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Shredder and Incinerator Technology for Treatment of Commercial Transuranic Wastes

**K. H. Oma
J. H. Westsik, Jr.
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October 1985

**Prepared for the U.S. Department of Energy
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SHREDDER AND INCINERATOR TECHNOLOGY FOR
TREATMENT OF COMMERCIAL TRANSURANIC WASTES

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SUMMARY AND CONCLUSIONS

Pacific Northwest Laboratory (PNL) is defining strategies, evaluating alternatives, and developing technology for treatment of radioactive wastes generated by commercial nuclear facilities. Treatment strategies for commercial transuranic (TRU) wastes have been identified and evaluated by Ross et al. (1985). Ross concluded that extensive treatment of the TRU wastes is warranted from both cost and waste form characteristics considerations. The evaluation recommended that wastes containing combustible materials be processed by shredding and incineration and that the resulting residue be incorporated into a cement waste form. This report describes the selection and evaluation of process equipment to accomplish the shredding and incineration of commercial TRU wastes.

Defense sites have been developing treatment technology for TRU wastes for many years and much of that technology can be used for some commercially generated wastes. The defense wastes are mostly contact-handled (CH), however, and result from glovebox operations with weapons-grade plutonium. Operation of a postulated commercial reprocessing plant will generate large quantities of TRU wastes that contain significant amounts of fission products. Radiation levels from commercial TRU wastes will therefore be higher than for defense wastes. As such, shredding and incineration equipment for the commercial application will be needed to process both remote-handled (RH) and CH wastes. Technology developed for defense waste treatment must be evaluated for application to remote operations required for the RH commercial waste.

Our review of current shredder and incinerator technologies indicated that the electrically driven, low-speed shredder process was preferred for TRU waste pretreatment. The review also indicated that the electrically heated controlled-air, gas-heated controlled-air, and rotary kiln incinerators were preferred over other incineration processes for the commercial TRU application. Based on the review of existing technology, an experimental program was undertaken to demonstrate the preferred technology on simulated commercial TRU wastes. The objectives of the tests were to: 1) confirm that shredders and incinerators can be used to effectively process commercially generated TRU

wastes, 2) evaluate the process equipment for adaptability to remote radioactive operation, and 3) select a reference shredding and incineration system for further testing and development.

Simulated wastes representing general process trash, sample and analytical cell waste, wood-framed HEPA filters and metal-framed HEPA filters were used for the test program. Special waste mixes considered difficult for the incinerator and shredder processes were also formulated and tested. Low-speed shredders manufactured by three different companies were tested and compared in terms of waste throughput, cutter force, cutter configuration and fragment size. The shredded waste was then used as feed material for the incineration tests.

The electrically heated controlled-air, gas-heated controlled-air and rotary kiln incineration processes were evaluated and compared based on technical merit and system cost. The technical merit of each process was judged by a five member panel using the Figure-of-Merit (FOM) process selection methodology. Performance criteria in the areas of incinerator product, equipment, and operations were established and used as a bases for the FOM comparison. The FOM numbers obtained were viewed as a measure of the overall process effectiveness for the commercially generated TRU waste application. Capital and operating costs were estimated for the shredding, incinerating, and off-gas treatment operations. Capital costs were also estimated for the portion of a hot cell facility that would contain these unit operations. Cost-effectiveness ratios were calculated using the cost/FOM ratio for each incineration process. These ratios were then used to select a reference shredder and incinerator process for further development.

The primary conclusions derived from this study are listed below:

- Shredding and incineration technology appears effective for converting simulated commercial TRU wastes to a noncombustible form.
- The gas-heated controlled-air incinerator received the highest technical ranking. On a scale of 1 to 10, the incinerator had an FOM number of 7.0. This compares to an FOM of 6.1 for the electrically heated controlled-air incinerator and an FOM of 5.8 for the rotary

kiln incinerator. The major advantages and disadvantages of each incinerator, which came out of the FOM evaluation, are summarized below.

