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# The Chlorination of Plutonium Dioxide

# Los Alamos

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# THE CHLORINATION OF PLUTONIUM DIOXIDE

by

Mike H. West, Michelle D. Ferran, and Keith W. Fife

## ABSTRACT

We investigated the conversion of $PuO_2$ to $PuCl_3$ with a number of chlorinating agents, sources of $PuO_2$, and reaction conditions, including temperature. We examined $Cl_2$, HCl, $CCl_4$, $Cl_2$-$CCl_4$, and HCl-$CCl_4$ as potential chlorinating agents. Our study showed that $Cl_2$-$CCl_4$ was the superior chlorinating agent. Using this agent, low-fired $PuO_2$—formed by calcining plutonium (III) oxalate at temperatures below 500°C—is more reactive toward chlorination than high-fired $PuO_2$, which is formed by calcining plutonium (III) oxalate at 850°C. Both the low- and high-fired $PuO_2$ feed materials are more reactive than when $PuO_2$ is produced by burning plutonium metal at 400–500°C (foundry oxide). The conversion efficiency of $PuO_2$ to $PuCl_3$ is relatively constant over a batch-size range of 10–300 g.

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## I. INTRODUCTION

In recent years, researchers have noted a resurgence of interest in synthesizing $PuCl_3$ for use in pyrochemical processes. Reasons for this renewed interest are broad, encompassing a range of processing activities. A primary driving force has been the desire to substitute $PuCl_3$ for $PuF_4$ in the traditional bomb-reduction (pressure vessel) process for the large-scale production of plutonium metal. For three decades, concerns have arisen over the $\{\alpha,n\}$ reaction from the $PuF_4$ molecule and the subsequent high neutron exposure rates for chemical operators.[1] In addition, the $CaCl_2$-$CaI_2$ slag—formed during the bomb-reduction process in which $PuCl_3$ is reduced by calcium metal in the presence of an iodine booster—has a lower melting point than the analogous slag ($CaF_2$-$CaI_2$), which is formed by the reduction of $PuF_4$. The $CaCl_2$-$CaI_2$ slag is also more readily dissolved in aqueous plutonium recovery schemes.

Other significant molten salt processes for purifying and producing plutonium metal that could incorporate $PuCl_3$ are the molten salt extraction (MSE) of americium from plutonium metal, electrorefining (ER) of plutonium metal, and the ambient pressure reduction (APR) of $PuCl_3$ to plutonium metal, with calcium metal or other reducing agents in a molten salt diluent matrix. The availability of $PuCl_3$ is also vital to fundamental electrochemical studies of trivalent plutonium in molten chloride salt systems.[2]

Los Alamos researchers believe it is worthwhile to replace $MgCl_2$ with $PuCl_3$ as an oxidant in the MSE and ER processes from the standpoint of eliminating magnesium as a system impurity. Magnesium metal volatilizes during foundry casting of plutonium metal, causing plutonium losses through splattering and damage to the casting equipment and the associated vacuum system.

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Magnesium also participates in an $\{\alpha, n\}$ reaction with plutonium and americium, leading to a potentially serious neutron exposure problem. Another reason for using $PuCl_3$ in the MSE and ER processes is the large distribution coefficient for the partitioning of americium between the metal and salt phases in the presence of $PuCl_3$.[3]

The eutectic point for the $CaCl_2$-$PuCl_3$ phase diagram occurs at 40 mole % $PuCl_3$ and 610°C.[4] Compound formation is not observed for this system. Thus, it may be possible to solubilize 0.4 moles $PuCl_3$ (138 g) in 0.6 moles $CaCl_2$ (66.6 g) at temperatures above 610° C and reduce the $PuCl_3$ to plutonium metal with calcium metal reductant at temperatures much lower than those employed in the conventional direct oxide reduction (DOR) process (>800°C).[5] This procedure is the APR process. Calcium chloride will also be an effective solvent for CaO produced by the reduction of unconverted $PuO_2$ present in $PuCl_3$. In theory, the $CaCl_2$ salt phase is recycled to subsequent reductions as a result of the small CaO content and the increased purity resulting from the calcium reduction step. For plutonium metal, we are also considering performing the ER process in the vessel used for the APR process.

The development of synthetic routes for $PuCl_3$ production dates to the Manhattan Project efforts at Los Alamos and the Metallurgical Laboratory of the University of Chicago, which is now Argonne National Laboratory.[6,7] In the Soviet Union, Budayev and Volsky used $CCl_4$ to chlorinate $PuO_2$, which was produced by calcining plutonium oxalate.[8] Rasmussen and Hopkins[1] chlorinated low-fired $PuO_2$ with $COCl_2$ at temperatures up to 500°C. A screw calciner operated at 250–350°C produced the $PuO_2$ that subsequently flowed countercurrent to $COCl_2$ in a vibrating tube chlorinator. These workers also investigated HCl-$H_2$ and CO-$Cl_2$ as potential chlorinating agents but found them less reactive toward $PuO_2$ than $COCl_2$. Another potential source of $PuCl_3$ relies upon the substoichiometric oxidation of plutonium metal by $ZnCl_2$ in a KCl salt diluent. The oxidation process is a modification to the three-step pyroredox process for upgrading impure plutonium metal to a feed suitable for electrorefining.[9] It remains to be seen whether trace quantities of zinc metal are deleterious to the use of $K_3PuCl_6$ in other processes. Reavis developed a two-step synthesis for preparing $PuCl_3$ that involved forming $PuH_{2.7}$ at 25–250°C from the reaction between plutonium metal and $H_2$. This reaction was then followed by a subsequent reaction with HCl at 450°C for producing $PuCl_3$.[10] The reversible reaction between $H_2$ and plutonium metal is vital to forming a large surface area for the subsequent reaction with HCl.

