ReO}_4 + \text{H}_2 &= \text{ReO}_2 + \text{NH}_4\text{OH} + \text{H}_2\text{O} \\
\text{ReO}_2 + 2\text{H}_2 &= \text{Re} + 2\text{H}_2\text{O}.
\end{align*}
\]

As noted above, this is a common method of preparing very pure rhenium metal.

**Sodium Perrhenate, NaReO₄.** This colorless salt is also prepared by acid-base neutralization. It is stable and much more soluble than the other common perrhenates. Its water solubility is about 653 g/l at zero C. (260) Its freezing point is 41.4 C and density is 5.24.

**Silver Perrhenate, AgReO₄.** Perrenic acid and silver nitrate form insoluble (4.3 g/l at zero C) silver perrhenate. (264) Its melting point is 455 C and density 6.96. It decomposes at 455 C. (259)

**Manganese Perrhenate, Mn(ReO₄)₂.** This pink salt was first obtained by Druce(329) by dissolving manganese carbonate in perrhenic acid which gave the trihydrate. On drying, the anhydrous salt appeared. The melting point is over 300 C according to Druce(265), but Smith and Maxwell(330) later found it to be much higher, 861 C. It is soluble to the extent of 3400 g/l at 27 C and has a density of 5.12.

**Other Perrhenates.** Copper, nickel, and cobalt perrhenates were first formed from an acid-carbonate interreaction by Briscoe, Robinson, and Rudge. (331) Addition of ammonia or ammonium hydroxide produced amines of the metal salts, such as Cu(ReO₄)₂·4NH₃, Ni(ReO₄)₂·NH₃, or Cu(ReO₄)₂·4NH₃. Smith(260, 264, 330, 332) also prepared other perrhenates. The more common anhydrous ones are given in the list on the following page.

Wilke-Dorfür and Gunzert(333) and Neusser(334) prepared some uncommon perrhenates, the former workers to show the similarity between perrhenic acid and other Group VII acids such as HMnO₄, and the latter while working on the microchemical determination of rhenium. The formulas and colors of the salts are given on page 69.
<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Color</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubidium perrhenate</td>
<td>RbReO₄</td>
<td>White</td>
<td>260</td>
</tr>
<tr>
<td>Cesium perrhenate</td>
<td>CsReO₄</td>
<td>White</td>
<td>260</td>
</tr>
<tr>
<td>Lithium perrhenate</td>
<td>LiReO₄</td>
<td>White</td>
<td>260</td>
</tr>
<tr>
<td>Barium perrhenate</td>
<td>Ba(ReO₄)₂</td>
<td></td>
<td>302</td>
</tr>
<tr>
<td>Thallium perrhenate</td>
<td>TIReO₄</td>
<td>White</td>
<td>302</td>
</tr>
<tr>
<td>Beryllium perrhenate</td>
<td>Be(ReO₄)₂</td>
<td></td>
<td>332</td>
</tr>
<tr>
<td>Magnesium perrhenate</td>
<td>Mg(ReO₄)₂</td>
<td></td>
<td>332</td>
</tr>
<tr>
<td>Calcium perrhenate</td>
<td>Ca(ReO₄)₂</td>
<td></td>
<td>332</td>
</tr>
<tr>
<td>Stannous perrhenate</td>
<td>Sn(ReO₄)₂</td>
<td></td>
<td>332</td>
</tr>
<tr>
<td>Mercuric perrhenate</td>
<td>Hg(ReO₄)₂</td>
<td></td>
<td>332</td>
</tr>
<tr>
<td>Cuprous perrhenate</td>
<td>Cu(ReO)₂</td>
<td></td>
<td>332</td>
</tr>
<tr>
<td>Cupric perrhenate</td>
<td>Cu₂(ReO₄)₂</td>
<td>White</td>
<td>264</td>
</tr>
<tr>
<td>Lead perrhenate</td>
<td>Pb(ReO₄)₂</td>
<td></td>
<td>332</td>
</tr>
<tr>
<td>Cobalt perrhenate</td>
<td>Co(ReO₄)</td>
<td>Purple</td>
<td>330</td>
</tr>
<tr>
<td>Nickel perrhenate</td>
<td>Ni(ReO₄)₂</td>
<td>Yellow</td>
<td>330</td>
</tr>
<tr>
<td>Ferrous perrhenate</td>
<td>Fe(ReO₄)₂</td>
<td>Dark red</td>
<td>330</td>
</tr>
<tr>
<td>Ferric perrhenate</td>
<td>Fe(ReO₄)₃</td>
<td>Black</td>
<td>330</td>
</tr>
<tr>
<td>Neodymium perrhenate</td>
<td>Nd(ReO₄)₃</td>
<td></td>
<td>265</td>
</tr>
<tr>
<td>Lanthanum perrhenate</td>
<td>La(ReO₄)₃</td>
<td></td>
<td>265</td>
</tr>
<tr>
<td>Salt</td>
<td>Color</td>
<td>Reference</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>---------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>([\text{Co}(\text{NH}_3)_6])(\text{ReO}_4)_3)</td>
<td>Orange yellow</td>
<td>333</td>
<td></td>
</tr>
<tr>
<td>([\text{Cu}(\text{NH}_3)_6])(\text{ReO}_4)_2)</td>
<td>Yellow</td>
<td>333</td>
<td></td>
</tr>
<tr>
<td>([\text{Cu} (\text{Co}(\text{NH}_3)_2)_2]_6(\text{ReO}_4)_3)</td>
<td>Green</td>
<td>333</td>
<td></td>
</tr>
<tr>
<td>([\text{Zn}(\text{NH}_3)_2\text{]}(\text{ReO}_4)_2)</td>
<td>White</td>
<td>333</td>
<td></td>
</tr>
<tr>
<td>([\text{Cd}(\text{NH}_3)_4])(\text{ReO}_4)_2)</td>
<td>Colorless</td>
<td>333</td>
<td></td>
</tr>
<tr>
<td>([\text{Co}(\text{NH}_3)_4])(\text{ReO}_4)_2)</td>
<td>Purple red</td>
<td>333</td>
<td></td>
</tr>
<tr>
<td>([\text{Ag}(\text{NH}_3)_4]\text{ReO}_4)</td>
<td>Colorless</td>
<td>333</td>
<td></td>
</tr>
<tr>
<td>((\text{NO})\text{ReO}_4)</td>
<td>Colorless</td>
<td>333</td>
<td></td>
</tr>
<tr>
<td>(<a href="%5Ctext%7BReO%7D_4">\text{Co}(\text{NH}_3)_6</a>_3\cdot 1\frac{1}{2}\text{H}_2\text{O})</td>
<td>Orange</td>
<td>334</td>
<td></td>
</tr>
<tr>
<td>([\text{Co}(\text{NH}_3)_5])(\text{ReO}_4)_3\cdot 3\text{H}_2\text{O})</td>
<td>Rose</td>
<td>334</td>
<td></td>
</tr>
<tr>
<td>([\text{Co}(\text{NH}_3)_5])(\text{ReO}_4)_2)</td>
<td>Red</td>
<td>334</td>
<td></td>
</tr>
<tr>
<td>([\text{Co}(\text{NH}_3)_5])(\text{ReO}_4)_2)</td>
<td>Yellow brown</td>
<td>334</td>
<td></td>
</tr>
<tr>
<td>([\text{Co}(\text{NH}_3)_4])(\text{ReO}_4)_4)</td>
<td>Granite red</td>
<td>334</td>
<td></td>
</tr>
</tbody>
</table>

**Salts of Hyporhenic, Rhenic, and Mesoperrhenic Acids**

According to Druce(335), very little is known concerning the rhenates, \(\text{M}_2\text{ReO}_4\), salts of rhenic acid. However, the Noddacks(302) prepared the sodium and barium salts, \(\text{Na}_2\text{ReO}_4\) and \(\text{BaReO}_4\), from rhenium dioxide, sodium hydroxide, and the appropriate perrhenate.

Mesoperrhenates are salts of mesoperrhenic acid, \(\text{H}_3\text{ReO}_5\), and Scharnow(336) prepared \(\text{Ba}_3(\text{ReO}_5)_2\), barium mesoperrhenate, by evaporation of barium perrhenate with excess barium hydroxide. The hyporhenates, salts of unisolated hyporhenic acid \(\text{HReO}_3\), have been listed by Druce(321) as:

- Sodium hyporhenate \(\text{NaReO}_3\)
- Sodium pyrorhenate \(\text{Na}_4\text{Re}_2\text{O}_7\)
- Sodium ortho-hyporhenate \(\text{Na}_3\text{Re}_4\)
The pinkish-brown potassium rhenate, KReO$_4$, and the pink rhenyl acetate, Na$_2$ReO$_4$, are also known to exist.

The Halides of Rhenium

Numerous halides and related halogen compounds of rhenium have been identified. Discussion of these compounds will be presented in six sections: Halides, Double Halides, Oxylides, Double Oxylides, Double Hydroxyhalides, and Carbonyl Halides.

Rhenium Halides

Fluorides. Two compounds of fluorine, rhenium hexafluoride, ReF$_6$, and rhenium tetrafluoride, ReF$_4$, are known to exist. The former was prepared by Ruff, Kwasnik, and Ascher(277) in a fluor spar tube:

$$\text{Re} + 3\text{F}_2 \rightarrow \text{ReF}_6.$$

Rhenium hexafluoride sublimes easily, giving off purple clouds in air. Its properties were determined by Ruff(337), Ruff and Kwasnik(266, 267, 268, 338), and others. This hexafluoride, a yellow crystalline material, melts at 18.8°C and boils at 47.6°C. The density is 4.251, and the vapor pressure at the melting point is 261.4 mm. With quartz, the hexafluoride reacts to form oxyl fluorides. It also can be oxidized to the oxyl fluorides by more common oxidants. Reduction by hydrogen or sulfur dioxide produces the tetrafluoride, and hydrolysis yields rhenium dioxide, and per henic and hydrofluoric acids.

Rhenium tetrafluoride, with a melting point of 124.5°C(267) was prepared by reduction of the hexafluoride as stated above. Another fluoride, ReF$_7$, was also mentioned, but information on it is sparse. A recent attempt(339) to prepare ReF$_5$ has been unsuccessful.

Chlorides. Several chlorides of rhenium exist. The lowest, rhenium dichloride (ReCl$_2$) was claimed by Schach er(102) in 1929, but evidently it does not exist, as no mention has since been made of it.

Rhenium trichloride, ReCl$_3$, was first reported by Nuddack(297), who formed it from the elements. It is most common, and forms bright red solutions. Other methods of preparation were developed, such as thermal decomposition of pentachlorides or of the double chlorides (as Ag$_2$ReCl$_6$(340), or by reaction between rhenium powder and sulfonyl chloride(341). The latter method is not recommended.
its intensely red solution contains a binuclear complex (290, 292, 342)

\[
\begin{array}{c}
\text{Cl} \quad \text{Re} \quad \text{Cl} \\
\text{Cl} \quad \text{Re} \quad \text{Cl}
\end{array}
\]

This can be assumed to be \( \text{Re}_2\text{Cl}_6 \).

The rhenium trichloride crystals are hexagonal, violet black in color and sublime at 560 to 550°C. The trichloride hydrolyzes to a hydrated oxide (343, 344) or an oxide, and can be oxidized by oxygen to give various oxychlorides:

\[
6\text{ReCl}_3 + 7\text{O}_2 = 4\text{ReO}_3\text{Cl} + 2\text{ReOCl}_4 + 3\text{Cl}_2.
\]

However, it is stable to any oxidation or reduction in acid solutions.\(^{(302)}\) In basic solution, reduction will normally proceed (without lower chlorides forming) directly to metallic rhenium\(^{(302, 343)}\), although zinc, sodium, or mercury will cause formation of \( \text{Re}^{+1} \). Precipitation with hydrogen sulfide is possible, but not quantitatively.\(^{(344)}\) Ammonium hydroxide causes complex reactions with rhenium trichloride\(^{(345)}\) and tensiometric examination shows the existence of ammoniates: \( \text{ReCl}_3 \cdot 14\text{NH}_3, \text{ReCl}_3 \cdot 7\text{NH}_3, \text{ReCl}_3 \cdot 6\text{NH}_3 \). The addition of sodium hydroxide causes a brown precipitate, and \( \text{Re}^{+2}, \text{Re}^{+4}, \) and \( \text{Re}^{+7} \) are found to be present. Insoluble double chloride salts can be obtained by additions of sodium or cesium chloride.

Rhenium tetrachloride, \( \text{ReCl}_4 \), was first reported in 1926\(^{(340)}\), but it may be nonexistent. Briscoe, Robinson, and Rudge\(^{(273)}\) believed they had made it by the Noddacks' method of heating rhenium metal in chlorine\(^{(302)}\), and double halides were then formed from it. This was substantiated by Yost and Shull\(^{(346)}\), who heated measured amounts of rhenium and chlorine in evacuated tubes. These authors believed the rhenium tetrachloride had at least partially polymerized to \( \text{Re}_2\text{Cl}_8 \). The tetrachloride was thought to form brown or reddish crystals and a blue solution. It was reasonably stable.

However, Geilmann, Wrigge, and Biltz\(^{(343, 347)}\) who worked extensively in the field of rhenium chemistry, tried to make the tetrachloride but could prepare only the pentachloride and the trichloride. Analysis showed that a mixture of the two latter chlorides and an oxychloride (also possibly present) could produce a molecular weight easily mistaken for that of rhenium tetrachloride.

As described above, rhenium pentachloride, \( \text{ReCl}_5 \), was prepared by the reaction of excess chlorine on rhenium metal. It is a brownish-black solid yielding dark-brown vapors. It cannot be volatilized at atmospheric pressure without decomposition. Reduction at 400 to 500°C will produce the trichloride\(^{(302, 343)}\) and chlorine. Oxidation\(^{(306)}\) produces oxychlorides:

\[
16\text{ReCl}_5 + 14\text{O}_2 = 16\text{ReOCl}_4 + 4\text{ReO}_3\text{Cl} + 17\text{Cl}_2.
\]
Alkalis cause a reaction of the type

\[ 3\text{ReCl}_5 + 16\text{NaOH} \rightarrow 2\text{ReO}_4^2- \cdot 2\text{H}_2\text{O} + \text{NaReO}_4 + 15\text{NaCl} + 4\text{H}_2\text{O}, \]

although intermediate compounds may be formed. Acids cause a reaction of the type

\[ 10\text{ReCl}_5 + 3\text{HCl} + 3\text{H}_2\text{O} \rightarrow 2\text{HReO}_4 + 8\text{H}_2\text{ReCl}_3 + 13\text{Cl}_2. \]

Neutral salts will form the rhenichloride of the metal involved when added to the pentachloride. (340) Klemm and Frischmuth (345) found ammoniates could be formed in the system \( \text{ReCl}_5 - \text{NH}_3 \), as with the trichloride. The specific compounds present were undetermined.

Noddack (297) claimed formation of rhenium hexachloride, \( \text{ReCl}_6 \), and Yost and Shull (346) reported it (along with the questionable tetrachloride) as a result of heating a 1:6 ratio of rhenium and chlorine. It was not isolated. Druce (340) doubts its formation with good reason, and no one since has produced it.

The highest possible chloride, rhenium heptachloride, \( \text{ReCl}_7 \), was thought formed by Druce and Loring (3, 340) from the action of hydrochloric acid and rhenium. According to Schröter (348) the Noddacks also produced a green crystalline heptachloride. However, this chloride, too, could not be separated and has not been prepared by more recent investigators.

**Bromides.** Rhenium tribromide, \( \text{ReBr}_3 \), was prepared at 500 C by combination of the elements (270). It sublimes slowly at 450 C and forms dark-green crystals on condensation. The addition or presence of oxygen at 400 C probably produces the oxybromide. As with the chlorides, the system \( \text{ReBr}_3 - \text{NH}_3 \) shows formation of ammoniates: \( \text{ReBr}_3 \cdot 20\text{NH}_3 \), \( \text{ReBr}_3 \cdot 14\text{NH}_3 \), \( \text{ReBr}_3 \cdot 9\text{NH}_3 \), \( \text{ReBr}_3 \cdot 7\text{NH}_3 \) (345).