Summary of Incinerator Advantages and Disadvantages

Incinerator	Major Advantages	Major Disadvantages
Electrically Heated Controlled-Air	• Minimum off-gas treatment required due to low flow and low ash entrainment • Low ash/residue retainment in the primary chamber • Long equipment life • Able to process wide range of feed materials	• Residue contains high fraction of fixed carbon • Process requires high level of feed pretreatment • Residue contains clinkers of carbon-rich wood • Remote maintenance is judged difficult
Gas-Heated Controlled-Air	• High burnout of fixed carbon is achieved • Process has been well developed for TRU and LL waste applications	(no major disadvantages identified)
Rotary Kiln	• Able to process wide range of feed materials • Minimal feed pretreatment is required	• Low retention of trace elements in residue • High off-gas treatment requirements due to high flow rate and high ash entrainment • Remote maintenance is judged difficult • Shorter refractory life attributes to increased maintenance and personnel exposure

- The present worth costs of the incineration processes for a postulated commercial reprocessing plant were lowest for the electrically heated and gas-heated controlled-air incinerators with costs of \$16.3 M and \$16.9 M respectively (1985 dollars). Due to higher capital and operating costs, the rotary kiln process had a present worth cost of \$20.8 M. These cost numbers are for comparative purposes only and are not adjusted for future inflation.
- The recommended process from the three evaluated for the commercial TRU waste application is the gas-heated controlled-air incinerator with a single stage of shredding for feed pretreatment. This process had the best cost-effectiveness ratio of 1.0 (normalized). The electrically heated controller-air incinerator had a rating of 1.2 and the rotary kiln rated a 1.5. It is important to note that all three incineration systems tested were excellent pieces of equipment and each has its advantages for different incineration applications. The selection of the gas-heated controlled-air process only applies to the specific application tested and should not be used to infer that the process is superior for other applications.
- Most of the simulated wastes were easily processed by the low-speed shredders evaluated here. The HEPA filters proved difficult to process, however. Wood-framed HEPA filters tended to ride on the cutter wheels and spacers without being gripped and shredded. Methods for feeding wood-framed HEPA filters and other wood-boxed items to the shredder need to be developed. The metal-framed HEPA filters and other difficult to shred items caused the shredders to periodically reach the torque limit and go into an automatic reversal cycle; however, the filters were eventually processed by the units. Metal-framed filters will require a shredder designed for high cutter tooth force and/or larger shredded fragment size. Some of the dust on loaded HEPA filters was released during the shredding operation. Methods for fixing the dust on the HEPA filters should be evaluated and tested.

- All three incinerators were ineffective for oxidizing the aluminum metal used as spacers in HEPA filters. Aluminum metal will cause an undesirable hydrolysis reaction in the cemented waste form.

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ACRONYMS

AGNS	Allied General Nuclear Services
BNFP	Barnwell Nuclear Fuel Plant
CFR	Code of Federal Regulations
CH	contact-handled
CSMRI	Colorado School of Mines Research Institute
ECP	Environmental Control Products
EPA	Environmental Protection Agency
GPT	general process trash
HEDL	Hanford Engineering Development Laboratory
HEPA	high efficiency particulate air
HLW	high level waste
INEL	Idaho National Engineering Laboratory
LANL	Los Alamos National Laboratory
LLW	low level waste
ORNL	Oak Ridge National Laboratory
PREPP	process experimental pilot plant
PVC	poly vinyl chloride
PWI	plutonium waste incinerator
RFP	Rock Flats Plant
RH	remote-handled
SAC	sample and analytical cell waste
SRL	Savannah River Laboratory
SWIFT	suspect waste incinerator facility test
TRU	transuranic
WERF	waste experimental reduction facility
WIPP	Waste Isolation Pilot Plant