Boreham et al. reported forming $PuCl_3$ from plutonium (III) and (IV) oxalates by the reaction with HCl or $COCl_2$.[11] Temperatures near 500°C were optimal for hydrochlorinating the plutonium (III) and (IV) oxalates. Nance at Los Alamos also successfully hydrochlorinated plutonium (III) oxalate.[12] Becker and Soine studied the influence of various molten salt systems on the dissolution of $PuO_2$ by $Cl_2$ or HCl gas sparge.[13] Maximum dissolution was observed for 0.3 LiCl-0.3 KCl-0.4 CsCl (mole fractions precede each salt component). The amount of $PuO_2$ dissolved and the concentration of tetravalent plutonium formed in the salt phase relative to the trivalent species depended directly upon the mole fraction of CsCl.

## RESULTS

Recent Los Alamos research focused on evaluating prospective chlorinating agents for synthesizing $PuCl_3$ from $PuO_2$.

### A. Small-Scale Chlorination Experiments

The first chlorinating agents investigated for $PuO_2$ were $Cl_2$ and HCl. Neither gas proved capable of chlorinating $PuO_2$ at temperatures up to 545°C (HCl) or 790°C ($Cl_2$). The thermodynamic data of Glassner suggest that chlorinating $PuO_2$ with HCl is not feasible.[14]

$$PuO_2 + 4HCl = PuCl_3 + 2H_2O + 1/2Cl_2, \tag{1}$$

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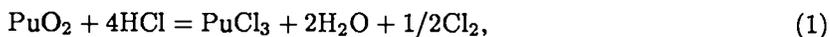
where $\Delta G_{1000K} = 29$ kcal/mole. Both low-fired and high-fired $PuO_2$ were studied in the case of $Cl_2$ and low-fired $PuO_2$ only with HCl. The inertness of $PuO_2$ toward HCl contrasts with $AmO_2$, which reacts with this reagent at 600°C to form $AmCl_3$.[15]

The first successful chlorinating agent for $PuO_2$ examined was $CCl_4$, which decomposes at elevated temperatures to a variety of compounds including $C_6Cl_6$, $C_2Cl_4$, $C_2Cl_6$, $CO_2$, CO, $Cl_2$, $COCl_2$, and C.[8] Argon was saturated with $CCl_4$ by bubbling the argon stream through $CCl_4$ contained in a gas-washing bottle (Fig. 1). The Ar-$CCl_4$ stream passed over $PuO_2$, which was contained in a quartz vessel heated by a Lindberg 55031 resistance furnace. The temperature of the reactor was monitored continuously using a type-K thermocouple protected by a quartz tube sealed at one end. Gases exiting the quartz reactor through a side arm were scrubbed by 5–6 $\underline{M}$ KOH.

The reaction proposed by Fullam and Soine[16] for the reaction of $CCl_4$ with $PuO_2$ is

$$PuO_2(s) + CCl_4(g) = PuCl_3(s) + CO_2(g) + 1/2Cl_2(g). \tag{2}$$
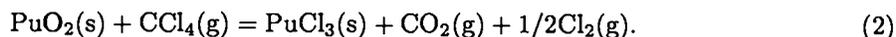
However, Fig. 2 shows that the $PuCl_3$ product formed by this reaction was a dark solid, suggesting carbon contamination from $CCl_4$ pyrolysis.

Therefore, the use of $Cl_2$ gas saturated with $CCl_4$ was explored as a means of synthesizing $PuCl_3$ unadulterated by carbon. The $Cl_2$ was saturated with $CCl_4$ by the technique described for argon. Figure 3 shows that the $PuCl_3$ resulting from chlorinating $PuO_2$ appeared relatively free of carbon contamination from $CCl_4$ pyrolysis.