The tetrabromide, \( \text{ReBr}_4 \), is claimed by Druce (338) to have also been identified, but no other evidence than his claim has been uncovered.

**Iodides.** The Noddacks (340) were reported to have made the tetra-iodide, \( \text{ReI}_4 \), but Rulf's and Elving (341) failed to produce it after attempting to do so by several methods.

**Summary.** As a summary of the known and the unconfirmed halides, a short tabulation is presented on the following page.
Physical properties of the more important halides are reported in Table 9. The following summary also lists the common known properties of all the definitely isolated halides:

<table>
<thead>
<tr>
<th>Halide</th>
<th>Name</th>
<th>Color</th>
<th>MP, C</th>
<th>BP, C</th>
<th>Density</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ReF₄</td>
<td>Rhenium tetrafluoride</td>
<td>Yellow</td>
<td>194.6</td>
<td>47.6</td>
<td>4.251</td>
<td>267, 268, 269, 337</td>
</tr>
<tr>
<td>ReF₆</td>
<td>Rhenium hexafluoride</td>
<td>Yellow</td>
<td>18.8</td>
<td>47.6</td>
<td>4.251</td>
<td>267, 268, 269, 337</td>
</tr>
<tr>
<td>ReCl₃</td>
<td>Rhenium trichloride</td>
<td>Violent black</td>
<td></td>
<td></td>
<td>Sublimes at 500</td>
<td>340</td>
</tr>
<tr>
<td>ReCl₅</td>
<td>Rhenium pentachloride</td>
<td>Brown black</td>
<td></td>
<td></td>
<td>Decomposes</td>
<td>340</td>
</tr>
<tr>
<td>ReBr₃</td>
<td>Rhenium tribromide</td>
<td>Green black</td>
<td></td>
<td></td>
<td>Sublimes at 500</td>
<td>270</td>
</tr>
<tr>
<td>ReBr₄</td>
<td>Rhenium tetrabromide</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>340</td>
</tr>
</tbody>
</table>

**Double Rhenium Halides**

Double rhenium halides, or rhenihalides, are the salts of rhenium halogen acids, such as chlororhenic acid, \( \text{H}_2\text{ReCl}_6 \). Except for this, none of these acids have been identified, but their salts do exist and are made from constituents other than the acids.

**Double Fluorides.** Potassium rhenifluoride, \( \text{K}_2\text{ReF}_6 \), has been reported by Ruff and Kwasnik (267) as a possible product from rhenium hexafluoride.

**Double Chlorides.** The afore-mentioned acid, \( \text{H}_2\text{ReCl}_6 \), was found by the Noddacks (269) to result from the interaction of hydrochloric acid and rhenium dioxide, and its most common salt is that of potassium, \( \text{K}_2\text{ReCl}_6 \), also called potassium chlororhenate. (269) It is prepared by...
filtration papier-filter, potassium and potassium iodide with hydrochloric acid. (102, 100, 274, 104 = 120, 180)

$$2KReO_4 + 6KCl + 16HCl = 2K_2ReCl_6 + 4KCl + 8H_2O + 3I_2.$$  

This general type of reaction is also utilized to form other metal rhenium chlorides. Potassium rhenium chloride may also be prepared from the pentachloride. (751)

$$2ReCl_6^- + 4KCl = 2K_2ReCl_6 + Cl_2.$$  

Bricoe, Robinson, and Stoddart (723) obtained it by heating rhenium and potassium chloride in a stream of chlorine gas, and Schmid (752) by electrolytic reduction. Enk (724) found the yellow-green crystals had a density of 3.34; he also determined the equivalent and specific conductivity of water solutions of the salt. It is only slightly soluble in water (702) and dissociates according to the reaction: (724)

$$K_2ReCl_6 = 2K^+ + ReCl_6^{-2},$$

but it then hydrolyses. It is unstable above 25 C. (723) A quantitative precipitation occurs if a solution is boiled, and electrolysis produces Re$^{+2}$ and Re$^{+4}$ at the cathode.

Two other double salts of the same elements were obtained by Krauss and Steinfield (753) and Dählmann (750). These were $K_3ReCl_6$ (brown) and $K_4Re_2Cl_{11}$ (yellow orange). The latter contained both Re$^{+3}$ and Re$^{+4}$.

Double chlorides with metal ions other than potassium have been prepared, usually by the reactions of the type

$$2KReO_4 + 16HCl + 6MCl = 2M_2ReCl_6 + 4MCl + 8H_2O.$$  

The double chlorides are here summarized:

<table>
<thead>
<tr>
<th>Salt</th>
<th>Color</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag$_2$ReCl$_6$</td>
<td>Orange</td>
<td>343</td>
</tr>
<tr>
<td>Ag$_3$ReCl$_6$</td>
<td>-</td>
<td>353</td>
</tr>
<tr>
<td>Rb$_2$ReCl$_6$</td>
<td>Yellow orange</td>
<td>349, 354</td>
</tr>
<tr>
<td>Rb$_3$ReCl$_6$</td>
<td>Yellow orange</td>
<td>350, 354</td>
</tr>
<tr>
<td>Cs$_2$ReCl$_6$</td>
<td>Yellow</td>
<td>350, 354</td>
</tr>
<tr>
<td>Cs$_3$ReCl$_6$</td>
<td>-</td>
<td>354</td>
</tr>
<tr>
<td>Tl$_2$ReCl$_6$</td>
<td>Yellow</td>
<td>351</td>
</tr>
<tr>
<td>Tl$_3$ReCl$_6$</td>
<td>-</td>
<td>353</td>
</tr>
<tr>
<td>Hg$_2$ReCl$_6$</td>
<td>Yellow</td>
<td>351</td>
</tr>
<tr>
<td>(NH$_4$)$_2$ReCl$_6$</td>
<td>-</td>
<td>349</td>
</tr>
</tbody>
</table>

A few organic halides of this type also exist; they will be discussed later in this report.

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Double Bromides. Bilz, et al. (355) claimed that treatment of hydrobromic acid with rhenium dioxide produced bromorrhenic acid, HReBr₆. Using this as a starting point, Krauss and Dählmann (350) and Krauss and Steinfield (355) re-examined several complex bromide salts by addition of light-metal bromides to a bromorrhenic acid solution:

<table>
<thead>
<tr>
<th>Salt</th>
<th>Color</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>K₂ReBr₆</td>
<td>Violet red</td>
<td>350, 352</td>
</tr>
<tr>
<td>Na₂ReBr₆</td>
<td>Dark red</td>
<td>350</td>
</tr>
<tr>
<td>Cs₂ReBr₆</td>
<td>Violet red</td>
<td>350</td>
</tr>
</tbody>
</table>

Double Iodides. Bilz, et al., (355) prepared rhenium hydriodic acid, HReI₆, by the reaction

\[ K_2ReI_6 + H_2SO_4 = K_2SO_4 + HI + HReI_5 \]

and extracted the acid with ether. This reaction is not possible with potassium rhenichloride or rhenibromide. The more probable acid of this type, iodorrhenic acid, H₂ReI₆, has not been isolated.

This potassium salt of iodorrhenic acid, K₂ReI₆, was found by Briscoe, Robinson, and Rudge (356) who heated potassium perrhenate, an excess of potassium iodide, and aqueous hydriodic acid at the boiling point of the acid. The rheniodide separated as crystals. Decomposition of the salt occurred at 300°C. Krauss and Dählmann (350) also prepared rheniodides in like manner, so that the known double iodides are:

<table>
<thead>
<tr>
<th>Salt</th>
<th>Color</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>K₂ReI₆</td>
<td>Brown black</td>
<td>350, 356</td>
</tr>
<tr>
<td>Na₂ReI₆</td>
<td>Black</td>
<td>350</td>
</tr>
<tr>
<td>Cs₂ReI₆</td>
<td>Black</td>
<td>350</td>
</tr>
</tbody>
</table>

Rhenium Oxyhalides

Oxyhalides of a substance are formed when a halogen is substituted for part of the oxygen in a metal oxide. For instance, with Re⁷⁺, one of the more common oxyhalides is ReO₂Cl₃. The oxide of Re⁷⁺, of course, is Re₂O₇.

Oxyfluoride. The first oxyfluoride prepared was probably ReOF₄, rhenium oxytetrafluoride. (277) It was prepared by hydrolysis of the hexafluoride:

\[ ReF₆ + H₂O = ReOF₄ + 2HF \]
This substance forms colorless crystals with a melting point of 59.7°C. Kuff and Kersnik (266, 267) produced the same compound, and others also from rhenium hexafluoride and quartz. Recently Wichterl (357) heated potassium perrhenate with hydrofluoric acid to produce the trioxofluoride:

$$\text{KReO}_4 + \text{HF} = \text{ReO}_3\text{F} + \text{KOH}.$$ 

Aynsley, Peacock, and Robinson (338) prepared two more by a reaction between fluorine (with nitrogen), rhenium dioxide, and potassium perrhenate.

The other known oxyfluorides are listed in the following tabulation:

<table>
<thead>
<tr>
<th>Salt</th>
<th>Name</th>
<th>MP, °C</th>
<th>BP, °C</th>
<th>Color</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ReOF₅</td>
<td>Rhenium oxypentfluoride</td>
<td>35.5</td>
<td>55</td>
<td>Cream</td>
<td>335</td>
</tr>
<tr>
<td>ReOF₄</td>
<td>Rhenium oxytetrafluoride</td>
<td>35.7</td>
<td>62.7</td>
<td>Colorless</td>
<td>266, 267, 277</td>
</tr>
<tr>
<td>ReOF₃</td>
<td>Rhenium oxydifluoride</td>
<td>-</td>
<td>-</td>
<td>Colorless</td>
<td>266, 267</td>
</tr>
<tr>
<td>ReOF₂F₅</td>
<td>Rhenium dioxytrifluoride</td>
<td>90-95</td>
<td>200</td>
<td>Pale yellow</td>
<td>336</td>
</tr>
<tr>
<td>ReOF₂F₃</td>
<td>Rhenium dioxydifluoride</td>
<td>185</td>
<td>-</td>
<td>Colorless</td>
<td>266, 267</td>
</tr>
<tr>
<td>ReOF₂</td>
<td>Rhenium oxytrifluoride</td>
<td>-</td>
<td>-</td>
<td>Colorless</td>
<td>266, 267, 277</td>
</tr>
</tbody>
</table>

**Oxychlorides.** The first oxychlorides were prepared by Brukl and Zeigler (275) by heating together rhenium heptoxide and rhenium tetrachloride. Fractional distillation gave rhenium trioxychloride, ReO₃Cl, as the first product. Geilman, et al., (343) also formed it, but by heating rhenium trichloride in oxygen. The substance is a colorless liquid, freezing at 4.5°C and boiling at 131°C. It is stable but will hydrolyze:

$$\text{ReO}_3\text{Cl} + \text{H}_2\text{O} = \text{HCl} + \text{HReO}_4.$$ 

A second product of the distillation is rhenium oxytetrachloride, ReOCl₄, which can also be prepared by heating chlorides in oxygen:

$$6\text{ReCl}_3 + 5\text{O}_2 = 4\text{ReOCl}_4 + 2\text{ReO}_3\text{Cl},$$

or in air:

$$6\text{ReCl}_3 + 5\text{O}_2 = 4\text{ReOCl}_4 + 2\text{ReO}_3\text{Cl} + 6\text{Cl}_2.$$ 

Either this trichloride or the pentachloride can be used. Heating the oxytetrachloride in oxygen yields the trioxychloride:

$$2\text{ReOCl}_4 + \text{O}_2 = 2\text{ReO}_3\text{Cl} + 3\text{Cl}_2.$$
This oxotetrafluoride(276) consists of brown crystals melting at about 30 C that will hydrolyze to hydrochloric acid, perchloric acid, and hydrated rhenium dioxide. It was also found that ammonia added to the solid oxotetrafluoride produced brown crystals, ReO(NH₄)₂Cl₂, which will hydrolyze in ice water to ReO(OH)₂(NH₄)₂. Heating and evacuating caused formation of ReO₂·NH₃.

Another oxochloride, ReO₂Cl₂, was prepared by Price, Robinson, and Rudge(356). This dioxotrichloride can be made in several ways:

(1) 2Re + 3Cl₂ + 2O₂ = 2ReO₂Cl₃,
(2) 2ReCl₄ + 2O₂ = 2ReO₂Cl₃ + Cl₂,
(3) 2Re₂O₅ + 6Cl₂ = 4ReO₂Cl₃ + O₂,

but the authors specify (1) as the best method. The salt forms needle-like red-brown crystals and melts to a yellow-brown liquid.

Brukl and Plettinger(359) carefully solvated rhenium oxotetrafluoride in organic solvents with small amounts of moisture present. A blue precipitate occurred, having a ratio of rhenium to chlorine of 1:2, but a varying ratio of oxygen to hydroxyl ion. The product could not be isolated, but there is a good possibility that it was rhenium oxydichloride, ReOCl₂.

The oxobromides and a summary of their important properties follow:

<table>
<thead>
<tr>
<th>Salt</th>
<th>Name</th>
<th>Color and State</th>
<th>MP, C</th>
<th>FP, C</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ReO₂Cl₂</td>
<td>Rhenium dioxychloride</td>
<td>Colorless liquid</td>
<td>4.5</td>
<td>131</td>
<td>269, 275</td>
</tr>
<tr>
<td>ReO₂Cl₃</td>
<td>Rhenium dioxytrichloride</td>
<td>Red brown solution</td>
<td>23.9</td>
<td>300</td>
<td>302</td>
</tr>
<tr>
<td>ReOCl₄</td>
<td>Rhenium oxydichloride</td>
<td>Brown solution</td>
<td>30</td>
<td>223</td>
<td>275</td>
</tr>
<tr>
<td>ReOCl₂</td>
<td>Rhenium oxydichloride</td>
<td>Blue solution</td>
<td>-</td>
<td>-</td>
<td>359</td>
</tr>
</tbody>
</table>

Oxybromides. Three oxybromides have been reported. Brukl and Zeigler(350) treated rhenium with oxygen and excess bromide to prepare the trioxybromide, ReO₃Br. This is a white solid with a melting point of 39.5 C. The reaction is:

2Re + 3O₂ + 2Br = 2ReO₃Br.

Preparation of the dioxydibromide, ReO₂Br₂, was more difficult since the compound decomposed before it melted (60-70 C) preventing purification. This caused it to retain an excess of 1-2 per cent of bromine. It has also

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been reported that the oxydibromide, ReOBr₂₂, forms a red solution. No other oxybromides are known.

<table>
<thead>
<tr>
<th>Salt</th>
<th>Name</th>
<th>Color and State</th>
<th>MP, °C</th>
<th>FP, °C</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ReOBr₂₂</td>
<td>Rhenium oxydibromide</td>
<td>Red solution</td>
<td>-</td>
<td>-</td>
<td>360</td>
</tr>
<tr>
<td>ReO₂Br₂</td>
<td>Rhenium dioxydibromide</td>
<td>-</td>
<td>Decomposes at 60-70°C</td>
<td>360</td>
<td></td>
</tr>
<tr>
<td>ReO₃Br</td>
<td>Rhenium trioxydibromide</td>
<td>White solid</td>
<td>39.5</td>
<td>163</td>
<td>360</td>
</tr>
</tbody>
</table>

**Oxyiodides.** No oxyiodides have been reported.

**Double Rhenium Oxyhalides**

Double halides of many of the rhenium compounds have been prepared and here reported. In like manner, double oxyhalides of the rhenium oxyhalides exist.