CONTENTS

INTRODUCTION	1
COMMERCIAL TRANSURANIC WASTE DEFINITION	5
EVALUATION OF TREATMENT TECHNOLOGIES	11
SHREDDER TECHNOLOGY	11
INCINERATOR TECHNOLOGY	14
Controlled-Air Incinerators	18
Rotary-Kiln Incinerators	20
Off-Gas Treatment Systems	23
SHREDDER TESTS	25
SHREDDER DESCRIPTIONS	26
TEST RESULTS	29
General Process Trash	30
Sample and Analytical Cell Wastes	30
Wood-Framed HEPA Filters	30
Metal-Framed HEPA Filters	32
Type 2 Wastes	33
Type 3 Wastes	33
Fragment Size Analysis	33
INCINERATOR TESTS	39
ELECTRICALLY HEATED CONTROLLED-AIR INCINERATOR	40
Equipment Description	40
Test Description	43
GAS-HEATED CONTROLLED-AIR INCINERATOR	46
Equipment Description	47

Test Description	49
ROTARY KILN INCINERATOR	50
Equipment Description	51
Test Description	52
TEST RESULTS	54
Residue Characteristics	54
Off-Gas Characteristics	58
Trace Element Behavior	60
COMPARISON OF INCINERATOR PROCESSES	63
INCINERATOR ECONOMICS	63
FIGURE-OF-MERIT ANALYSIS	68
COST EFFECTIVENESS ANALYSIS	70
DEVELOPMENT NEEDS	75
REFERENCES	77

FIGURES

1	Process and Equipment Flow Diagram for the Noncombustible Waste Forms Option	2
2	Simulated SAC Waste Ready for Shredding Tests	8
3	Cutter Wheel Configuration of a Typical Low-Speed Shredder	13
4	LANL Gas-Heated Controlled-Air Incineration System	19
5	SRL-PWI Electrically-Heated Controlled-Air Incinerator System	21
6	INEL-PREPP Rotary Kiln Incineration System	22
7	Model 1600 Electric Drive Shredder	27
8	Model AZ-80 Electric Drive Shredder	28
9	Model 36-22 Hydraulic Drive Shredder	29
10	Larger Metal and Wood Pieces of SAC Waste After Shredding by Test Unit 1	35
11	Wood-Framed HEPA Filters Processed by Single Stage Shredding and Dual Stage Shredding	36
12	Electrically Heated Controlled-Air Test Incinerator Schematic	41
13	Electrically Heated Controlled-Air Test Incinerator	41
14	Gas-Heated Controlled-Air Test Incinerator Schematic	48
15	Gas-Heated Controlled-Air Test Incinerator	48
16	Rotary-Kiln Test Incinerator Schematic	51
17	Rotary-Kiln Test Incinerator	51

TABLES

1	Description of the Noncombustible Waste Forms Option	1
2	Annual Untreated Quantity of Wastes Projected From a 1500 MTU/yr Reprocessing Plant	5
3	Average Waste Compositions	6
4	Simulated TRU Waste Compositions	7
5	Incinerator Feed Makeup	8
6	Estimated Radionuclide Content of Commercial TRU Wastes	9
7	Advantages and Disadvantages of High-Speed Shredders	12
8	Advantages and Disadvantages of Hydraulic and Electric Drives for Low-Speed Shredders	14
9	Summary of U.S. DOE Radioactive Waste Incinerator Treatment Systems	15
10	Shredder Test Unit Comparison	26
11	Shredder Performance Comparison	31
12	Shredded Waste Size Analysis	34
13	Incinerator Operating Data Summary	45
14	Incinerator Weight and Volume Reductions	55
15	Chemical Analysis of Incinerator Ash	56
16	Residual Carbon Analysis of Incinerator Product	57
17	Incinerator Test Off-Gas Characteristics	59
18	Distribution of Trace Elements in the Incinerator Product and Off-Gas Particulate	61
19	Incineration System Equipment Requirements Used for Cost Estimate	64
20	Capital Costs for Incinerator Processes	66
21	Annual Labor Requirements and Operating Cost Estimate for Incineration Processes	67

22	Figure-of-Merit Model for Incinerator Process Comparison	71
23	Figure-of-Merit Results for Individual Panel Members	73