During subsequent experiments with $Cl_2$-$CCl_4$, we investigated the influence of both chlorination temperatures and calcination temperatures for plutonium (III) oxalate on the extent of $PuCl_3$ formation from $PuO_2$ at the 10-g scale. Plutonium (III) oxalate is typically calcined at temperatures <500°C to produce what is commonly referred to as low-fired $PuO_2$. Figure 4 shows that the synthesis of $PuCl_3$ is more complete as the chlorination reaction temperature approaches 500°C. Through x-ray powder diffraction analyses we demonstrated that unreacted $PuO_2$ is present in $PuCl_3$. Low-fired $PuO_2$ is more reactive towards $Cl_2$-$CCl_4$ at all temperatures than high-fired $PuO_2$. High-fired $PuO_2$ is prepared by calcining the low-fired product at 800–900°C. This process prepares $PuO_2$ for use in the Los Alamos DOR operation during which plutonium metal is prepared by reducing
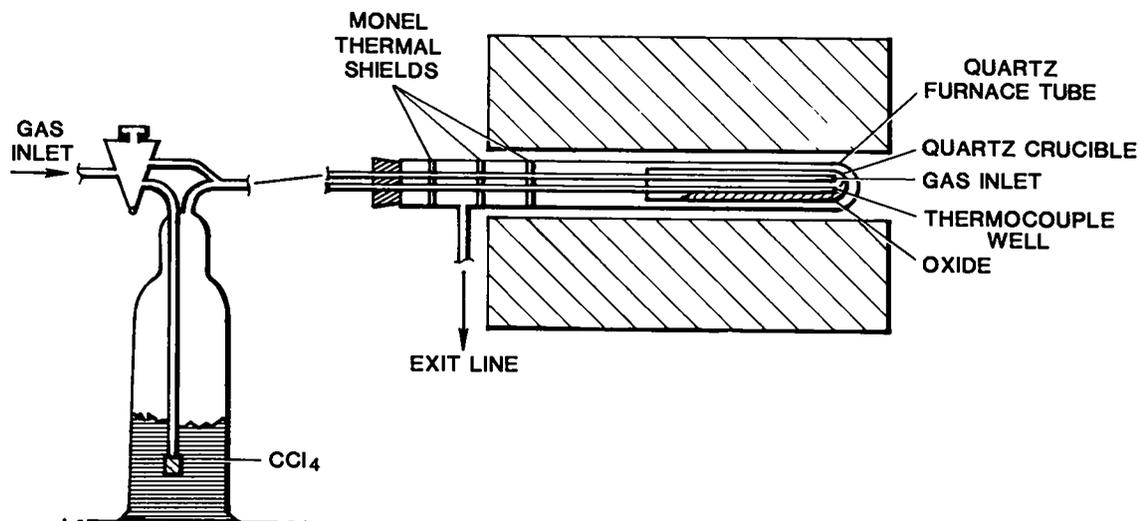


Fig. 1. Quartz reactor for exploratory chlorination experiments with $PuO_2$.

**Fig. 2.** Plutonium trichloride from a small-scale chlorination of $PuO_2$ with $CCl_4$. Carbon contamination of $PuCl_3$ results in a black coloration of the sample.



**Fig. 3.** Plutonium trichloride from a small-scale chlorination of $PuO_2$ with $Cl_2$-$CCl_4$. The absence of carbon during the process results in a lighter coloration of the sample, which contrasts Fig. 2.

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the oxide with calcium metal in molten $CaCl_2$. By decreasing the chlorination reactivity of $PuO_2$ as it is calcined at increasingly higher temperatures (800–900°C), we substantiate the work of Bjorkland and Staritsky.[17] They found that as the calcination temperature increases, the reactivity of $PuO_2$ toward aqueous HCl-KI decreases. Correspondingly, the x-ray diffraction pattern of the oxide intensifies, indicating a more stable crystalline state.

Figure 5 shows that a similar series of experiments was performed using HCl-$CCl_4$ with nearly identical results. However, the conversion of low-fired $PuO_2$ to $PuCl_3$ is not as complete with HCl-$CCl_4$ as with $Cl_2$-$CCl_4$. In addition, carbonaceous deposits are present after chlorination with HCl-$CCl_4$.

Foundry oxide was also chlorinated with $Cl_2$-$CCl_4$ but not until the reactor temperature approached 700°C. Foundry oxide is unreactive toward concentrated $HNO_3$-dilute HF solutions. Bjorkland and Staritsky reported a 2.40 refractive index for oxide prepared from the metal at 170°C.[17] An identical value for the refractive index was obtained for oxide prepared from plutonium (IV) oxalate at 1000°C. The lack of reactivity is related to a stable $PuO_2$ crystal structure formed upon burning plutonium metal in air.

Plutonium trichloride, formed by chlorinating $PuO_2$, was transported from the main body of $PuO_2$ toward the monel heat reflectors shown in Fig. 1 and was deposited as a mass of green needles (Fig. 6). The chlorination rate appeared to depend on the transport of $PuCl_3$ from the reaction site. Plutonium trichloride has a negligible vapor pressure at 700°C (0.00029 mm),[18] but $PuCl_4$ has a substantial vapor pressure at the same temperature (3.7 mm).[19] Researchers believe the $PuCl_3$ is thus formed as in Eq. (2) and transported as in Eqs. (3) and (4).