By the reaction of hydrochloric acid with potassium perrhenate and potassium iodide, Jakob and Jezowska(300) prepared potassium oxyrhenichloride, K₂ReOCl₅. These yellow-green crystals hydrolyzed in moist air and were soluble in dilute acid. They hydrolyzed on further dilution, and heating caused decomposition.

Ammonium oxyrhenichloride, (NH₄)₂ReOCl₅, was prepared in the same manner utilizing ammonium instead of potassium salts. These crystals were also greenish-yellow colored.

Several other double oxyhalides have also been found; all are listed below:

<table>
<thead>
<tr>
<th>Salt</th>
<th>Color</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>K₂ReOCl₅</td>
<td>Yellow green</td>
<td>300</td>
</tr>
<tr>
<td>(NH₄)₂ReOCl₅</td>
<td>Yellow green</td>
<td>300</td>
</tr>
<tr>
<td>K₄Re₂OCl₁₀</td>
<td>-</td>
<td>349, 353</td>
</tr>
<tr>
<td>(NH₄)₄Re₂OCl₁₀</td>
<td>-</td>
<td>349, 353</td>
</tr>
<tr>
<td>Ag₄Re₂OCl₁₀</td>
<td>-</td>
<td>353</td>
</tr>
<tr>
<td>K₂Re₂OBr₁₀</td>
<td>-</td>
<td>302</td>
</tr>
</tbody>
</table>

**Double Rhenium Hydroxyhalides**

In the classical preparation of rhenichlorides and oxyhalides from perrhenic and hydrochloric acid and the metal iodide, intermediate salts...
may be formed. Some of these are rhenihaalides with one or more hydroxyl groups substituted for halides. These compounds are called hydroxyhalides and exist as double salts. Actually, they may be considered in form by hydrolysis of a rhenichloride as follows:

\[
K_2\text{ReCl}_5 \cdot 5\text{H}_2\text{O} = K_2\text{ReCl}_5 \cdot \text{OH} + \text{HCl},
\]

Kvaasa and Dählimann\(^{(350)}\), Jezowska and Jodko\(^{(349)}\), and Jakob and Jezowska\(^{(361, 362)}\), identified some of these substances. The latter electrolyzed hydriodic acid solutions of potassium perrhenate and iodine to form a dihydroxyhalide. The salts are:

<table>
<thead>
<tr>
<th>Salt</th>
<th>Color</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_2\text{Re(OH)Cl}_5)</td>
<td>Green</td>
<td>349, 350</td>
</tr>
<tr>
<td>(K_2\text{Re(OH)}_2\text{Cl}_5)</td>
<td>-</td>
<td>361, 362</td>
</tr>
<tr>
<td>(\text{Rb}_2\text{Re(OH)Cl}_5)</td>
<td>Yellow</td>
<td>349, 350</td>
</tr>
<tr>
<td>(\text{Rb}_2\text{Re(OH)}_2\text{Cl}_5)</td>
<td>Green</td>
<td>350</td>
</tr>
<tr>
<td>(\text{Cs}_2\text{Re(OH)Cl}_5)</td>
<td>Yellow</td>
<td>350</td>
</tr>
<tr>
<td>(\text{Cs}_2\text{Re(OH)}_2\text{Cl}_5)</td>
<td>Yellow</td>
<td>350</td>
</tr>
<tr>
<td>(\text{(NH}_4)_2\text{Re(OH)Cl}_5)</td>
<td>Yellow</td>
<td>349</td>
</tr>
<tr>
<td>(\text{Cs}_2\text{Re(OH)Br}_5)</td>
<td>Red</td>
<td>350</td>
</tr>
</tbody>
</table>

**Rhenium Carbonyl Halides**

These are compounds of the type \(\text{Re(CO)}_5\text{X}_3\), of which the most common is \(\text{Re(CO)}_5\text{Cl}\). This was prepared by Schulten\(^{(363)}\) by three different reactions, all at 230° C for 30 hours under 250 atmospheres pressure.

1. \(\text{ReCl}_5 + 4\text{Cu} + 9\text{CO} \rightarrow \text{Re(CO)}_5\text{Cl} + 4\text{CuCl} \cdot \text{CO}\)
2. \(\text{ReCl}_5 + 2\text{Cu} + 7\text{CO} \rightarrow \text{Re(CO)}_5\text{Cl} + 2\text{CuCl} \cdot \text{CO}\)
3. \(K_2\text{ReCl}_2 + 3\text{Cu} + 8\text{CO} \rightarrow \text{Re(CO)}_5\text{Cl} + 3\text{CuCl} \cdot \text{CO} + 2\text{KCl}\)

The rhenium pentacarbonyl chloride is extracted with ether, appearing as a fine grayish powder. The iodide and bromide salts can also be prepared by identical methods. All are odorless, insoluble in water, and are decomposed by hydrogen peroxide-sodium hydroxide mixtures.

Nieber, Schuh, and Fuchs\(^{(364)}\) also tried to make rhenium carbonyls. They repeated the methods of Schulten and also derived new methods but were at first unsuccessful. Eventually they were able to prepare two compounds by the reaction:

\[\text{Re} + \text{CuCl}_2 + 6\text{CO} = \text{Re(CO)}_5\text{Cl} + \text{CuCICO}.\]
This was essentially the same as Schitten's method, occurring at high temperatures and pressures. Re(CO)₅Cl, Re(CO)₅Br, and Re(CO)₅I could be made by this method. Another method was the reaction:

\[ \text{KReO}_4 + 
\text{CCl}_4 + 8\text{CO} = \text{Re(CO)}_5\text{Cl} + \text{KCl} + \text{COCl}_2 + 3\text{CO}_2. \]

This also occurred at high temperature and pressure. One halide can also be made by another reaction:

\[ 2\text{Re(CO)}_5\text{I} + \text{Br}_2 = 2\text{Re(CO)}_5\text{Br} + I_2. \]

The boiling point of these compounds ranges from 90 to 140°C decreasing in order from the iodo- to the chloro-compound. This represents steps of increasing stability.

Hieber and Fuchs (279) then found that rhenium carbonyl, Re(CO)₅, could be prepared by two methods, neither of which involved removing halogens from the halide carbonyls. Either potassium perrhenate, rhenium heptoxide, or one of the lower oxides were treated with carbon monoxide at 200 to 250°C and 250 to 270 atmospheres:

\[ 2\text{Re}_2\text{O}_7 + 20\text{CO} = 4\text{Re(CO)}_5 + 7\text{O}_2. \]

The crystalline carbonyl is pseudo-tetragonal, and resistant to acids and bases. It melts at 177°C, but is decomposed by nitric or sulfuric acid on heating (400°C). The presence of sulfur causes catalysis and may involve formation of compound, ReH(CO)₅. The carbonyl is probably dimeric, existing as \([\text{Re(CO)}_5]_2\).

**Sulfur Compounds of Rhenium**

Rhenium, like any other metal, forms two types of sulfur compounds, the sulfides, where the metal combines with sulfur alone and directly, and the thiosalts, which involve the metal, sulfur, and some other element.

**Thio-Salts**

Feit (318, 365) treated saturated potassium perrhenate solution with hydrogen sulfide. A yellow solution appeared which Feit reported as a thioperrhenate:

\[ \text{KReO}_4 + \text{H}_2\text{S} = \text{KReO}_3\text{S} + \text{H}_2\text{O}. \]

This compound hydrolyzed, forming monothioperrhenic acid:

\[ \text{KReO}_3\text{S} + \text{H}_2\text{O} = \text{HReO}_3\text{S} + \text{KOH}. \]
Sulfides

Noddack (297) originally reported that the action of hydrogen sulfide on rhenium produced three sulfides, Re$_2$S$_7$, ReS$_3$, and ReS$_2$. This view was supported by Schacherl (102), who stated that rhenium disulfide was the only one of the three that was stable.

**Rhenium Heptasulfide, Re$_2$S$_7$.** This was prepared by precipitation when perrhenate solutions were treated with hydrogen sulfide: (272, 306, 366)

$$2\text{HReO}_4 + 7\text{H}_2\text{S} = \text{Re}_2\text{S}_7 + 8\text{H}_2\text{O}.$$  

However, there was some difficulty in securing a precipitate and the reaction was not thought to be quantitative, so Briscoe, Robinson, and Stoddard (272) prepared the heptasulfide by treating potassium perrhenate with sodium thiosulfate in acid solution. They claimed this method was better than the hydrogen sulfide precipitation. Biltl and Wiebke (366) refuted the statement that the hydrogen sulfide precipitation of rhenium heptasulfide was not quantitative. They prepared the heptasulfide, and found it to be a black powder, easily oxidized in air. Its density was 4.866 and it decomposed exothermically at 460 to 480°C. It was nearly insoluble in water, and was attacked by nitric acid.

**Rhenium Disulfide, ReS$_2$.** Rhenium disulfide may be prepared by heating the heptasulfide in nitrogen or carbon dioxide; sulfur is sublimed: (366)

(a) $\text{Re}_2\text{S}_7 = 2\text{ReS}_2 + 3\text{S}$.

The disulfide may also be prepared directly from the elements:

(b) $\text{Re} + 2\text{S} = \text{ReS}_2$,

or by the method of Tiede and Lehmke (228), who heated rhenium metal and the heptasulfide at 1400°C:

(c) $3\text{Re} + 2\text{Re}_2\text{S}_7 = 7\text{ReS}_2$.

In Method (b), a pressure of hydrogen sulfide must be maintained.
The disulfide is quite stable; Juzw and Hilte(271) found it did not decompose until heated above 1000°C. It was black and possessed a density of 7.5. It will attack quartz. Heating in air caused decomposition by oxidation:

\[ 4\text{ReS}_2 + 15\text{O}_2 = 2\text{Re}_2\text{O}_7 + 8\text{SO}_2. \]

Heating in hydrogen forced reduction to the metal:

\[ \text{ReS}_2 + 2\text{H}_2 = \text{Re} + 2\text{H}_2\text{S}. \]

Rhenium Trisulfide, \( \text{ReS}_3 \). The trisulfide, \( \text{ReS}_3 \), mentioned by Noddack(297) and Schacheri(102), has not been prepared since. Its existence must be considered questionable.

The sulfide compounds are valuable in the chemical analysis of rhenium, where sulfide precipitation for the separation of elements is common. This subject will be covered completely in the Analytical Chemistry section of this report. A summary of the more important rhenium sulfur compounds that have been identified follows:

<table>
<thead>
<tr>
<th>Compound</th>
<th>Name</th>
<th>Color</th>
<th>Density</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{ReS}_2 )</td>
<td>Rhenium disulfide</td>
<td>Black</td>
<td>7.5</td>
<td>102,297,366</td>
</tr>
<tr>
<td>( \text{Re}_2\text{S}_7 )</td>
<td>Rhenium heptasulfide</td>
<td>Black</td>
<td>4.866</td>
<td>102,297,366</td>
</tr>
<tr>
<td>( \text{HReO}_3\text{S}_4 )</td>
<td>Mono-thioperhenic acid</td>
<td>-</td>
<td>-</td>
<td>318,363</td>
</tr>
<tr>
<td>( \text{KReO}_3\text{S}_4 )</td>
<td>Potassium thioperhenate</td>
<td>Yellow</td>
<td>-</td>
<td>318,363</td>
</tr>
<tr>
<td>( \text{TlReO}_3\text{S}_4 )</td>
<td>Thallium thioperhenate</td>
<td>Yellow</td>
<td>-</td>
<td>318</td>
</tr>
<tr>
<td>( \text{TlReS}_4 )</td>
<td>Thallium thiothenite</td>
<td>-</td>
<td>-</td>
<td>318</td>
</tr>
<tr>
<td>( \text{Pb(ReO}_3\text{S}_4 )</td>
<td>Plumbic thioperhenate</td>
<td>Red</td>
<td>-</td>
<td>318</td>
</tr>
<tr>
<td>( \text{Hg(ReO}_3\text{S}_4 )</td>
<td>Mercuroic thioperhenate</td>
<td>Yellow</td>
<td>-</td>
<td>318</td>
</tr>
</tbody>
</table>

Miscellaneous Inorganic Compounds

Selenides

Two selenides of rhenium have been prepared by Briscoe, Robinson, and Stoddard.(272) Both are analogous to the sulfides and are formed in the same manner.
Rhenium Heptaselenide, Re₇Se₇. This was prepared by treating ammoniated aqueous potassium perselenate with hydrogen selenide:

2KReO₄ + 7H₂Se = Re₇Se₇ + 6H₂O + 2KOH.

Like the sulfide, it is a black powder.

Rhenium Diselenide, ReSe₂. If the heptaselenide was heated for nine hours at 330°C in vacuum, reduction to the diselenide occurred:

Re₇Se₇ = 2ReSe₂ + 3Se₂.

Phosphides

Haraldsen (367) heated rhenium and phosphorus together and observed compound formation around and above 780 to 800°C. The possible compounds formed were:

- ReP₃ Rhenium triphosphide
- ReP₂ Rhenium diphosphide
- ReP Rhenium phosphide
- Re₂P Rhenium subphosphide

Silicides

Only one silicide has been reported, and that, the disilicide, ReSi₂, by Wallbaum (368). The compound is isomeric with molybdenum silicide, MoSi₂.

Arsenides

Weichmann, Heimberg, and Biltz (369, 370) studied the system rhenium-arsenic. They reported only one compound was formed, Re₃As₇. The arsenide decomposed at 780°C and no intermediate compounds were formed. The affinity of rhenium for phosphorus is greater than the affinity of rhenium for arsenic.

Rhenides

The possibility that rhenium existed in the Re⁻¹ state was discussed in the Valence States section of this report. Ruleis and Elving (371), assuming that Re⁻¹ would act like a halide, attempted to separate insoluble silver,
It was not reduced by Re⁻¹, was assayed as the cation. Evidently the compound was prepared in solution, but could not be precipitated because thallium chloride and thallium bromide, also present, are less soluble.

Organic Compounds of Rhenium

Alkanes

Trimethylrhenium, Re(C₃H₃)₃. This trialkylrhenium compound was prepared by Druce (280) by treating the trichloride of rhenium with a Grignard reagent:

\[ 2\text{ReCl}_3 + 6\text{CH}_3\text{MgI} \rightarrow 2\text{Re(C}_3\text{H}_3\text{)}_3 + 3\text{MgI}_2 + 6\text{MgCl}_2. \]

The organic is a volatile, colorless, inflammable oil, heavier than water with an ethereal odor. It boils at 60°C.

Triethylrhenium, Re(C₂H₅)₃. Druce claimed (372) that he also prepared this compound in like manner to the trimethylrhenium. It had the same general properties as the methyl compound, but boiled at 30°C.

Other authors (352, 373) have also tried to formulate these organics. They were generally unsuccessful, and stated that rhenium chloride catalyzed a reaction between methyl magnesium iodide and methyl iodide, producing only methane or ethane as product. Druce's explanation of their troubles was that "impurities" caused the failure.

Pyridine Perrhenates

Copper Tetrapyridine Perrhenate, [Cu(C₅H₅N)₄]ReO₄. Wilke-Dörfert and Gunzert (333) isolated this compound after treating pyridine with cupric chloride and perrhenic acid. It is a blue crystalline salt, slightly soluble in water and possessing a density of 2.338.

Silver Tetrapyridine Perrhenate, [Ag(C₅H₅N)₄]ReO₄. This was prepared by the above investigators in the same manner. It is unstable, yielding a pyridine group, C₅H₅N, to form tripyridine perrhenate, also an unstable complex.
Tripyridyl Perrhenate, \( \text{C}_5\text{H}_5\text{N} \cdot \text{NC}_5\text{H}_5 \cdot \text{HReO}_4 \), and 2, 2', 2''-Tripyridyl Perrhenate, \( \text{C}_5\text{H}_5\text{N} \cdot \text{C}_5\text{H}_5\text{N} \cdot \text{C}_5\text{H}_5\text{N} \cdot \text{HReO}_4 \). According to Druce(335, 351), these were prepared by Turkiewicz(294) and reported by Morgan(374). The substances separate from a solution of the pyridine base in perrhenic and acetic acids.