INTRODUCTION

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INTRODUCTION

Commercial transuranic (TRU) wastes are being studied for processing prior to disposal in a deep geologic repository. Shredding and incineration followed by cementation of the ash and residue has been identified as the most effective strategy for the treatment of combustible TRU wastes generated during the reprocessing of commercial spent fuel (Ross et al. 1985). This treatment strategy was selected from six treatment options ranging from "no treatment" to "process to noncombustible waste forms." Table 1 shows the recommended treatment processes for expected waste types and Figure 1 shows a schematic of the recommended treatment strategy. The shredding/incineration/cementation method produces a noncombustible cemented waste form. Incinerator ash has been effectively produced and incorporated into cemented waste forms during LLW studies (Treat et al. 1983, Westsik 1984). Metallic wastes including fuel hulls and failed equipment would be consolidated by melting (Montgomery 1983). Cost savings for these treatments result from the volume reduction achieved and the resulting lower transportation and disposal costs. The Nuclear Waste Treatment Program at the Pacific Northwest Laboratory has the responsibility for developing these processes for the U.S. Department of Energy (DOE). If reprocessing of commercial spent fuel becomes a reality, the waste treatment technologies will be ready for use.

TABLE 1. Description of the Noncombustible Waste Forms Option (Ross et al. 1985).

<u>Waste Type</u>	<u>Treatment</u>
Hardware and Hulls	Size reduce as required and melt in remote-handled batches in metal melter.
Failed Equipment	Size reduce as required and melt in either contact-handled or remote-handled batches in metal melter.
Filters	Shred in either contact-handled or remote-handled shredder and incinerate. Incorporate ash, media, concentrated scrub solution and metals into cement waste form using remote-handled in-drum mixer.
Fluorinator Solids	Mix with sufficient cement in in-drum mixer to form LLW.
GPT and SAC Wastes	Treat noncombustibles as failed equipment when segregation is possible. Shred and incinerate all combustibles. Incorporate ash and scrubber solution into cement waste form.

FIGURE 1. Process and Equipment Flow Diagram for the Noncombustible Waste Forms Option (Ross et al. 1985)

General Process Trash (GPT), Sample and Analytical Cell Waste (SAC), and HEPA filters are TRU wastes that contain combustible material. These wastes are present in both contact-handled (CH) and remote-handled (RH) forms. As a result, much of the equipment required in the treatment the TRU wastes must be designed to operate remotely. The TRU waste strategy document (Ross et al. 1985) recommends that these wastes be size reduced in a CH and RH shredder and that the waste be incinerated in a RH incinerator.

Commercial shredders and U.S. DOE-developed incinerators were reviewed and evaluated with respect to their ability to process commercially generated TRU wastes. Based on our review, simulated TRU wastes were processed through candidate shredders and incinerators to determine the process applicability for effectively treating the waste. This report contains the results of the initial review, as well as a description of the shredder and incinerator tests. Incinerator systems are compared using system economics and a Figure-of-Merit

evaluation of product, equipment, and operation considerations. Based on this comparison, a reference process is selected and development needs and recommendations are identified.

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**COMMERCIAL
TRANSURANIC WASTE DEFINITION**

COMMERCIAL TRANSURANIC WASTE DEFINITION

Quantities and compositions of TRU wastes from a commercial reprocessing plant have been estimated by Darr (1983) for the Barnwell Nuclear Fuels Plant (BNFP) and are used in this report as the basis for evaluation of waste processing equipment. Included in the wastes are spent fuel hulls and fuel assembly hardware, general process trash (GPT), used HEPA filters, failed equipment, sample and analytical cell wastes (SAC), and fluorinator solids. Of these, the GPT, SAC, and HEPA filters would require treatment via shredding and/or incineration. Failed equipment may also require size reduction via shredding.

Table 2 lists the annual volumes and weights of GPT, SAC, filter, and failed equipment wastes anticipated to be generated at a 1500 MTU/yr commercial reprocessing plant (Ross et al. 1985). Approximately 75 wt% of the waste is contact handled and the remainder requires remote handling (radiation dose >200 mR/hr at the surface of the waste container). The waste containers are expected to be recycled and will not be shredded with the waste.