$$PuCl_3(s) + 1/2Cl_2(g) = PuCl_4(g) \ @ \ 700°C \tag{3}$$

$$PuCl_4(g) = PuCl_3(s) + 1/2 \ Cl_2(g) \ @ \ < 700°C. \tag{4}$$

The vapor-phase absorption spectrum of $PuCl_4$ at 925°C reported by Gruen and DeKock provides additional evidence for its existence in the vapor phase.[20]
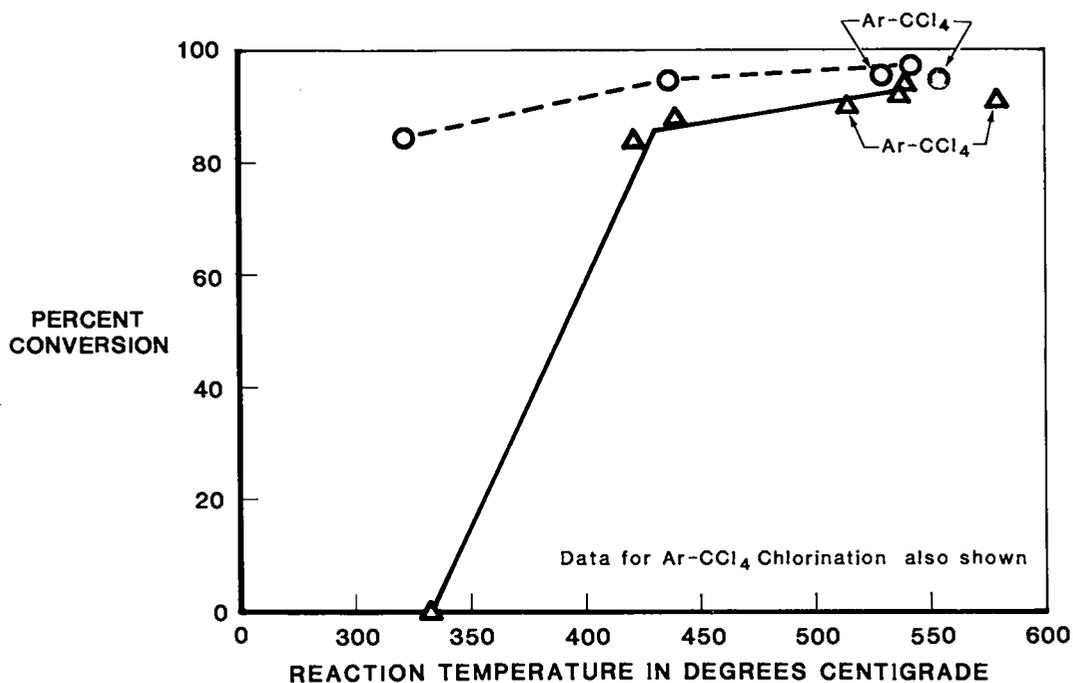


Fig. 4. Chlorination of low-fired (◯) and high-fired (△) $PuO_2$ with $Cl_2$-$CCl_4$ as a function of temperature.
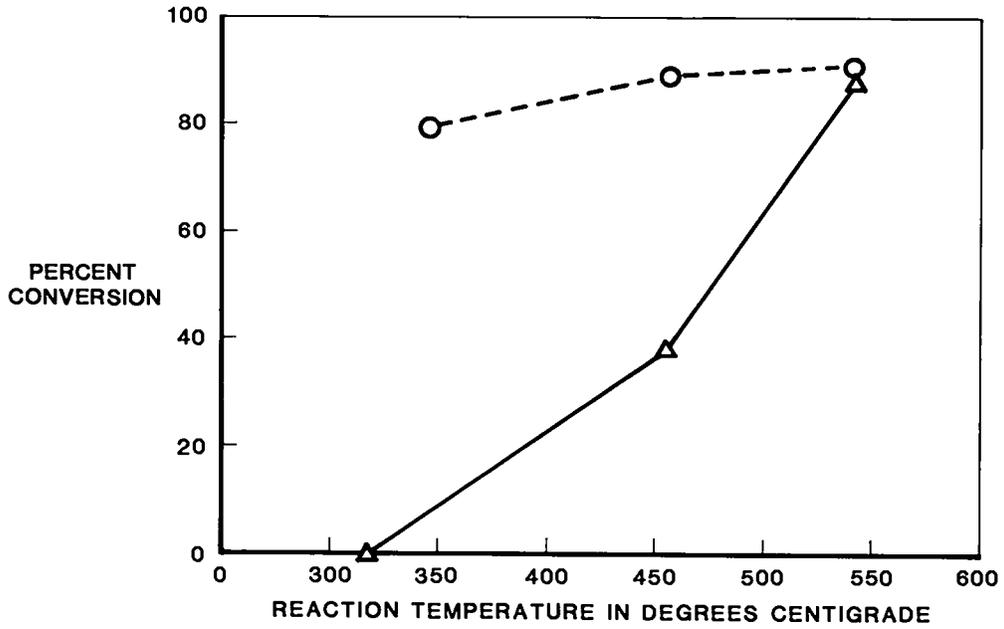
Fig. 5. Chlorination of low-fired (⊙) and high-fired (△) $PuO_2$ with $HCl\text{-}CCl_4$ as a function of temperature.
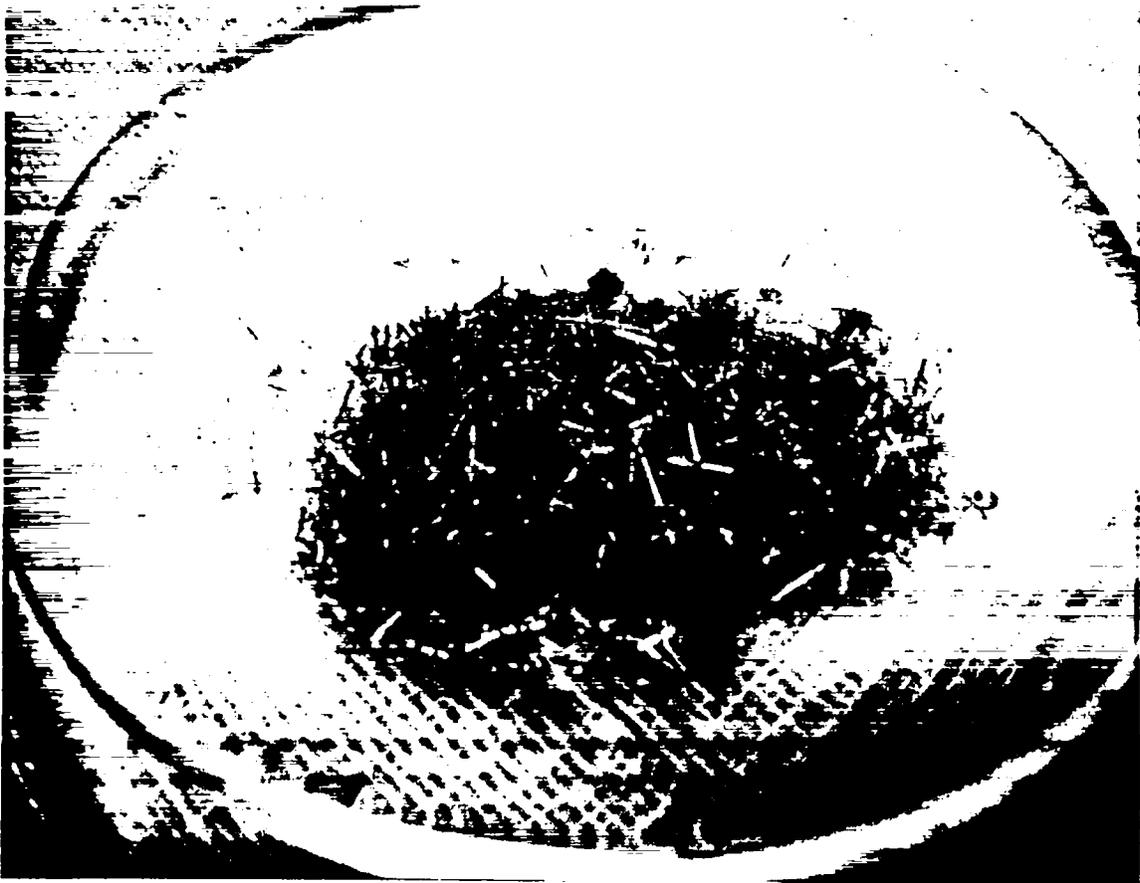