Alkyl Oxides

Rhenium Triethoxide, \( \text{Re(OC}_2\text{H}_5)_3 \), and Rhenium Tri-iso-propyloxide, \( \text{Re(O} \text{C}_3\text{H}_7)_3 \). Sodium ethoxide or sodium propoxidc were treated by Druce(375) with rhenium trichloride:

\[
\text{ReCl}_3 + 3\text{NaOC} \text{C}_2\text{H}_5 = 3\text{NaCl} + \text{Re(OC}_2\text{H}_5)_3
\]

\[
\text{ReCl}_3 + 3\text{NaOC} \text{C}_3\text{H}_7 = 3\text{NaCl} + \text{Re(O} \text{C}_3\text{H}_7)_3.
\]

These organics are brown solids decomposed by water, acids, or alkalies. They are stable in air.

Organic Halides

Turkiewicz(294) has already been mentioned for his preparation of pyridyl perrhenates. In addition, he treated the pyridine base with chloro-rhenic and hydrochloric acids, causing formation of three pyridyl chlorides:

(1) 2, 2'-Dipyridyl Rhenichloride, \( \text{C}_5\text{H}_4\text{N} \cdot \text{C}_5\text{H}_4\text{N} \cdot \text{H}_2\text{ReCl}_6 \)
(2) Bis-2, 2'-Dipyridyl Rhenichloride, \( (\text{C}_5\text{H}_4\text{N} \cdot \text{C}_5\text{H}_4\text{N})_2 \text{H}_2\text{ReCl}_6 \)
(3) 2, 2', 2''-Tripyridyl Rhenichloride, \( \text{C}_5\text{H}_4\text{N} \cdot \text{C}_5\text{H}_4\text{N} \cdot \text{C}_5\text{H}_4\text{N} \cdot \text{H}_2\text{ReCl}_6 \)

The dipyridyl salt (1) appeared as yellow needles, and the bis-salt (2) as green ones. The bis- and tri-salts, (2) and (3), are only slightly soluble in water.

Numerous authors have prepared other complex organic halides. The formulas, names and references for many of these compounds have been compiled in Table 12. Lebedinskii and Ivanov-Lmin(376) claim that their stable complexes are the first examples of rhenium in the cation.

Carbonyls

Rhenium Tri-carbonyl Pyridine, \( \text{Re(CO)}_3(\text{C}_5\text{H}_5\text{N})_2 \). This was prepared by Hicher and Fuchs(377) from rhenium carbonyl and pyridine:

\[
\text{Re(CO)}_5 + 2\text{C}_5\text{H}_5\text{N} \to \text{Re(CO)}_3(\text{C}_5\text{H}_5\text{N})_2 + 2\text{CO}.
\]
<table>
<thead>
<tr>
<th>Formula and Name</th>
<th>Color</th>
<th>Author</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₆H₄N₄·C₆H₅N·H₂ReCl₆</td>
<td>Yellow</td>
<td>Morgan and Davies</td>
<td>51</td>
</tr>
<tr>
<td>2,2'-dipyridyl rhenium dichloride</td>
<td></td>
<td>Turkiewicz</td>
<td>294</td>
</tr>
<tr>
<td>(C₆H₄N₄·C₆H₅N)H₂ReCl₆</td>
<td>Green</td>
<td>Morgan and Davies</td>
<td>51</td>
</tr>
<tr>
<td>Turkiewicz</td>
<td>294</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₆H₄N₄·C₆H₅N·H₂ReCl₆</td>
<td></td>
<td>Turkiewicz</td>
<td>294</td>
</tr>
<tr>
<td>2,2'-dipyridyl rhenium dichloride</td>
<td></td>
<td>Druce</td>
<td>375</td>
</tr>
<tr>
<td>C₂H₅Re(OH)Cl₃</td>
<td></td>
<td>Druce</td>
<td>375</td>
</tr>
<tr>
<td>Ethyl rhenium hydroxychloride</td>
<td></td>
<td>Druce</td>
<td>375</td>
</tr>
<tr>
<td>C₃H₇Re(OH)Cl₃</td>
<td></td>
<td>Druce</td>
<td>375</td>
</tr>
<tr>
<td>Propyl rhenium hydroxychloride</td>
<td></td>
<td>Druce</td>
<td>375</td>
</tr>
<tr>
<td>(C₆H₄CH₃NH₂)H₂ReCl₆</td>
<td>Yellow brown</td>
<td>Schmid</td>
<td>352</td>
</tr>
<tr>
<td>Di-toluidyl rhenium dichloride</td>
<td></td>
<td>Schmid</td>
<td>352</td>
</tr>
<tr>
<td>C₅H₇N·C₈H₈N·H₂ReCl₆</td>
<td>Yellow brown</td>
<td>Schmid</td>
<td>352</td>
</tr>
<tr>
<td>Di-quinodiy rhenium dichloride</td>
<td></td>
<td>Schmid</td>
<td>352</td>
</tr>
<tr>
<td>C₅H₇N·C₈H₈N·C₅H₄N·H₂ReCl₆·H₂O</td>
<td></td>
<td>Morgan and Davies</td>
<td>51</td>
</tr>
<tr>
<td>2,2',2'-tripyrindyl rhenium dichloride hydrate</td>
<td></td>
<td>Lebedinski and</td>
<td>376</td>
</tr>
<tr>
<td>[ReO₂(C₂H₅(NH₂)₂)₂]Cl</td>
<td>Yellow</td>
<td>Lebedinski and</td>
<td>376</td>
</tr>
<tr>
<td>Rhenium dioxodithylenediamine chloride</td>
<td></td>
<td>Ivanov-Emin</td>
<td></td>
</tr>
<tr>
<td>[ReO₂(C₂H₅(NH₂)₂)₂]I</td>
<td>Yellow</td>
<td>Lebedinski and</td>
<td>376</td>
</tr>
<tr>
<td>Rhenium dioxodithylenediamine iodide</td>
<td></td>
<td>Ivanov-Emin</td>
<td></td>
</tr>
<tr>
<td>[ReO(UH)C₂H₅(NH₂)₂]Cl₂</td>
<td></td>
<td>Lebedinski and</td>
<td>376</td>
</tr>
<tr>
<td>Rhenium dioxodithylenediamine dichloride</td>
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<td>Lebedinski and</td>
<td>376</td>
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<td>[ReO(OH)(C₂H₅(NH₂)₂)₂]Cl₆</td>
<td></td>
<td>Lebedinski and</td>
<td>376</td>
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<td>Rhenium oxydihydroxyethylenediamine platin chloride</td>
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<td>Lebedinski and</td>
<td>376</td>
</tr>
<tr>
<td>[ReO(OH)(C₂H₅(NH₂)₂)₂]Co(NO₃)₆</td>
<td></td>
<td>Lebedinski and</td>
<td>376</td>
</tr>
<tr>
<td>Rhenium oxydihydroxyethylenediamine cobalt nitrate</td>
<td></td>
<td>Lebedinski and</td>
<td>376</td>
</tr>
<tr>
<td>[ReO(NH)₃(C₆H₅(NH₂)₂)₂]Cl₃</td>
<td>Blue</td>
<td>Lebedinski and</td>
<td>376</td>
</tr>
<tr>
<td>Rhenium hydroxydihydroxyethylenediamine trichloride</td>
<td></td>
<td>Lebedinski and</td>
<td>376</td>
</tr>
<tr>
<td>(C₆H₄N₄)₄Re₆OCl₁₀</td>
<td></td>
<td>Jesowska and</td>
<td>349</td>
</tr>
<tr>
<td>Tetrapyridine rhenium oxochloride</td>
<td></td>
<td>Jodko</td>
<td></td>
</tr>
<tr>
<td>(C₆H₄N₄)₂Re(OH)Cl₆</td>
<td></td>
<td>Jesowska and</td>
<td>349</td>
</tr>
<tr>
<td>Dipyridine rhenium hydroxychloride</td>
<td></td>
<td>Jodko</td>
<td></td>
</tr>
<tr>
<td>Sr(C₂H₅)₂Cl</td>
<td></td>
<td>Druce</td>
<td>371</td>
</tr>
<tr>
<td>Bis(ethyl) rhenium chloride</td>
<td></td>
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</tr>
</tbody>
</table>
Chloro- and Tricarbonyl Pyridine. ReCl\((\text{CN})_4\) \(\cdot\) \(\text{C}_2\text{H}_5\text{N}\). This can also be made with iodine replacing the chlorine. It is a derivative in which the organic base can be regarded as replacing some of the carbonyl radicals in compounds like rhenium pentacarbonyl chloride, Re(\(\text{CO}\))\(_5\)Cl.

-o-Phenanthroline also substitutes in an analogous manner to pyridine. The reaction is considered simpler to accomplish than with pyridine itself.

**Oxycyanides**

In 1935, Morgan\(^{(374)}\) produced a complex organic cyanide, potassium rhenium oxycyanide, \(K_3[\text{ReO(CN)}_4]\), from potassium perrhenate. The dioxy-salt was prepared next by Klemm and Frischmuth\(^{(281)}\) from potassium rhenium chloride, potassium cyanide, and hydrogen peroxide. This salt, \(K_3[\text{ReO}_2(CN)_4]\), occurred as red monoclinic crystals. It was soluble in water and stable up to 300°C. The density at 40°C was 2.704. The thallium salt, \(\text{Tl}_3[\text{ReO}_2(CN)_4]\), was also made by the same process. Later, Morgan and Davies\(^{(51)}\) made the hydrated salt of sodium, \(\text{Na}_3[\text{ReO}_2(CN)_4] \cdot 2\text{H}_2\text{O}\), and also potassium sodium rhenium dioxy cyanide, \(K_3\text{Na}[\text{ReO}_2(CN)_4] \cdot 6\text{H}_2\text{O}\). Morgan\(^{(374)}\) had already prepared the monoxy-salt of this series. Druce\(^{(371)}\) reported that Turkiewicz made a partially hydrated compound, \(K_3[\text{ReO(CN)}_4 \cdot \text{OH}]\), from rhenium dioxide and potassium cyanide.

Hölemann\(^{(378)}\) produced many of this type of complexes, but never analyzed them. He did, however, report that the average valence of rhenium was about 5, and evidently prepared rhenium oxycyanide salts of silver, copper, mercury, and lead in addition to those light-metal salts already reported.

Tribalat\(^{(379)}\) studied the reduction of perrhenates with potassium thiocyanate and stannous chloride, a reaction typical of the type leading to preparation of these salts. She found that:

\[
\text{HReO}_4 + \text{HCl} + \text{SnCl}_2 + \text{KCNS} \rightarrow \text{Re}^{+4}.
\]

The reaction is quantitative if the hydrochloric acid is four normal. At this point, the stannous chloride reduces the Re\(^{+7}\) to Re\(^{+4}\). If the acid is one normal and excess SnCl\(_2\) is used, both Re\(^{+4}\) and Re\(^{+5}\) are present.

The oxycyanides are summarized in the tabulation on the following page.
Thiocyanates

Druce and Miller prepared the only reported compounds of this type by the following reactions:

\[ 2\text{HReO}_4 + 10\text{HCl} + \text{SnCl}_2 = 2\text{ReOCl}_4 + \text{SnCl}_4 + 6\text{H}_2\text{O} \]
\[ \text{ReOCl}_4 + 4\text{KCNS} = \text{ReO(CNS)}_4 + 4\text{KCl} \]

Rhenium oxythiocyanate, \( \text{ReO(CNS)}_4 \), is a dark-red crystalline material which decomposes to a yellow organic sublimate and residue when heated. Organic salts may be easily prepared, so Druce made the double derivatives of pyridine and quinoline, analogous to uranyl salts of the same type:

<table>
<thead>
<tr>
<th>Salt</th>
<th>Color</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{ReO(CNS)}_4 )</td>
<td>Dark red</td>
<td>380, 381</td>
</tr>
<tr>
<td>( (C_6H_5N\cdot\text{HCNS})_2\text{ReO(CNS)}_4 )</td>
<td>-</td>
<td>380</td>
</tr>
<tr>
<td>( (C_5H_4N\cdot\text{HCNS})_2\text{ReO(CNS)}_4 )</td>
<td>-</td>
<td>380</td>
</tr>
</tbody>
</table>
Microchemical Reactions (Spot Tests)

Noddack(297) first suggested that rhenium could be distinguished from molybdenum by the formation of a yellow-red color when potassium thio-
cyanate was added to a rhenium-containing solution.

Geilmann and Brünger(382) then showed that cesium and rubidium perrhenates would be dyed red if precipitated in the presence of \(\text{MnO}_4^-\). They claimed that 0.00025 mg of rhenium could be detected in 0.00035 cc of solution by this method.

Nitron is an organic precipitant often used in both qualitative and quantitative determinations of rhenium. Kronman and Bibikova(383) added nitron acetate to a drop of acid potassium perrhenate. Gelatin was superimposed on this, and titanium trichloride added on top of the gelatin. The titanium trichloride diffused down through the gelatin and caused the nitron perrhenate crystals to be dyed brownish yellow. Another author(384) found that hydrogen iodide and an iodine crystal will give dark crystalline precipitates of the form \(\text{M}_2\text{ReI}_6\) if added to \(\text{ReO}_4^-\) ion. Salts of potassium, rubidium, cesium, thallium, mercury (ous), or silver are those which, of course, must be present to provide the \(\text{M}^+\) cation. Molybdenum and tungsten interfere.

One of the earlier methods was the borax bead test, to which rhenium imparted a black color if heated in a reducing flame. (385) Yagoda(386) used a sodium carbonate bead. If more than 50 per cent manganese was present, rhenium caused a black to yellow to white color change in the reducing flame. Any flame was usable if there was no manganese present, and tungsten or molybdenum did not interfere. 0.015 mg of rhenium could be detected.

Stannous chloride will reduce tellurates, such as \(\text{Na}_2\text{TeO}_4\), if rhenium is present to catalyze the reaction. A black precipitate or color will result. Poluektov(387) detected as little as 0.025 x 10^{-6} gram in .05 cc by this method, but molybdenum and other elements interfered. This problem can be solved by first distilling the rhenium from the impurities as the heptox-
ate, (388) Anisimov(389) used the same type of reaction, but added potassium thio-
cyanate to the stannous chloride. Molybdenum interference was elimi-
nated by decolorizing with \(\text{NH}_2\text{OH} + \text{HCl}\), and tungsten interference eliminated by adding phosphoric acid.
Organics are popular for spot tests. For example, cesium chloride added to perhenate provoked an orange colattantic perhenate, $Cs(NH_4)_6(ReO_4)_2(H_2O)$, which will detect $1.1 \times 10^{-6}$ gram of rhenium. Dilute iodine gives a green color with molybdenum, but the color is much stronger with rhenium. Zwicker's reagent or thallium nitrate will detect small amounts of rhenium as bluish crystals. Acridine is also used, but pyridine is better.

Wenger and Duckert, in a general evaluation of qualitative data, found that two tests, that with stannous chloride and sodium tellurate or another with stannous chloride and DMG (dimethylglyoxime) which produced a yellow color, were the only fully satisfactory methods of detection.

Several authors have suggested methods for preparation of rhenium salts, followed by confirmation of their occurrence by microscope. Hurd, in Scott's Standard Methods of Chemical Analysis, recommended the following procedure:

1. Precipitate rhenium heptasulfide by acid hydrogen sulfide.
2. Remove molybdenum by addition of sodium sulfide to (1). In this step the molybdenum will be extracted, the rhenium sulfide remaining insoluble.
3. Digest sulfide in sodium hydroxide and hydrogen peroxide; a soluble sodium perrhenate will now be present.
5. Add solid cesium chloride to one drop of Solution (4).
6. Identify the resultant crystals of $CsReO_4$ microscopically.

Several other final precipitants can also be used, such as rubidium chloride. Geitmann and Wrigge precipitated and identified the crystals characteristic of double chlorides, prepared from acid solutions of rhenium trichloride by addition of rubidium, cesium, pyridine, quinoline, acridine, and others. Salts of the type $K_4ReCl_6$, $CsReCl_4$, and $C_6H_5NHReCl_4$ are produced. Photomicrographs of a few of these crystals are reproduced in Figure 12.

**General Qualitative Tests**

Closed- and open-tube reactions were studied at an early date by Geitmann and Wrigge. The closed-tube reactions were unsatisfactory,
FIGURE 12. PHOTOMICROGRAPHS OF COMPLEX RHENIUM HALIDE CRYSTALS SUSPENDED FOR COMPLEX IDENTIFICATION

GALILEE MEMORIAL INSTITUTE
Fig. 1 Rubidium-Rheniumtrichlorid
Fig. 2. Caesium-Rheniumtrichlorid
Fig. 3 Pyridin-Rheniumtrichlorid
Fig. 4
but those with the open tube were evaluated as good. Very small quantities of rhenium can be determined. If a test tube containing rhenium is heated, the following will occur:

(1) A bluish oxide will form near the test substance, particularly if sulfur dioxide is added. Druce(385) suggested that this was the oxide $\text{Re}_3\text{O}_8$.

(2) Farther away, yellow hygroscopic crystals of rhenium heptasulfide form.

(3) White drops, possibly impure rhenium heptoxide, appear on the coolest part of the tube.

(4) White, odorless fumes at the open end of the tube color the Bunsen flame yellowish green.

(5) The oxide deposit can be dissolved in water, perhydrol, and ammonia. Treatment with potassium or rubidium chloride yields potassium or rubidium perrhenate.

If rhenium compounds are placed on charcoal in an oxidizing flame(385), fumes, a green color, and a bronze-red deposit are formed. Geilmann and Wrigge said this and other flame tests were poor.

Yoe(397) added the following reagents to rhenium solutions in the order given, and noted the color changes. The solution was first prepared with hydrochloric acid and ammonium acetate. Then "aluminon" (the ammonium salt of aurintricarboxylic acid) was introduced, causing formation of a red solution. Ammonium hydroxide turned the solution pale yellow, and ammonium carbonate destroyed all color.

Potassium thiocyanate and stannous chloride were presented as reagents by Geilmann, Wrigge, and Weibke.(398) As little as 0.5 x $10^{-6}$ gram of rhenium could be detected. The thiocyanate was added to an acid solution containing stannous chloride. The presence of rhenium was indicated by a yellow color: ether extraction removed the yellow complex and evaporation of the extracted solution left a red solid. This reaction was modified by Hurd and Babler(399) and, in a general study, was later stated by Hurd(400) to be the best laboratory test for the detection of $\text{Re}^{+7}$. Hurd also found that ethyl xanthate would separate molybdenum from rhenium by formation of a molybdenum complex, removable by carbon tetrachloride extraction. The rhenium is then free to be detected if present. This reaction separates Group III elements in the analysis system developed by Wenger, Duckert, and Ankajdio.(401)

Hurd(400) discovered that rhenium will appear in the test for arsenic using the system of Prescott and Johnson. Their text(402), noting that
rhenium belongs to the hydrogen sulfide group, suggested detection by fusion of the heptasulfide with sodium hydroxide. In the absence of chromium, manganese, rubidium, and osmium, a yellow color appeared. Water extraction and precipitation of ammonium or potassium perrhenate give further proof if desired.

Rhenium can be determined in Noyes and Bray's system, although much rhenium is thought to be lost in acid hydrogen sulfide precipitations. However, this can be avoided, and final detection by stannous chloride, potassium thiocyanate, and hydrogen sulfide is recommended.

Geilmann and Bode have recently compiled extensive information on the techniques of separating rhenium from the hydrogen sulfide group and other metal ions. Some of the methods for cation removal follow:

1. Ag⁺ - Precipitate as a chloride or metal from basic solution.
2. Hg⁺₂ - Precipitate as Hg by hydrogen peroxide from basic solution, or by reduction with hydrazine.
3. Pb⁺² - Separate as the chromate, thiocyanate, or thiosulfate.
4. Bi⁺³ - Remove as the oxychloride or phosphate.
5. Cu⁺² - Precipitate by hydrogen peroxide from basic solution or remove by electrolysis.
6. Cd⁺² - Precipitate by 8-hydroxyquinoline.
7. As⁺⁵ - Remove as (NH₄)₃AsO₄·3H₂O.
8. Sb⁺³ - Remove with thionalide, or separate the rhenium by hydrogen sulfide.
9. Sn⁺⁴ - Separate by boiling in a buffered acetate solution.
10. Au⁺¹ - Separate with sulfur dioxide, hydroquinone, or oxalic acid.
11. Mo⁺⁵ - Precipitate with oxime.
12. Ge⁺² - Separate as Mg₂GeO₂.
14. Te⁺⁴ - Precipitate with hydrazine and sulfur dioxide.
Rhenium belongs to the hydrogen sulfide group, suggested detection by fusion of the heptasulfide with sodium hydroxide. In the absence of chromium, manganese, niobium, and tantalum, a yellow color appeared. When extraction and precipitation of ammonium or potassium oxalate give further proof is desired.

Rhenium can be determined in Noyes and Bray's system, although rhenium is thought to be lost in acid hydrogen sulfide precipitations. (203, 404) However, this can be avoided, and final detection by ammonium chloride, potassium thiocyanate, and hydrogen sulfide is recommended.

Geilmann and Bode (405, 406) have recently compiled extensive information on the techniques of separating rhenium from the hydrogen sulfide group and other metal ions. Some of the methods for cation removal follow:

1. $\text{Ag}^{+1}$—Precipitate as a chloride or metal from basic solution.
2. $\text{Hg}^{+2}$—Precipitate as Hg by hydrogen peroxide from basic solution, or by reduction with hydrazine.
3. $\text{Pb}^{+2}$—Separate as the chromate, thiocyanate, or thiosulfate.
4. $\text{Bi}^{+3}$—Remove as the oxychloride or phosphate.
5. $\text{Cu}^{+2}$—Precipitate by hydrogen peroxide from basic solution or remove by electrolysis.
6. $\text{Cd}^{+2}$—Precipitate by 8-hydroxyquinoline.
7. $\text{As}^{+5}$—Remove as $(\text{NH}_4)_3\text{AsO}_4 \cdot 3\text{H}_2\text{O}$.
8. $\text{Sb}^{+3}$—Remove with thionalide, or separate the rhenium by hydrogen sulfide.
9. $\text{Sn}^{+4}$—Separate by boiling in a buffered acetate solution.
10. $\text{Au}^{+1}$—Separate with sulfur dioxide, hydroquinone, or oxalic acid.
11. $\text{Mo}^{+3}$—Precipitate with oxalate.
12. $\text{Ge}^{+2}$—Separate as $\text{Mg}_2\text{GeO}_3$.
13. $\text{Se}^{+4}$—Remove by reducing agents. Not usually harmful.
14. $\text{Te}^{+4}$—Precipitate with hydrazine and sulfur dioxide.
Special Methods

Heyrovsky(407), who originally laid a claim to the discovery of rhenium, with his photomicrograph, later stated the instrument would detect a five to six-mol/L solution. The rhenium must be present as the sulfide. This work of Heyrovsky's was separate from the discovery claim (which was later abrogated) and is considered fully accurate.

Electrolysis and spectroscopy were utilized by Schleicher(408), who electrolyzed a small volume of solution with a copper wire as cathode. The anode was a platinum crucible lid which contained the solution. After electrolysis the residue and solution were evaporated in an electric arc giving rhenium spectral lines.

Summary

Table 13 lists a number of characteristic qualitative reactions, including spot tests, special methods, and some of the general methods. A few reactions not discussed in the text are also reported. Where possible, the test is evaluated.

Many of the qualitative methods presented herein are either inaccurate or too complicated. However, most authors agree that the microscopic identification of crystals is a positive, straightforward method. The chemical reactions are simple and few, and a permanent pictorial record of the crystals can readily be maintained.

Quantitative Analysis

Chemical Methods

The first significant step in the development of chemical methods of quantitative analysis was taken by Gailmann and Voigt(86, 412) in 1930 when they applied the organic base, nitron (1, 4-diphenyl-3, 5-endo-anilino-4, 5-diphenyl-1, 2, 4-triazole), formerly used for determination of nitrates, to the analysis of perrhenates. Slightly acid potassium perrhenate, treated with nitron, forms very insoluble precipitates in water (0.18 mg/l) and even less soluble ones in the presence of nitron acetate. The rhenium is normally determined gravimetrically as ReO

If molybdenum is present, it interferes, but can be removed with 8-hydroxyquinoline. Many methods(409) for the quantitative analysis of rhenium use nitron for the final determination, no matter what the prior steps. Melaven(33), however, currently producing rhenium metal at the University of Tennessee, does not recommend nitron, and prefers the organic precipitate tetraphenyl arsonium chloride, to be discussed below.
One common method of the nitric type is that of Rössing chemists, who first separated both rhenium and molybdenum from acid solutions as nitrites. The precipitate was then oxidized with alkaline hydrogen peroxide to cause conversion to perrhenates and molybdates. Care must be taken here as the peroxide may contain nitrite. Molybdenum was removed by 3-hydroxyquinoline, and the rhenium determined with nitron.

It was long believed that if rhenium could be precipitated from basic instead of acid solution, separation from molybdenum would occur in that step. This had been considered impossible until Müller and LaLande claimed that treatment of perrhenate solutions with hydrogen sulfide under pressure produced a slow but practically quantitative precipitation. This was done only with difficulty. Recently, however, it has been shown that rhenium heptasulfide is appreciably soluble in alkaline sulfide solutions, refuting the claim of Müller and LaLande.

More recently, acid sulfide precipitations have been carried out under pressure. Geilmann and co-workers summarized sulfide precipitations from various types of rhenium solutions:

- \( \text{Re}^{+3} \) - Precipitate from 0.05-1.0N hydrochloric acid solutions at room temperature. A mixture of sulfides results.
- \( \text{Re}^{+4} \) - Stronger acid solutions can be used. Rhenium disulfide precipitates.
- \( \text{Re}^{+7} \) - Add warm ammonium polysulfide, then add acid. If desired, rhenium of other valences can be oxidized to \( \text{Re}^{+7} \) prior to precipitation. However, this method is considered poor, as the precipitation may be sulfur contaminated.
- \( \text{Re}^{\text{Any}} \) - Saturate with hydrogen sulfide at room temperature, then heat the closed flask to 100°C. Rhenium sulfide will precipitate under the pressure generated.

Geilmann and Bode have also devised a sodium thiosulfate type of sulfide precipitation. Reduction of rhenium sulfides with hydrogen at elevated temperatures has been suggested.

Krauss and Steinfeld found that thallium acetate, \( \text{TlC}_2\text{H}_3\text{O}_2 \), would separate insoluble thallium perrhenate from \( \text{Re}^{+7} \) solution. The determination was gravimetric and chlorides interfered. However, thallium perrhenate is soluble in cold water to the extent of 1.15 g/l and, on this basis, the method cannot be recommended for quantitative analysis.

The volatility of rhenium heptoxide is useful for separation from molybdenum. Volatilization was originally obtained by heating the perrhenates with sulfuric acid in air. This was objectionably slow, so hydrogen...
TABLE 13. SOME SIMPLE TESTS FOR RE

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Color of Result</th>
<th>Amount Detectable, ppm</th>
<th>Interfering Elements (if mentioned)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitate rhenium as:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) KBReO₄</td>
<td>Yellow</td>
<td>0.25</td>
<td>Mo</td>
</tr>
<tr>
<td>(2) Na₂ReO₄</td>
<td>Red</td>
<td>0.10</td>
<td>Mo</td>
</tr>
<tr>
<td>(3) CaReO₄</td>
<td>Red</td>
<td></td>
<td>Mo</td>
</tr>
<tr>
<td>in presence of Mo₄⁻</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open-tube reactions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bluish oxide</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow crystals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White droplets</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White fumes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaCl₂ and KCl₆</td>
<td>Yellow</td>
<td>0.8</td>
<td>Mo</td>
</tr>
<tr>
<td>HCl and NH₄Ac plus:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) Aluminium</td>
<td>Red</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2) NH₄OH</td>
<td>Pale yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3) (NH₄)₂CO₃</td>
<td>Colorless</td>
<td></td>
<td></td>
</tr>
<tr>
<td>in that order,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitron, Na₂S, gelatin plus:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiCl₄</td>
<td>Brownish yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HI and I crystal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dark precipitate</td>
<td></td>
<td></td>
<td>Mo, W</td>
</tr>
<tr>
<td>(1) SnCl₂ + Ferrocyanide</td>
<td>Red</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2) SnCl₂ + Dimethylglyoxime</td>
<td>Yellow</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>(3) Heat (2)</td>
<td>Green</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O₂, KMnO₄, RbCl</td>
<td>Identify crystals by microscope</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SnCl₄ and Na₂TeO₄</td>
<td>Black</td>
<td>0.025</td>
<td>V, W, As, Os, Mo</td>
</tr>
<tr>
<td>Na₂CO₃ bead, &gt;50% Mn, heat in reducing flame</td>
<td>Black to yellow to white</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Roseo chloride</td>
<td>Orange</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>HCl plus: Rb, Cs, pyridine, quinoline, amide, aniline, base</td>
<td>Identify crystals by microscope</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toluidine 3, 4-dithiol and KCNS</td>
<td>Green</td>
<td>5</td>
<td>Mo</td>
</tr>
<tr>
<td>Zweiker's Reagent and Vaseline</td>
<td>Identify blue crystals</td>
<td>10-15</td>
<td></td>
</tr>
<tr>
<td>in TiNO₃ and Vaseline</td>
<td>by microscope</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Photograph</td>
<td>No step, no Re</td>
<td>10⁻⁶ molar solution</td>
<td></td>
</tr>
<tr>
<td>Spectrograph</td>
<td>Characteristic lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-ray spectrum, Li₂O, and H₂P₄</td>
<td>Characteristic lines</td>
<td>0.72</td>
<td>Mo for b₄₁</td>
</tr>
<tr>
<td>with halothionol and H₂SO₄</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Event, How by</td>
<td>Non-Newtonian Flow</td>
<td>Determination by</td>
<td>Author</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------</td>
<td>------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Poor</td>
<td>Geilmann and Wrigge</td>
<td>395</td>
<td></td>
</tr>
<tr>
<td>Poor</td>
<td>Geilmann and Wrigge</td>
<td>396</td>
<td></td>
</tr>
<tr>
<td>Poor</td>
<td>Best Lab test for Re&gt;17</td>
<td>Geilmann, Wrigge, and Weibke</td>
<td>396</td>
</tr>
<tr>
<td>Poor</td>
<td>Kronman and Bibikova</td>
<td>383</td>
<td></td>
</tr>
<tr>
<td>Poor</td>
<td>Kronman and Berkman</td>
<td>384</td>
<td></td>
</tr>
<tr>
<td>Poor</td>
<td>Tougartinoff</td>
<td>409</td>
<td></td>
</tr>
<tr>
<td>Poor</td>
<td>Kao and Chang</td>
<td>395</td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td>Polimahtkov</td>
<td>388</td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td>Yagoda</td>
<td>388</td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td>Neumie</td>
<td>334</td>
<td></td>
</tr>
</tbody>
</table>
| Ca, Rh  
 good    | Geilmann and Wrigge | 584              |        |           |
| Ca, Rh  
 acetadine  
good   | Miller              | 381              |        |           |
| Poor         | Haynoyevéy         | 5                |        |           |
| Poor         | Kholstov           | 608              |        |           |
| Poor         | Pravat              | 415              |        |           |
| Poor         | Tribel              | 421              |        |           |
chloride was passed through the perrhenate-sulfuric acid solution, causing a rapid distillation. Further developments occurred, and now the method is to acidify the test solution with nitric and hydrochloric acids, partially evaporate, treat with sulfuric acid, and steam distill.