Fig. 6. Crystals of $PuCl_3$ from chlorination of foundry $PuO_2$ with $Cl_2\text{-}CCl_4$ at 700°C.

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## B. Large-Scale Chlorination Experiments with $Cl_2$-$CCl_4$

The initial work to scale up the batch chlorination experiments used a 3-in. (outer diameter) quartz vessel with a coarse porosity frit (Fig. 7), on which rest the $PuO_2$ feed; a 3-in. (inner diameter) Lindberg furnace (MK-3012) heated the reaction vessel. A gas inlet tube and thermocouple well, constructed from quartz, penetrated a silicone rubber stopper placed in a standard taper 24/40 ground joint at the vessel's top. Later, the rubber stopper was replaced with a Pyrex male ground joint with a thermocouple well and gas inlet tube, whereas a ball joint and elbow fitted with Tygon formed the exit line. Chlorine saturated with $CCl_4$ flowed into the top of the vessel through the inlet tube and exited through Tygon tubing at the vessel's bottom. Once the reaction neared completion, excess $CCl_4$ condensed in the off gas line. Fullam and Soine observed this phenomenon for the stirred-bed batch chlorinator.[16] Figure 8 shows that volatile chlorides, such as $FeCl_3$ and pyrolysis products of $CCl_4$, collect below the frit in the cool region of the furnace. The preliminary experiments used a 50-g batch size of $PuO_2$. The reactivity of the low-fired $PuO_2$ partially determined the time required for complete chlorination. We needed to double the $Cl_2$ flow rate through $CCl_4$ to achieve complete chlorination of 100-g batches of $PuO_2$ within a normal working day (one 8-hour shift). Figure 9 shows a 175-g batch size of $PuCl_3$ resting on the frit.

Table I illustrates the considerable variation in reactivity toward chlorination even among low-fired $PuO_2$ blends. The data in Table I also illustrate comparable reactivity for high-fired and some low-fired $PuO_2$ samples. Plutonium dioxide was originally derived by calcining plutonium (III) and (IV) oxalates.

Table I. Chlorination Reactivity of Some Selected Low-Fired
and High-Fired $PuO_2$ Blends

| Oxide Source | Pu (%) | Cl (%) | Reaction Time (h) at 500°C | Batch Size (g) |
|---|---|---|---|---|
| MSTPPB9C05 (a) | 70.94 | 27.5 | 5 1/6 | 100.0 |
| PUTHR2KFC5 (b) | 70.71 | 27.1 | 6 2/3 | 50.0 |
| MSTPPB334C (a) | 70.17 | 28.3 | 13 5/6 | 200.0 |

(a) Low-fired $PuO_2$.
(b) High-fired $PuO_2$.

The MSTPPB $PuO_2$ blends, which are low-fired oxides, are normally suitable for fluorination to $PuF_4$ with HF for the synthesis of plutonium metal by the bomb-reduction process because fluorination also requires active or low-fired $PuO_2$.

Fifty-gram batches from blended, low-fired $PuO_2$ were chlorinated for periods between 1 and 6 hours at 500°C and 600°C. Chlorination appeared more rapid at the higher temperature, requiring approximately 3 hours, but work at 600°C requires using quartz, which is considerably more expensive, harder to fabricate, and more difficult to shape than Pyrex. For these reasons, chlorination at 500°C was chosen with approximately 4 hours required for a complete reaction (Fig. 10).