Still other methods have been reported for securing a rhenium-molybdenum separation. Hoffmann and Lundell reduced the molybdenum to an ether-soluble complex with mercury and potassium thiocyanate. The ether extract was used to determine molybdenum. Stannous chloride then reduced the rhenium to an ether-soluble state, which was extracted and determined. Hurd and Hiskey varied this procedure slightly by extracting molybdenum and rhenium together with ether, then removing the rhenium by distillation. Geilmann and Bode studied these ether separation methods, and recommended that the molybdenum be removed by 8-hydroxyquinoline. In this case, it was suggested that potassium xanthate be added and the molybdenum then be extracted as a molybdenum xanthate complex with chloroform.

Melaven and Whelse suggested that α-benzoinoxime be substituted for 8-hydroxyquinoline. Melaven had also evaluated the foregoing methods. He found that the molybdenum xanthate-chloroform extraction of Hurd was satisfactory for qualitative but not quantitative work. Ether extraction with steam distillation was satisfactory for rhenium determinations in manganese ores, but not in molybdenite. The mercury reduction method of Hoffmann and Lundell was satisfactory, but long and detailed.

In the α-benzoinoxime method, the molybdenum was precipitated from solution with the reagent and separated by filtration, leaving rhenium in solution. Potassium thiocyanate and stannous chloride were added. These caused formation of a rhenium thiocyanate color complex, the transmittance of which was measured with a photoelectric spectrophotometer and compared with a blank, thus determining the rhenium content. The method is not recommended if the sample contains large amounts of molybdenum.

Willard and Smith found that tetraphenyl arsonium ion, \((\text{C}_6\text{H}_5)_4\text{As}^+\), formed the complex \((\text{C}_6\text{H}_5)_4\text{AsReO}_4\) with perrhenates. This is a white, crystalline solid, insoluble in cold water. From 0.43 to 133.0 milligrams of \(\text{ReO}_4^-\) can be determined gravimetrically in a moderate excess of the reagent. A potentiometric-type determination can be substituted if desired. Precipitation is usually carried out in hot sodium chloride solution. Nitrate must be avoided, but molybdenum does not interfere if a few simple precautions are taken. A few other ions such as \(\text{MnO}_4^-\), \(\text{Hg}^{2+}\), and \(\text{Sn}^{2+}\) interfere. This method is presently used and recommended by those working on rhenium at the University of Tennessee. However, consistently low results were at first obtained, so W. Smith and Long suggested a modification of Willard and C. Smith's method. Normally the
accumulated precipitate containing rhenium was washed with water. The modification involved substitution of a saturated solution of tetraphenyl arsonium perrhenate for washing, which corrected this difficulty. Tribala(\textsuperscript{436}, 437, 438), an active French worker in rhenium chemistry, also has used this method recently with considerable success.

Another organic base, sodium diethylidithiocarbamate, has also been suggested as a possible reagent.\textsuperscript{439}

After separation of the rhenium from interfering elements, determination may be accomplished by gravimetric methods (as above) or by volumetric or colorimetric methods. In general, colorimetric methods seem to have been the most popular. Color-producing reducing agents such as bromine\textsuperscript{(427, 430)} or stannous chloride with thiocyanates\textsuperscript{(429, 431, 433, 436)} are reacted with the unknown, standards are prepared, and measurements taken by comparison in Nessler tubes. Recently, photoelectric spectrophotometers, which measure the transmittance of light, have been introduced.\textsuperscript{(433, 434)}

Titration methods have been used extensively in rhenium determinations, but recently have yielded to more rapid methods such as the colorimetric determinations. Geilmann and Hurdl\textsuperscript{(440)}, for instance, dissolved the lower oxides of rhenium by oxidation with perhydrol, and then titrated the resultant perrhenic acid with a base. Although this method of oxidation of the lower oxides has now been declared unreliable,\textsuperscript{(441)} ferric sulfate, potassium dichromate, or ceric sulfate can be used for oxidation purposes if desired.\textsuperscript{(442)} Excess oxidizer may be titrated with permanganate. Perrhenates have also been titrated with silver nitrate, using potassium chromate as an indicator.\textsuperscript{(443)}

Geilmann and Hurdl\textsuperscript{(444)} found it possible to determine chlororhenic acid in the presence of perrhenic acid with tetron (N, N'-tetramethyl-o-tolidine) which precipitated a weighable complex containing Re\textsuperscript{4}.

Special Methods

Electrolytic methods have been developed. The Tomiceks\textsuperscript{(445)} cathodically reduced perrhenate ion in sulfuric acid solution causing the rhenium to deposit completely on the cathode; it was then oxidized and titrated. Vollg\textsuperscript{(446)} varied this method by forming cathodic deposits from ammoniacal solutions. Mercury served as the cathode and was distilled off, leaving a rhenium residue which was examined polarographically.\textsuperscript{(447)}

This polarographic method has been studied extensively by Lingane,\textsuperscript{(287, 448)} using hydrochloric or perchloric acid as the supporting electrolyte, the perrhenate was reduced to Re\textsuperscript{4} at the dropping-mercury cathode. The diffusion current was well defined and directly proportional to the concentration of perrhenate ion. The half-wave potential in 4N perchloric acid is
-0.4 v and in 2N and 4.2N hydrochloric acid is -0.45 v and -0.31 v, respectively, versus the standard calomel electrode. A double wave was produced in neutral unbuffered potassium chloride solutions. The first part of this wave was caused by a reduction to Re\(^{-1}\), and the second part by hydrogen discharge. In a phosphate buffer of pH 7, ReO\(_4^{-1}\) produced a catalytic wave at -1.6 v.

Polarograms of Re\(^{-1}\) solutions in 1-2N sulfuric acid at zero C showed three anodic waves. Their half-wave potentials were \(\alpha = 0.54\) v, \(\beta = 0.34\) v, \(\gamma = 0.07\) v. A similar polarogram was obtained in 1N perchloric acid with some modifications, including separation of the \(\beta\)-wave into two components. In each medium the corresponding waves pertained to the same oxidation states. The \(\alpha\)-wave represented oxidation of Re\(^{-1}\) to Re\(^{+2}\), the \(\beta\)-wave to Re\(^{+3}\), the \(\beta'\)-wave to Re\(^{+5}\), and the \(\gamma\)-wave to Re\(^{+7}\).

Reduction of rhenium in alkaline, neutral, and acid solutions were observed by Geyer\(^{449}\), who found that six steps occurred. The steps are listed below. Geyer recommends that Steps (1), (5), and (6) are analytically valuable.

<table>
<thead>
<tr>
<th>Step</th>
<th>Acidity</th>
<th>Potential, volts</th>
<th>Characteristic Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Alkaline to weak acid</td>
<td>-0.9 to -1.5</td>
<td>(\text{ReO}_4^{-1} \rightarrow \text{Re})</td>
</tr>
<tr>
<td>(2)</td>
<td>Alkaline to weak acid</td>
<td>-1.3 to -1.7</td>
<td>(\text{Re} \rightarrow \text{Re}^{-1})</td>
</tr>
<tr>
<td>(3)</td>
<td>Normal acidity</td>
<td>0.0 to -0.3</td>
<td>(\text{Re}^{+7} \rightarrow \text{Re})</td>
</tr>
<tr>
<td>(4)</td>
<td>Normal acidity</td>
<td>-0.5 to +0.9</td>
<td>(\text{Re} \rightarrow \text{Re}^{-1})</td>
</tr>
<tr>
<td>(5)</td>
<td>High acidity</td>
<td>+0.4 to +1.0</td>
<td>(\text{Re}^{+7} \rightarrow \text{Re}^{+4})</td>
</tr>
<tr>
<td>(6)</td>
<td>High acidity</td>
<td>-0.1 to -0.3</td>
<td>(\text{Re}^{+4} \rightarrow \text{Re})</td>
</tr>
</tbody>
</table>

Hölemann\(^{328}\) found that hot perrhenate solutions reduced so smoothly with stannous chloride that ReO\(_4^{-1}\) could be determined potentiometrically. In 4N HClO\(_4\) and 2N KCl, these perrhenate reductions have been found to be irreversible.\(^{450}\)

The catalytic properties of rhenium can be utilized for a semiquantitative determination, as they control reduction of sodium tellurate by stannous chloride\(^{451}\) to tellurium metal. If a protective colloid is used, the tellurium will remain suspended in solution and can be determined "colorimetrically" to give a measure of the rhenium present. The accuracy is only about 10 to 20 per cent.

Analysis of rhenium in materials such as meteorites has been accomplished by irradiation of the specimens in an atomic pile.\(^{28}\) The substance was compared with a standard and the relative radioactivity gave a measure of the rhenium present.
Summary

For general determinations of rhenium, the method of Willard and G. Smith (436) using tetraphenyl arsonium chloride is recommended and used by most researchers today. The modification of W. Smith and Long is, of course, mandatory.

In conclusion it should also be noted that the work of Geilmann (with numerous co-workers) presents almost a step-by-step history of the analytical chemistry of rhenium, from 1940 to the present, in his series, "The Analytical Chemistry of Rhenium." There are no less than 20 sections in this splendid series, published in Germany in the Z. anorg. allgem. Chem., and in the Z. anal. Chem.

ELECTRODEPOSITION

Höflmann (87) foreshadowed successful plating of rhenium in 1933 when he precipitated pure rhenium metal by the electrolysis of acid solutions containing perrhenate and fluoride ions. He claimed both high current and high material efficiency, but was unable to produce a satisfactory plate. A year later, Fink and Deren (88) obtained hard, bright, compact deposits of rhenium from acid, neutral, and alkaline baths, by controlling the pH very carefully. The pH value depended upon the electrolytes (other than rhenium) present. Plating temperature was important and can be considered to increase with the pH. Four baths are given as examples in Table 14. In addition to these, an oxalate bath of pH 1.2 to 1.5 and a sodium bicarbonate-ammonium sulfate bath of pH 7.5 to 3.5 were developed.

The plate obtained was found to be mirror bright if deposited on a polished surface. It was highly resistant to hydrochloric acid attack. The rhenium was deposited on several metals such as brass, copper, and tungsten and could be codeposited with other metals such as nickel and cobalt. Lundell and Knowles (284) claimed satisfactory electrodeposition of rhenium from dilute sulfuric acid solutions at much lower current densities, i.e., 0.25 amp/dm².

Young (452) somewhat disagreed with Fink and claimed the sulfuric acid concentration must be raised to give a bright plate. Young could not plate rhodium over rhenium but found that if he flash-plated rhodium onto the base metal first, then deposited the rhenium, he could finally plate rhodium that would adhere satisfactorily.

Netherton and Holt (85) also reviewed Fink's work, particularly with respect to current efficiency. They found that the CCE (cathode-current efficiency) was generally quite low. Bath No. 3 in Table 14 was recommended as the most satisfactory, where, if a current density of 9 ampds/dm²
TABLE 14. FOUR RHENIUM-PLATING BATHS SUGGESTED BY FINK AND DEREN

<table>
<thead>
<tr>
<th>Bath No.</th>
<th>Perchlorates</th>
<th>Other Electrolytes</th>
<th>pH</th>
<th>Temp</th>
<th>Current Density, amp, dm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>KReO₄</td>
<td>H₂SO₄</td>
<td>0.9</td>
<td>25-30</td>
<td>10-14</td>
</tr>
<tr>
<td></td>
<td>11 g/l</td>
<td>5 g/l (Sp. gr. 1.84)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>HReO₄</td>
<td>H₂SO₄</td>
<td>0.7-1.2</td>
<td>25-30</td>
<td>10-15</td>
</tr>
<tr>
<td></td>
<td>20 g/l</td>
<td>5 g/l (Sp. gr. 1.84)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>KReO₄</td>
<td>H₂SO₄</td>
<td>0.80-1.00</td>
<td>25-45</td>
<td>10-16</td>
</tr>
<tr>
<td></td>
<td>10-15 g/l</td>
<td>90 g/l (Sp. gr. 1.84)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>NH₄OH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 cc (28% NH₃)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>KReO₄</td>
<td>H₃PO₄</td>
<td>2.1</td>
<td>80-90</td>
<td>13-17</td>
</tr>
<tr>
<td></td>
<td>12 g/l</td>
<td>48 g/l (Sp. gr. 1.7)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Na₂HPO₄</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>60 g/l</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At 70°C was used, the CCE was 15 per cent. These authors also developed an ammoniacal citrate bath, found to be the best for thin plates. The rhenium deposits tarnished in air but possessed good resistance to hydrochloric and sulfuric acids.

Recently these authors (247, 248) investigated the conditions for co-deposition of other metals with rhenium, using nickel, cobalt, and iron. Ammoniacal citrate baths were most commonly utilized. Compositions of the most successful baths are recorded in Table 15. pH variations markedly affected the alloy composition and were carefully controlled. The corrosion resistance of the alloys plated was evaluated and is reported in the Corrosion Resistance section of this report.
TABLE 15. PLATING BATHS FOR THE CODEPOSITION OF NICKEL, COBALT, OR IRON WITH RHENIUM AS RECOMMENDED BY NETHERTON AND HOLT

<table>
<thead>
<tr>
<th>Plate</th>
<th>Bath Composition</th>
<th>pH</th>
<th>Temp, °C</th>
<th>Current Density, amp/dm²</th>
<th>CCE, %</th>
<th>Per Cent Rhenium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re-Ni</td>
<td>KReO₄, 10 g/l, Citric acid, 66 g/l, NiSO₄·6H₂O, 56 g/l, NH₄OH to pH of 12</td>
<td>12</td>
<td>70</td>
<td>5</td>
<td>90</td>
<td>70</td>
</tr>
<tr>
<td>Re-Co</td>
<td>KReO₄, 10 g/l, Citric acid, 66 g/l, CoSO₄·7H₂O, 60 g/l, NH₄OH to pH of 7</td>
<td>7</td>
<td>70</td>
<td>5</td>
<td>85</td>
<td>75</td>
</tr>
<tr>
<td>Re-Fe</td>
<td>KReO₄, 10 g/l, Citric acid, 66 g/l, FeSO₄·7H₂O, 59.4 g/l, NH₄OH to pH of 7</td>
<td>7</td>
<td>70</td>
<td>5</td>
<td>65</td>
<td>85</td>
</tr>
</tbody>
</table>

BIOLOGICAL PROPERTIES

Toxicity

Rabbits were dosed with 200 milligrams of potassium perrhenate per kilogram of body weight. No unusual effect was observed, even though the lethal dose of manganese in analogous experiments was 5 to 6 mg/kg of body weight. Repeated doses of rhenium also had no ill effect. The lethal dose for rats, injected intraperitoneally as sodium perrhenate, is about 1000 mg/kg of body weight. Molybdates are roughly tenfold more poisonous than perrhenates, and rhenium chlorides are somewhat more toxic also, due to hydrochloric acid liberation.
Physiological Effects

Rhenium has no effect on the blood pressure of rats and has no hemopoietic action. (454) Radioactive rhenium was found to concentrate in the thyroid, but practically all of it was excreted through the urine within two days.

Botanical Properties

Druce(455) reported that cress seedlings watered with a 0.1 per cent solution of potassium perrhenate did not grow quite as well as the control seedlings watered with rain water, but the rhenium-watered seedlings grew better than those watered with a 0.1 per cent solution of potassium permanganate. Geraniums watered with perrhenate solutions cast off leaves that were found to contain rhenium, and specimens of mullein (Verbascum thapsus) were found to do poorly, compared with the control plants when treated similarly.

USES OF RHENIUM

Rhenium, to date notably a rare and expensive metal, has found use only in such specialized applications as catalysis, thermometry, and pen-point alloys. It is in great part due to prospective catalytic properties that the chemistry of rhenium has been so well developed. Metallurgical applications have remained in the background, probably due to lack of cheap massive metal, and the paucity of information on rhenium's metallurgical properties bear this fact out. Electronic and lamp applications of rhenium have been slow in development also, but show great future promise.