To achieve more rapid chlorination of $PuO_2$ and, concurrently, to increase the batch size, we constructed a Pyrex vessel from a 600-mL Büchner-type, fritted disc funnel. A standard taper 55/50 ground joint sealed the top of the reactor with an 18/7 ball joint and elbow forming an exit line. With this reactor vessel and a standard 6-in. (inner diameter) Lindberg furnace (MK-6015-S-V), up to 300-g batches of $PuO_2$ have been successfully chlorinated at 500°C in less than 7 hours. Table II summarizes the extent of chlorination for batch sizes ranging from 10 to 300 g.
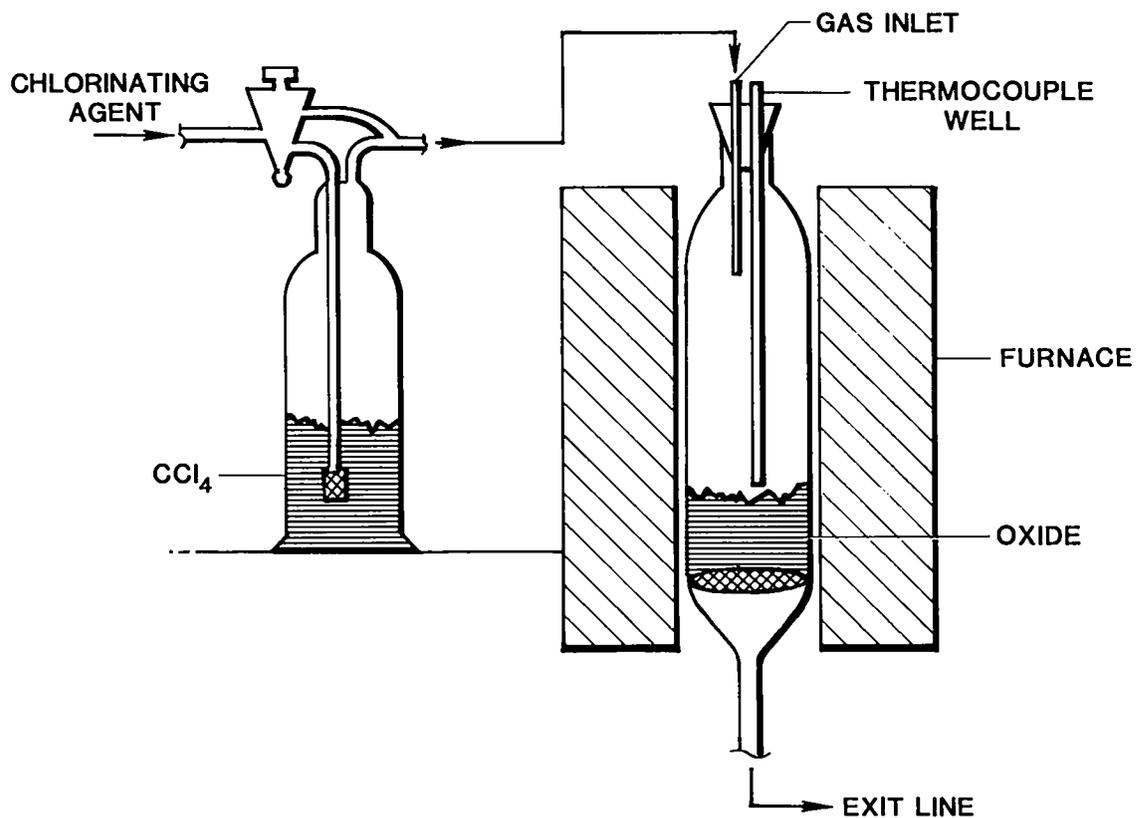
Fig. 7. Apparatus for chlorination experiments with PuO$_2$ (50–100 g).



Fig. 8. Condensation of volatile chlorides and CCl$_4$ pyrolysis products at the reactor exit. The reddish deposits represent the products of the FeCl$_3$ distilling process. The whitish deposits present in the condensate represent CCl$_4$ pyrolysis products.

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**Fig. 9.** Plutonium trichloride from a large-scale chlorination experiment (175 g $PuO_2$) using $Cl_2$-$CCl_4$.
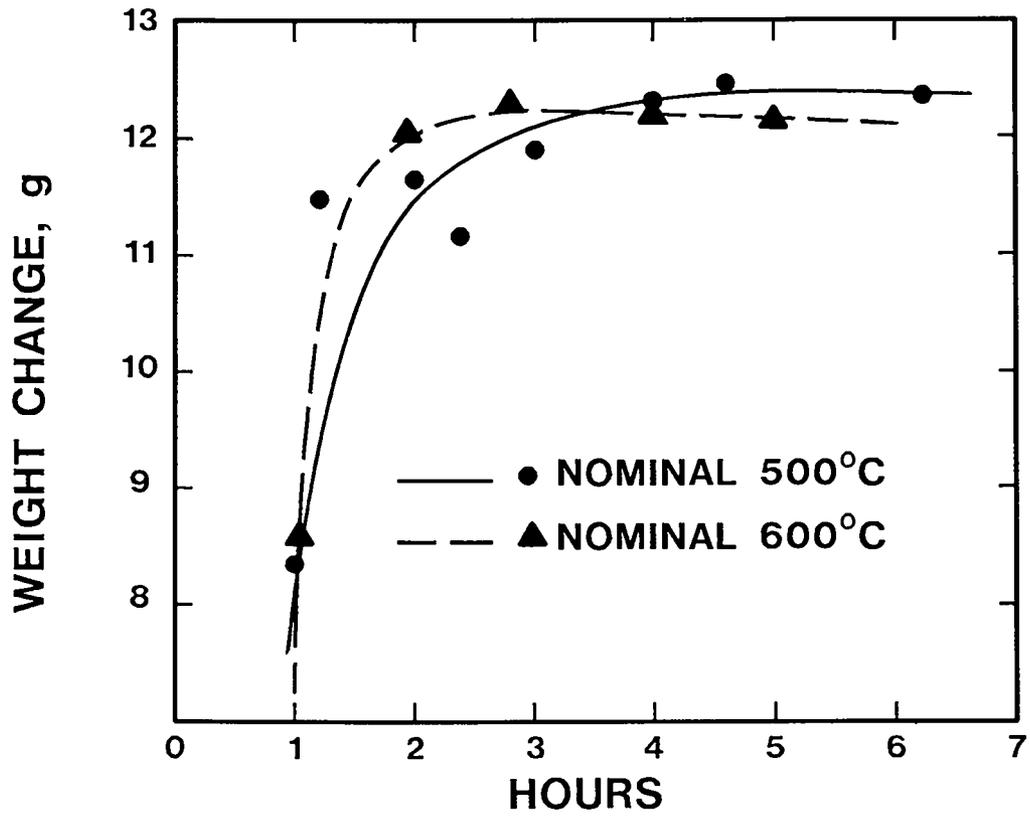