The general situation may be well summed up by the words of Ida and Walter Noddack(24), discoverers of rhenium and still active in its chemistry: "Rhenium can never be made into massive articles in industry, but it will find application where it possesses a singular property of special value, as in the case of the platinum metals".

Past and Present Applications

Catalysis

Rhenium was first suggested for catalytical use in 1929 by the Noddacks(456, 457) for oxidation processes. Free or combined rhenium on
a tungsten and quartz carrier promoted oxidation of sulfites to sulfates, nitrites to nitrates, and aniline to aniline black. The heats of formation of rhenium oxides are small, so rhenium is a good oxygen transmitter. Oxidation of ammonia was conducted utilizing a rhenium-platinum alloy or rhenium plated on platinum. These catalysts were all in the form of gauze.

Other investigators, meanwhile, found rhenium valuable for destructive and constructive hydrogenation, the refinement of anti-knock fuels, and desulfurization. Shortly, Anisimov, Krasheninnikova, and Platonov, who commenced a series of articles on the catalytic properties of rhenium, claimed that rhenium was poor for hydrogenation and oxidation, but an effective dehydrogenation agent. In the dehydrogenation of ethanol to acetaldehyde, maximum yields of about 12 per cent occurred at 300 and 600 C, with a minimum yield at 400 C. Propanol gave 20 per cent propionaldehyde at 400 C. The propionaldehyde formed was practically undecomposed and the propanol was not dehydrated. Much better results were obtained in the dehydrogenation of isopropanol to acetone. At 400 C the yield was a maximum of 85 per cent. Chloroform was also produced by the catalytic action of rhenium at this time. Finely divided rhenium metal failed to hydrogenate either maleic acid or cyclohexene effectively, but if the metal was prepared by hydrogen reduction of ammonium perrhenate, catalytic action was improved for all uses, including both hydrogenation and dehydrogenation. However, a copper-rhenium catalyst was just as effective as rhenium alone and considerably less expensive.

The Russians continued their work on a wide scope and carried out a number of additional organic reactions by rhenium catalysis, a summation of which is given in Table 16. Eventually their best rhenium-metal catalyst was prepared by dissolving the rhenium metal in nitric acid, neutralizing with ammonium hydroxide, and then evaporating to dryness. This product was reduced in hydrogen for 1 to 2 hours at 150 to 170 C, 1 hour at 170 to 250 C, 2 hours at 400 C, and a final 2 hours at 400 C.

Colloidal rhenium catalysts are considered the best rhenium catalysts at the present time. Zenghelis and Stathis prepared catalytic rhenium in a colloidal form by treating potassium perrhenate with protolactic acid and chloroform, or by treating potassium rhenium chloride with gum arabic, hydrazine, and formaldehyde. The colloidal solution catalyzed the decomposition of hydrogen peroxide and hydrogenated maleic acid. These authors also moistened rhenium metal with sulfuric acid and found it possible to synthesize ammonia from its elements thereby. The decomposition of ammonia over rhenium has also been studied. However, Zenghelis and Stathis evaluated rhenium as a catalyst and found it just fair, compared with ruthenium, palladium, and platinum.

Rhenium can be alloyed with these and other elements to form effective catalytic alloys. The metal or its compounds can also be adsorbed on powdered, activated charcoal or coal. In the latter state it was claimed...
**TABLE 16. THE EFFECT OF RHENIUM CATALYSTS ON A FEW ORGANIC REACTIONS**
(Compiled from the data of Anisimov, Krashemikova, and Platonou)

<table>
<thead>
<tr>
<th>Starting Compound</th>
<th>Product</th>
<th>Temp, °C</th>
<th>Yield, %</th>
<th>Catalyst</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_3$(CH)$_2$OH</td>
<td>CH$_3$CHO</td>
<td>300</td>
<td>11</td>
<td>NH$_4$ReC$_4$</td>
<td>462, 463</td>
</tr>
<tr>
<td>(ethyl alcohol)</td>
<td>(acetaldehyde)</td>
<td>600</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO</td>
<td>N$_2$</td>
<td></td>
<td>Good</td>
<td>NH$_4$ReC$_4$</td>
<td>463</td>
</tr>
<tr>
<td>CH$_3$(CH)$_2$OH</td>
<td>CH$_3$CH$_2$CHO</td>
<td>200-</td>
<td>21</td>
<td>Re metal</td>
<td>464</td>
</tr>
<tr>
<td>(n-propyl alcohol)</td>
<td>(propionaldehyde)</td>
<td>400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(CH$_3$)$_2$CHOH</td>
<td>CH$_3$(CO)CH$_3$</td>
<td>400</td>
<td>85</td>
<td>Re metal</td>
<td>464</td>
</tr>
<tr>
<td>(iso-propyl alcohol)</td>
<td>acetone</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH$_3$(CH$_2$)$_3$OH</td>
<td>CH$_3$(CH$_2$)$_2$CHO</td>
<td>350-</td>
<td>-</td>
<td>Re metal</td>
<td>467</td>
</tr>
<tr>
<td>(n-butyl alcohol)</td>
<td>(n-butyraldehyde)</td>
<td>450</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(CH$_3$)$_2$CHCH$_2$OH</td>
<td>CH$_3$(CO)CH$_2$CH$_3$</td>
<td>350</td>
<td>-</td>
<td>Re metal</td>
<td>467</td>
</tr>
<tr>
<td>(isobutyl alcohol)</td>
<td>(methyl ethyl ketone)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCO$_2$H</td>
<td>CO$_2$</td>
<td>230</td>
<td>100</td>
<td>Re metal</td>
<td>468</td>
</tr>
<tr>
<td>(formic acid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH$_3$OH</td>
<td>HCOH</td>
<td></td>
<td>Good</td>
<td>Re poisoned by H$_2$S or As$_2$O$_3$</td>
<td>469</td>
</tr>
<tr>
<td>(methyl alcohol)</td>
<td>(formaldehyde)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyclohexanol</td>
<td>Cyclohexanone</td>
<td>250-</td>
<td>Good</td>
<td>Re metal</td>
<td>470</td>
</tr>
<tr>
<td>Cyclohexanol</td>
<td>Phenol</td>
<td>500</td>
<td>79</td>
<td>ReS$_2$</td>
<td>470, 472</td>
</tr>
<tr>
<td>Alcohols</td>
<td>Aldehydes or ketones</td>
<td>400-500</td>
<td>Good</td>
<td>ReS$_2$</td>
<td>471, 472</td>
</tr>
</tbody>
</table>
to be valuable for hydrogenation, desulfurization, or conversion of phenols, cresols, etc., organics commonly found in coal tar and mineral oil.\(^{(480)}\)

Recently, Tribalat\(^{(481)}\) catalyzed the following reductions with per-rhenate ion so that they occurred quantitatively. The oxidation potentials for these reactions are listed below, but the abstract consulted did not indicate the products formed.

<table>
<thead>
<tr>
<th>Reduction</th>
<th>Oxidation Potential, (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{NO}_3^-) (\text{by SnCl}_2)</td>
<td>1.05</td>
</tr>
<tr>
<td>(\text{NO}_3^-) (\text{by FeSO}_4)</td>
<td>1.00</td>
</tr>
<tr>
<td>(\text{NO}_3^-) (\text{by HAsO}_3)</td>
<td>1.03</td>
</tr>
<tr>
<td>(\text{HNO}_2) (\text{by SnCl}_2)</td>
<td>1.29</td>
</tr>
<tr>
<td>(\text{NH}_2\text{OH}) (\text{by SnCl}_2)</td>
<td>1.35</td>
</tr>
<tr>
<td>(\text{HNO}_2) (\text{by NH}_4\text{OH})</td>
<td>-0.05</td>
</tr>
<tr>
<td>(\text{HNO}_2) (\text{by N}_2\text{H}_4)</td>
<td>-1.87</td>
</tr>
</tbody>
</table>

If the evaluation of Zenghelis and Stathis is correct, rhenium is not of great worth as a catalyst. At the present time its price does not compare favorably with certain other metals more commonly used for these purposes. Rhenium evidently is effective catalytically, but so are many other metals and materials. Rhenium is not unique as a catalyst, but merely good.

**Thermocouples**

Rhenium was early recommended\(^{(240)}\) as a replacement for rhodium in rhodium-platinum thermocouples. Three to fifteen per cent rhenium was suggested, and it was also found that three or more per cent rhenium prevents brittleness in these wires. Schulze\(^{(482)}\) and Goedecke\(^{(483)}\) extensively investigated the properties of rhenium for thermoelectric use. Rhenium produced a potential three times as great as rhodium when equal percentages of each were tested as platinum alloys against pure platinum. The comparison is shown in Figure 13. Characteristics of the couples \(\text{Pt8Re/Pt}\) and \(\text{Pt4.5Re5Rh/Pt}\) are plotted in Figure 14. These couples produced voltages as high as those of Chromel-Alumel couples. More recent literature\(^{(52)}\) indicated use of a \(\text{Pt5.4Re3.5Rh/Pt}\) couple in Germany. The couple \(\text{Ir/60Re40Ir}\) produced a remarkably straight characteristic curve (Figure 15).
FIGURE 13. EMF PRODUCED BY ADDITION OF VARIOUS ALLOYING ELEMENTS TO PLATINUM IN ALLOY-PLATINUM VERSUS PLATINUM THERMOCOUPLES AT 1200°C
Schulze\(^{(482)}\)

FIGURE 14. EMF PRODUCED BY PLATINUM ALLOY THERMOCOUPLES
Schulze\(^{(482)}\)
Due to these properties, attempts were made to replace at least part of the critical rhodium in platinum-rhodium couples with rhenium in German thermocouple wires. However, it was claimed (241) that excessive volatilization of the rhenium above 1000 to 1100 C (a result of oxidation followed by volatilization of the oxide) caused changes in the thermocouple emf, precluding the use of rhenium above this temperature. The Pt8Re/Pt couple definitely did this, but Goedecke claimed that the Pt4.5Re5Rh wire did not.

Some reports (24) stated that rhenium thermocouples (alloys unspecified) were good up to 1900 C and for long time periods. Goedecke and Schulze did specify the alloy: it was Rh6Re/Rh and possessed an emf of 7.2 mv at that temperature. If volatilization occurs, this high-temperature usability is questionable, but the presence of a neutral atmosphere would eliminate all trouble.

Contact Materials

Several patents have been issued (243, 244, 484) for rhenium-containing electrical contact alloys, previously mentioned in the metallurgical section of this review. In general, rhenium comprised about 10 per cent of the
composition; the balance consisted of about 1 to 29 parts molybdenum or vanadium and the remainder tungsten. These materials could be prepared by powder-metallurgy techniques and very fine-grained hard compacts with melting points over 2900°C resulted. They were excellent for make-and-break contacts, due to innate toughness and low electrode emissivity. According to Weiger (485) there was little tendency for arcing, pitting, oxidation, or transference of the metal during operation, and small amounts of impurities did not interfere with their properties. They were also valuable as refractory bases suitable for impregnation with copper, silver, or gold.

The Noddacks (24) explained that the excellency of rhenium for make-and-break contact alloys is a result of oxygen absorption by the reduced metal. The oxygen combines with rhenium to form lower oxides which are good conductors and can be thermally decomposed.

Wear-Resistant Alloys

Several alloys of rhenium possessing high wear resistance have been developed in Germany. (245, 246) Their primary use has been to replace the alloys containing osmium formerly used for pen points. (52) Several typical compositions have been recorded in the section under alloys. The rhenium content varied widely, but in most of the alloys it was present from 50 to 99 per cent. Many other metals were contained in the compositions, the most prevalent being tungsten, nickel, cobalt, molybdenum, and platinum. These alloys were usually prepared by powder-metallurgy methods, crushed, sieved, and hand-tweezer picked for suitable pen points. Far more worthwhile uses for rhenium than in wear-resistant types of alloys for pen points have been suggested, but evidently not yet applied. These will be discussed below.

Lamp Filaments

Since rhenium has been found to be readily deposited on tungsten filaments by the halide-thermal-decomposition processes, early suggestions were forthcoming for its use as a lamp filament. (486) The Noddacks (487) found that rhenium volatilized less in vacuo than tungsten and thus could be used up to 2550°C. They also suggested (488) forming filaments by working up rhenium and ammonium perrhenate into a plastic mass, forcing it through nozzles or dies as a filament, and finally reducing the perrhenate binder in the resultant filament with hydrogen.

Agte (235) recalled that attempts to coat tantalum carbide on a tungsten wire base were unsuccessful. Tantalum carbide is a better filament material than tungsten, but more brittle. The filaments were unsuccessful because the tungsten core became carburized and the tantalum carbide lost its fine filament properties. Agte claimed that rhenium formed no carbides (which is not wholly accurate) so he developed a layer of tantalum carbide
Photographic Emulsions

Halide salts of rhenium, of the type $R_2ReX_6$ (where $R$ is a metal and $X$ is a halide), were found to be excellent fog inhibitors. \(489\) A fog inhibitor of this type was added to the emulsion after final digestion or following the after-ripening during preparation of the plate. A time lag after processing improved the fog-inhibiting properties.

Potential Uses for Rhenium

Facts and data show that rhenium has been used but little to date. The literature seems to indicate that a low German production of about 2 to 400 pounds a year for 10 to 12 years (time period estimated) after 1930 probably went to three sources: (1) research, (2) thermocouples, and (3) pen points. The first source undoubtedly took the lion's share. The other uses so far suggested for rhenium have been largely confined to experimental applications. U. S. production from the University of Tennessee(33) in the main part has been sent to universities and institutions for research. In the Western World today, rhenium is 99 per cent a laboratory metal.

This situation should not last much longer. So far, its development has been retarded by the exceedingly high price, its scarcity, and a lack of knowledge about some of its very interesting properties. It appears, for instance, that rhenium should be able to do most of the things tungsten does in electron tubes, and should be able to do some of them better. Other possible uses are also known, but all applications, including the electronic ones, must stand on a firmer foundation of physical, metallurgical, and electronic knowledge than is presently available. Simultaneously with the advent of this information, the potential uses of rhenium will have crystallized, and with utility and markets for the metal in sight, the present excessively high cost will be reduced.

The following is a discussion of some of the possible future uses of rhenium.
Physical and Electrical Properties for Electron-Tube Applications.

Rhenium has several properties which indicate that it would be more desirable for certain electron-tube applications than tungsten or other metals. The melting point of rhenium has been generally accepted to be 3440 ± 60 K. (118) Evidence from the literature indicates that the resistance of rhenium to attack by residual gases in evacuated containers is much greater than that of tungsten. (88) These properties would be a very important factor in increasing the life of electron-tube heaters.

Rhenium is more ductile after being heated to high temperatures than tungsten. (91, 94) This property would give a filament constructed from rhenium greater resistance against mechanical shock than the usual tungsten filament. The electrical resistivity is about four times that of tungsten. (120) This would permit filaments of rhenium to be constructed with a larger cross section than tungsten filaments but with no change in the total resistance of the filament. The larger cross section of a rhenium filament would give added ruggedness to the filament, while the higher resistivity would permit use of the same voltage source for heater power which is required for a tungsten filament with a smaller cross section.

The spectral emissivity of rhenium has been reported to be about 0.366. (119) This would make the use of pure rhenium as an anode material in high-power tubes undesirable since other materials would dissipate more heat by radiation.

Application of Rhenium for Electron-Tube Heaters. The cathodes in vacuum tubes may be classified as directly heated and indirectly heated cathodes. The directly heated cathode is, as the name implies, a cathode whose emitting surface is heated by the passage of the heater current directly through the emitter material. The indirectly heated cathode is one in which the emitter material is coated on a sleeve, or cap, which encloses the heater element. The sleeve, or cap, is heated indirectly by radiation and conduction from the heater element. As a rule, the directly heated type cathode is used in tubes where the power and/or voltage requirements are very high. They are also employed in battery-operated tubes in which it is desired to employ the minimum amount of power to heat the filament. The indirectly heated cathodes are used where the power requirements are not unusually high and where efficiency is fairly important.