**Fig. 10.** Weight change (g) versus chlorination time at 500°C and 600°C.

Table II. The Effect of Batch Size on the Chlorination
of PuO$_2$ with Cl$_2$-CCl$_4$

| PuO$_2$ Batch Size (g) | PuCl$_3$ (%) | Number of Runs |
|---|---|---|
| 10.0 | 95.4 | 2 |
| 50.0 | 94.5 | 2 |
| 75.0 | 94.2 | 1 |
| 100.0 | 94.8 | 14 |
| 125.0 | 94.6 | 3 |
| 150.0 | 95.1 | 1 |
| 200.0 | 95.2 | 8 |
| 300.0 | 94.6 | 6 |

The conversion efficiency is essentially constant at 95% as the batch size increases by an order of magnitude. The Appendix summarizes all chlorination experiments up to and including the 300-g batch size.

## III. FUTURE WORK

We must continue our experimental work to evaluate other potential chlorinating agents including CO-Cl$_2$, photosensitized CO-Cl$_2$ mixtures, and COCl$_2$. (Phosgene was the optimum chlorinating agent for PuO$_2$ reported by the Hanford Atomic Products Operation.)[1]

Once researchers select an optimum reagent for production of PuCl$_3$, we must evaluate construction materials under reactor-like conditions to ensure they are corrosion-resistant.[21]. The most corrosion-resistant materials will be used for constructing large-scale chlorination vessels comparable to those used on the metal preparation line. Large-scale production of PuCl$_3$ will enable researchers to more rapidly evaluate potential uses of PuCl$_3$. We continue our efforts to incorporate and evaluate PuCl$_3$ in the processes of MSE, APR, ER, and bomb reduction.

## ACKNOWLEDGMENTS

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## Appendix

Summary of Plutonium and Chloride Analyses for Chlorination Experiments with $Cl_2$-$CCl_4$

| | initial weight (g) | final weight (g) | oxide batch | chlorinating agent | Pu, % | Cl, % | PuCl₃ (based on % Cl) | Cl/Pu |
|---|---|---|---|---|---|---|---|---|
| PUCL3-5P | 9.4 | 11.6 | MSTPPBMWC1 | CCl₄ | 68.98 | 29.2 | 94.8 | 2.85 |
| PUCL3-6P | 10.1 | 12.7 | | | 69.37 | 29.4 | 95.5 | 2.86 |
| PUCL3-7P | 10.0 | 12.4 | PUTHR2KFC5 | | 70.39 | 28.1 | 91.2 | 2.69 |
| PUCL3-8P | 10.0 | 12.4 | | | 70.34 | 27.7 | 89.9 | 2.65 |
| PUCL3-9P | 9.9 | 12.3 | | CCl₄-Cl₂ | 69.06 | 28.9 | 93.8 | 2.82 |
| PUCL3-17P | 10.0 | 12.5 | | | 69.18 | 29.9 | 97.0 | 2.91 |
| PUCL3-20P | 10.0 | 12.3 | | | 69.87 | 28.3 | 91.8 | 2.73 |
| PUCL3-23P | 10.0 | 12.4 | MSTPPBMWC1 | HCl-CCl₄ | 67.77 | 28.1 | 91.2 | 2.79 |
| PUCL3-24P | 10.0 | 12.6 | PUTHR2KFC5 | | 69.69 | 27.0 | 87.7 | 2.61 |
| PUCL3-31P | 10.0 | 12.4 | MSTPPBMWC1 | CCl₄-Cl₂ | 69.53 | 28.0 | 90.9 | 2.71 |
| PUCL3-32P | 20.0 | 24.7 | | | 69.55 | 27.5 | 89.3 | 2.67 |
| PUCL3-33P | 30.0 | 37.0 | | | 70.57 | 27.9 | 90.6 | 2.66 |
| PUCL3-39P | 50.0 | 62.0 | | | 68.64 | 29.1 | 94.5 | 2.86 |
| PUCL3-40P | 50.0 | 62.3 | | | 68.95 | 29.1 | 94.5 | 2.85 |
| PUCL3-45P | 75.0 | 94.0 | | | 69.18 | 29.0 | 94.2 | 2.83 |
| PUCL3-46P | 100.0 | 124.6 | | | 67.26 | 29.3 | 95.1 | 2.94 |
| PUCL3-47P | 125.0 | 155.6 | | | 68.27 | 29.7 | 96.4 | 2.93 |
| PUCL3-52P | 50.0 | 60.4 | PUTHR2KFC5 | | 70.71 | 27.1 | 88.0 | 2.58 |
| PUCL3-54P | 100.0 | 123.2 | MSTPPBCO5 | | 70.94 | 27.5 | 89.3 | 2.61 |
| PUCL3-55P | 100.0 | 125.1 | KHCB1C3 | | 69.41 | 29.6 | 96.1 | 2.88 |
| PUCL3-56P | 125.0 | 156.3 | | | 69.76 | 28.8 | 93.5 | 2.78 |
| PUCL3-57P | 125.0 | 156.2 | | | 68.12 | 29.1 | 94.5 | 2.88 |
| PUCL3-58P | 150.0 | 187.3 | | | 69.20 | 29.3 | 95.1 | 2.85 |
| PUCL3-59P | 175.0 | 218.0 | | | 69.98 | 28.6 | 92.9 | 2.76 |
| PUCL3-60P | 100.0 | 124.5 | KHCB2C5 | | 69.81 | 29.9 | 97.1 | 2.89 |
| PUCL3-68P | 100.0 | 124.1 | | | 69.79 | 29.0 | 94.2 | 2.80 |
| PUCL3-78P | 100.0 | 124.6 | KHCB1C3 | | 69.76 | 29.5 | 95.8 | 2.85 |
| PUCL3-79P | 100.0 | 124.2 | KHCB2C1 | | 69.95 | 29.0 | 94.2 | 2.79 |
| PUCL3-80P | 100.0 | 123.6 | | | 69.76 | 29.2 | 94.8 | 2.82 |
| PUCL3-81P | 100.0 | 123.6 | | | 69.92 | 29.1 | 94.5 | 2.81 |
| PUCL3-82P | 100.0 | 124.1 | | | 69.96 | 29.1 | 94.5 | 2.80 |
| PUCL3-83P | 100.0 | 124.4 | | | 69.80 | 28.9 | 93.8 | 2.79 |
| PUCL3-84P | 100.0 | 124.5 | | | 69.85 | 29.2 | 94.8 | 2.82 |
| PUCL3-85P | 100.0 | 124.2 | | | 69.96 | 28.8 | 93.5 | 2.78 |
| PUCL3-86P | 100.0 | 124.2 | | | 69.47 | 29.1 | 94.5 | 2.82 |
| PUCL3-87P | 100.0 | 124.4 | | | 69.50 | 29.1 | 94.5 | 2.82 |

## Appendix (cont.)

| | initial weight (g) | final weight (g) | oxide batch | chlorinating agent | Pu, % | Cl, % | PuCl₃ (based on % Cl) | Cl/Pu |
|---|---|---|---|---|---|---|---|---|
| PUCL3-89P | 200.0 | 248.6 | | | 69.67 | 29.4 | 95.5 | 2.84 |
| PUCL3-90P | 200.0 | 249.6 | | | 69.53 | 29.3 | 95.1 | 2.84 |
| PUCL3-92P | 250.0 | 311.2 | | | 69.60 | 29.4 | 95.5 | 2.85 |
| PUCL3-93P | 250.0 | 308.3 | | | 69.72 | 29.1 | 94.5 | 2.81 |
| PUCL3-94P | 300.0 | 373.7 | | | 69.78 | 29.4 | 95.5 | 2.84 |
| PUCL3-95P | 300.0 | 373.0 | | | 69.74 | 29.4 | 95.5 | 2.84 |
| PUCL3-96P | 201.9 | 251.8 | KHCB2C4 + KHCB2C1 | | 69.66 | 29.2 | 94.8 | 2.83 |
| PUCL3-97P | 200.0 | 249.6 | | KHCB2C4 | 69.47 | 29.5 | 95.8 | 2.86 |
| PUCL3-98P | 300.0 | 372.8 | | | 69.71 | 29.0 | 94.1 | 2.80 |
| PUCL3-100P | 300.0 | 372.7 | | | 69.87 | 28.9 | 93.8 | 2.79 |
| PUCL3-104P | 200.0 | 248.7 | | KHCB2C4 | 69.79 | 29.1 | 94.5 | 2.81 |
| PUCL3-105P | 200.0 | 248.5 | | | 69.50 | 29.3 | 95.1 | 2.84 |
| PUCL3-106P | 200.0 | 249.1 | | | 69.65 | 29.6 | 96.1 | 2.87 |
| PUCL3-107P | 200.0 | 249.0 | | | 69.72 | 29.3 | 95.1 | 2.83 |
| PUCL3-108P | 200.0 | 247.3 | MSTPPB334C | | 70.17 | 28.3 | 91.9 | 2.72 |
| PUCL3-109P | 300.0 | 371.5 | KHCB2C4 | | 69.94 | 29.2 | 94.8 | 2.81 |
| PUCL3-110P | 300.0 | 374.4 | MPB22ERC1 | | 69.46 | 29.4 | 95.5 | 2.85 |

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| 101-125 | A06 | 251-275 | A12 | 401-425 | A18 | 551-575 | A24 |
| 126-150 | A07 | 276-300 | A13 | 426-450 | A19 | 576-600 | A25 |
| | | | | | | 601-up* | A99 |

*Contact NTIS for a price quote.