The materials which are most commonly employed in directly heated cathodes are tungsten and thoriated tungsten. It appears that pure rhenium may be as good as, or better than, tungsten as an electron emitter. If it is a comparable emitter, rhenium should be considered as a replacement for tungsten for directly heated cathodes. Rhenium cathodes are particularly interesting since they may be safely operated at a temperature higher than...
tungsten with no more evaporation of material, as a result of the lower vapor pressure of rhenium. Deterioration of the cathode is from evaporation, sputtering by residual gases, and chemical attack. Operation at higher temperatures would also increase the total emission current from the cathode.

With directly heated cathodes, a larger diameter of rhenium cathode of a given length will have the same resistance as a smaller diameter cathode of tungsten. This requires a basic redesign of tubes which employ directly heated cathodes in order for the desired operating temperature to be obtained from a balance between the radiated energy and the energy input from the filament supply.

A possible application for a directly heated rhenium cathode might be in filament X-ray tubes which are employed for X-ray analysis. In this type of tube, the evaporation of tungsten poses a serious problem. When the target of the X-ray tube becomes coated with evaporated tungsten, the X-ray diffraction lines of tungsten appear in the diffraction patterns. These lines seriously interfere with the interpretation of the analyses. Since rhenium is reported not to deposit to any great degree on the walls of tubes in which it is heated, this problem would be minimized by the use of rhenium filaments.

The possibility of the use of rhenium for application in indirectly heated cathodes is fairly good. The physical and electrical properties of rhenium indicate promise as a heater for this type of cathode. Since the resistivity in ohm-cm of rhenium is higher than that of tungsten, a filament for operation on the same voltage would have a larger cross section, and consequently be more resistant to shock and vibration. The increased cross section and the ductility of rhenium would give added ruggedness to the heater. The low volatility and resistance to attack by residual gases of rhenium should increase the life of a rhenium heater over that of tungsten. It is also probable that the possibility of contamination of the emitting surface of the cathode by evaporation or migration of the heater material to the cathode-emitting material would be minimized by the use of rhenium as a heater element.

Thoriated Rhenium Emitters. In high-voltage tubes which require large emission currents, thoriated tungsten is usually employed. Since this cathode is seriously damaged by positive-ion bombardment, it is limited to application in tubes having operating potentials of less than about 10,000 volts.

Tungsten is thoriated by adding a small amount of thorium oxide to the tungsten before it is drawn into the desired size of wire. The cathode formed from the wire is flashed at a high temperature to reduce the thorium oxide to the metal. The cathode is activated by operating at a temperature which allows the thorium metal to diffuse to the surface of the tungsten wire.
more rapidly than it is evaporated. This permits the formation of patches of thorium on the surface of the cathode. The operating temperature is maintained at a value which permits the thorium that is evaporated to be replaced by diffusion of thorium to the surface of the cathode.

Several factors are involved in the preparation of a thoriated rhenium emitter. The success of such an emitter would depend largely upon the rate of diffusion of thorium to the surface of rhenium. If the rate of diffusion were too low, then patches of thorium could not be maintained on the surface of the rhenium. There are reports, however, that thoriated rhenium emitters have been constructed and have promising operating characteristics. The possibilities of a thoriated rhenium emitter warrant investigation, since thoriated tungsten emits about 1000 times as much current as is obtained from pure tungsten. The mechanical properties of rhenium are such that thoriated rhenium should be more rugged than thoriated tungsten.

Use of Rhenium in Electron-Tube Elements Other Than Heaters. On the basis of the indicated physical, electrical, and mechanical properties of rhenium, it appears to be promising for other elements in vacuum tubes in addition to cathodes. Since the other components are either grids or plates, the requirements for each will be considered with respect to the characteristics of rhenium.

The materials which are employed as anodes for high-power tubes must be capable of dissipating the heat which they receive as a result of the current flowing through the tube. This heat is dissipated almost entirely by radiation from the anode surface. For the dissipation of the same energy, the anode material with the spectral emissivity nearest 1 will be the coolest. Anodes are often coated on the outer surface with some material which approaches 1. The spectral emissivity of 0.366, which has been reported for rhenium, indicates that this metal would not be a good heat radiator. The high melting point and ductility do, however, not exclude the possibility of using rhenium for such an application. If employed, the outside surface would probably increase the emissivity, and consequently, increase the radiation of heat. The only advantage of coated rhenium over other refractory metals would be its strength at high temperatures. This does not appear too important for most applications.

As a grid material for electron tubes, rhenium appears to be little better than materials which are now in use. The material from which grids are constructed should have a low secondary-electron emission coefficient in order to reduce the grid current. For high-power tubes, the grid material must be physically strong and should have a low rate of sputtering under ion bombardment. The secondary-emission yield of rhenium is 1.30, which is only slightly less than the 1.38 reported for tungsten. Since the secondary-emission coefficient for all metals in this atomic weight range is about the same, rhenium has no marked advantage over other materials from this standpoint. The secondary emission from grid wires is frequently reduced.
by coating the metal which forms the grid structure with gold, or nickel. As a rule, the wires of the grid structure are of tungsten when high power is involved. The objective is to obtain strength at high temperatures. In low-power tubes, the grid is usually made of nickel, which is easier to fabricate and has a low secondary-electron emission coefficient. It is possible that rhenium would fulfill most of the requirements for a good grid material, particularly in high-power tubes. Certainly it would compete with tungsten since it is believed to have a lower vapor pressure and a higher resistance to attack by residual gases.

**Powdered Rhenium in Cermet-Type Heaters.** In the past few years, work has been carried on in the development of cermet cathodes. Cermets are mixtures of a metal and refractory insulating materials, which are first pressed to shape and then sintered. Cermets for cathodes contain just enough metal to give the cermet the desired electrical conductivity, since an excess of metal reduces the electrical resistance and increases the danger of cracking on repeated heating and cooling cycles. The cermet cathode is heated by passing current through it. The materials for cermets on which the most work has been performed are tungsten, or molybdenum mixed with thorium oxide. In 1950, G. A. Espersen made some tests on a cermet composed of rhenium and thorium oxide. The emission constants which were determined for the rhenium and thorium oxide cermet were a work function of 2.83 electron-volts when the Richardson constant was 11.7 amp cm⁻² K⁻². The emission current which was obtained from the rhenium and thorium oxide cermet was about twice that obtained from a similar cermet formed from tungsten and thorium. It was also reported that there was less deposit on the glass bulb after 150 hours of life test at 2040 K from the rhenium and thorium oxide cermet than from the tungsten and thorium oxide cermet.

Although the cermet-type cathode is not in general use in electron tubes at the present time, it appears that it will find widespread use in applications where a high-power, rugged cathode is needed. It appears that rhenium is adaptable for the construction of cermets of promising materials. From the available data it appears that rhenium will be even better than tungsten for this application.

**Lamp Filaments**

Numerous suggestions indicate the possible use of rhenium for incandescent lamp filaments. Undoubtedly, rhenium would be excellent in this application. It can be operated at higher filament temperatures, should be stronger than tungsten, and does not enter into the deleterious water cycle as does tungsten. Druece has never heard of or seen incandescent lamp bulbs with rhenium filaments on the open market, so the field is evidently virgin. Patents developed to cover this property were drawn in the early 1930's, so it is probable that they have now.
expired or are about to expire. Probably the only reasons for lack of rhenium filaments on the market are their scarcity and high price.

High Temperature Construction Material

Rhenium should possess excellent high-temperature structural properties. It has a melting point almost as high as tungsten, and it probably does not become as embrittled as does tungsten. Rhenium or rhenium alloys might be used above 2500 C if protected from oxidation, and Arend(492) has suggested it for use in aircraft-mounted gas turbines. However, it is probable that high cost and low production volume of rhenium preclude large-scale use of the massive metal, but for certain critical applications, utilizing small amounts of metal, rhenium might be used for construction purposes for service at extremely high temperatures. Cladding or coating to prevent oxidation is, of course, mandatory.

Thermocouples

Because of the high emf produced in thermocouples due to the presence of rhenium as an alloying ingredient, its use in this field may become widespread. Some accounts(241) claim that excessive oxidation and volatilization of the oxide of the rhenium above 1100 C prevents use of the couple Pt8Re/Pt except at low temperatures. However, the Pt4.5Re5Rh/Pt thermocouple does not do this and other alloys yet to be developed may not also. These thermocouples can be used for long periods and produce three to four times the potentials of usual noble metal couples. The couple Rh8Re/Rh(482, 483) can be used up to 1900 C, an extremely high thermocouple temperature. The Noddacks(24) state that the following thermoelements have distinct possibilities:

<table>
<thead>
<tr>
<th>PtRe/Pt</th>
<th>PtRe/Pd</th>
</tr>
</thead>
<tbody>
<tr>
<td>PtRe/Rh</td>
<td>RhRe/Rh</td>
</tr>
<tr>
<td>IrRe/Ir</td>
<td></td>
</tr>
</tbody>
</table>

They further declared that in their opinion, the best future use for rhenium lies in this field.

Electrical Contacts

The several patents and papers on this subject indicate good potentials for make-and-break electrical contact materials of rhenium, rhenium alloys, and/or sintered compacts which contain rhenium. These could be used as facings in large circuit breakers, or in smaller contacts such as internal-combustion engine distributor points. Rhenium content of the alloys recommended in the past has been low (usually around 10 per cent)
and no objections to the performance of the alloys have been recorded in
the literature. Evidently they perform very well, but the expense of rheni-
um has so far stifled their development.

**Wear-Resistant Alloys**

The use of pen-nib tips composed of rhenium alloys developed to re-
place scarce osmium alloys may be but a preview of the applications of
rhenium in this field. Pivot bearings and wear-resistant surfaces of all
types should be developed as an outgrowth of the limited German pen-point
business. Watch bearings, compass bearings, scale edges, and other
high-use parts of instruments and machinery could be made of rhenium
alloys. The watch industry, balance makers, and all types of precision
instrument manufacturers should be interested in wear-resistant applica-
tions for both civilian and military consumption.

It is possible that rhenium alloys might be highly resistant to erosion
corrosion by abrasive fluids, although no tests on this type of wear have
been conducted. Application would be found in needle valves and similar
fluid-control devices.

**Corrosion Resistance**

Rhenium has been noted as possessing remarkable ability to with-
stand the ravages of hydrochloric acid. This acid is a notably bad actor
and construction materials for containing hydrochloric acid are hard to
find. Stainless steels, for instance, have a tendency to be pitted by the
acid, despite their overall high corrosion resistance in this medium. If
rhenium should show no tendency to pit in hydrochloric acid, its use is a
distinct possibility. It probably would be present as an electroplate or
cladding on less expensive base metals.

**Catalysis**

Catalysis was amply covered in the Past and Present Applications
section of this survey. The information presented therein stands as fair
evidence that rhenium is little better as a catalyst than either less ex-
pensive metals (copper, nickel), or equally dear but more abundant metals
(platinum). However, catalytic uses where no other catalysts are satis-
factory are a possibility.

**Miscellaneous Metallurgical Applications**

The Muddles (24) point out the fact that rhenium is one of the very
few alloying additions that hardens steel without causing embrittlement.
Rhenium also improves other mechanical properties of iridium markedly. It has been reported that very thin foil and very fine wire can be prepared from iridium-rhenium alloys. Additions to platinum will improve the corrosion resistance of electrodes. Such alloys might have application in electronic or corrosion-resistant fields.

EVALUATION OF THE DATA

This section of the report presents a general commentary on the versatility and value of the data and information compiled in this survey.

It should be noted that this report has been based only on published, nonclassified type information. If it had been possible to add certain confidential data to the survey, the picture drawn might have been colored differently, particularly from the production and resources point of view.

Occurrence, Abundance, and Production

It is obvious that rhenium is rare and costly, but its potential is sufficiently great to warrant considering it as a special-purpose material. The information on world deposits is quite confusing. The concentrations of rhenium reported by various investigators have not been placed on a comparable basis, i.e., reduced to percentage of rhenium in the whole native ore. Rather, the percentages reported are often at some advanced stage of ore concentration, resulting in figures like the 25 per cent on Swedish molybdenite reported by Aminoff (43, 44). If rhenium comes into high demand, a survey of the mineral deposits should be made to ascertain their true value. In any case, rhenium produced in this country would come from native molybdenite, relatively easily recovered and yielding an appreciably high production. (55B)

Extraction and Reduction

From the literature and from personal observation of the Tennessee process, two modern processes appear to have economical and practical merit: the Tennessee Process and the French Process. As described in the text, both are simple and direct, and both are operating at the present time.

Two other methods deserve mention. The ion-exchange procedure developed at the University of Wisconsin (in laboratory scale only) shows...
great promise, but its economic worth has not been proven. In addition, the Russians are probably using Feit's old process or a modern adaptation thereof. Since they are undoubtedly actively recovering rhenium, Feit's process must be considered as a practical one.

The most widely used reduction methods for the final recovery of rhenium are the reduction of heated perrhenates and the thermal-dissociation processes. If rhenium is desired directly in a consolidated form, the thermal-dissociation method will produce "hot-wire" rhenium crystal bar from rhenium halides in one step. This method has been widely used for research production of rhenium filaments. Most common, however, is the reduction of heated potassium or ammonium perrhenates with hydrogen. These are simple reactions to conduct and result in a pure powder suitable for pressing and sintering.

Consolidation and Fabrication

Little real work has been done along these lines by previous investigators, so their sparse data can be considered only a vague guide for future work.

Physical Properties

Some of the physical properties are fairly well established. Others are only phantoms, the dimensions of which have hardly been even estimated. The atomic weight, crystal structure, melting point, magnetic properties, optical and X-ray spectra, and nuclear properties seem to have been fairly well determined. Unless future experimentation indicates serious flaws in these properties, they should not have to be re-determined.

However, due to conflicting data or lack of sufficient verification, numerous physical constants come under question. Among these are the density, boiling point, specific heat, thermal expansion, electrical resistivity, and spectral emissivity. No attempt has been made to determine the vapor pressure or any of the other physical properties not mentioned in the text.

Electronic Properties

The electronic properties have been determined in part, but those evaluated have not been adequately verified. The thermionic-emission constants have been determined by only two investigators, and these two
disagree. The photoelectric threshold and Hall effects have been measured by only one investigator apiece. In general, the electronic properties appear promising, but they require verification and amplification.

**Metallurgical Properties**

The metallurgical constants so far reported are subject to great question. The basic properties of tensile strength and elongation have been reported by only one writer, and the material used was only a fine wire in the as-deposited condition.

In the field of rhenium alloys, little is known about any alloys except those with tungsten, osmium, and iron. There is no reason to suspect the accuracy of the data for these systems, but even here the data available are sketchy.

**Chemical Properties**

A great deal of disagreement occurred early in the history of rhenium over the various chemical properties. With time, these disagreements seem to have been largely settled. Thus, the chemistry of rhenium is now fairly well known, although numerous minor mistakes are apparent in present-day literature. Where observed, these mistakes were filtered out of this report; great care should be exercised when reading literature on the chemistry of rhenium, as previous reviewers have often misquoted the original source.

**Analytical Chemistry**

Much work has also been done in this field of chemistry. After evaluation of the methods proposed for both types of analysis by the many investigators, it is suggested that microscopic identification of characteristic crystals is perhaps the most positive way to qualitatively determine the presence of rhenium. The tetraphenyl arsonium chloride method of Willard and Smith for rhenium seems to be a very widely accepted method of quantitative analysis.

**Electrodeposition**

Most of the experimentation in this field seems to have been ultimately successful and reasonably unchallenged. There is little other comment that can be made on it.
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1926


1927


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1945


1946


1947


1949


CTS:ENW/mpw:PLIST
January 14, 1952