TABLE 2. Annual Untreated Quantity of Wastes Projected From a 1500 MTU/yr Reprocessing Plant^(a)

Waste Type	CH/RH	Net Wt, kg	Net Vol, m ³	Packaged Vol, m ³	Container Capacity, L (gal)	Number of Containers
Filters	CH	16,380	117.6	347.9	208 (55)	50
					303 (80)	1,114
	RH	3,710	30.3	140.2	303 (80) 2,270 (600)	133 44
GPT & SAC Waste	CH	11,340	104	112.3	208 (55)	540
					208 (55) 2,270 (600)	198 37
	RH	7,080	70.3	125.2	208 (55) 2,270 (600)	198 37
Failed Equipment	CH	17,600	19.8	23.6	208 (55)	70
					2,270 (600)	4
	RH	3,600	6.2	9.1	2,270 (600)	4

(a) Based on Barnwell Nuclear Fuel Plant (Ross et al. 1985).

Table 3 shows the estimated compositions for the TRU waste streams considered here. The GPT and SAC wastes contain both combustible and noncombustible fractions, which would be segregated at the point of origin only for the GPT. The HEPA filters have either wooden or metallic frames, organic adhesives and gasket materials, noncombustible filter media, and aluminum spacers. Failed equipment consists primarily of stainless steel and may be shredded prior to volume reduction in a metal melter.

Nonradioactive, simulated TRU wastes were prepared for processing by the shredders and incinerators evaluated in this study. Table 4 lists the nominal composition of the five simulated wastes as formulated for the shredder tests. An example of the SAC waste which was prepared is shown in Figure 2. Type 2

TABLE 3. Average Waste Compositions

<u>Waste Type</u>	<u>Reference</u>	<u>Constituent</u>	<u>Composition, Wt%</u>
Filters	U.S. DOE (1979)	Wood ^(a)	52
		Metal	8
		Glass media	40
			<u>100</u>
GPT and SAC	Darr (1983)	Combustible	
		Plastic and rubber ^(b)	26.7
		Cloth and wood	26.7
		Paper	26.7
	U.S. DOE (1979)	Noncombustible	
		Metal ^(c)	18
		Glass	2
			<u>100</u>
		Combustible	
		Paper/Rags	40
		PVC	20
		Neoprene	11
		Polyethylene	14
		Latex	11
		Wood	4
		Noncombustible (no data given)	---
			<u>100</u>

(a) Combustible glues and adhesives may constitute up to one third of the weight of the filters.

(b) PVC is 30 wt% of the plastic and rubber (AGNS 1978, p. E-2).

(c) Metals include stainless steel, carbon steel, copper, and aluminum in the form of various structural shapes, pipe, tools, wire rope, plate, etc.

TABLE 4. Simulated TRU Waste Compositions

Waste Component	Waste Composition, wt%				
	GPT	SAC	HEPA Filters(a)	Type 2	Type 3
Combustibles:(b)					
Paper	33.2	16.4	-	9.5	-
Rags	15.2	7.5	-	8.8	-
Wood	15.6	7.9	-	8.7	-
Neoprene	11.6	7.0	-	7.6	-
Latex	8.1	4.0	-	-	-
Polyurethane	-	-	15.0	-	-
Polyethylene	8.5	6.6	-	-	-
PVC	7.8	3.0	-	7.9	-
SUBTOTAL	100.0	52.4	15.0	42.5	0.0
Noncombustibles:(c)					
Carbon steel	-	32.1	-	33.6	38.2
Stainless steel	-	11.8	54.0	10.0	17.0
Glass	-	3.7	31.0	3.7	14.9
SUBTOTAL	0.0	47.6	85.0	47.3	70.1
Composite:					
Electric motors	-	-	-	7.3	20.0
Insulated wire	-	-	-	2.9	9.9
SUBTOTAL	0	0	0	10.2	29.9
TOTAL	100.0	100.0	100.0	100.0	100.0

(a) Composition shown is for 0.61 x 0.61 x 0.30-m metal-framed HEPA filters. Wood-framed HEPA filters were also used; however, their compositions were not determined.

(b) Paper added as magazines, computer paper, books, and sheetgoods. Rags included clothing and canvas. Neoprene added as sheets, leaded gloves and regular gloves. Latex added as gloves. Polyethylene added as sheet, bags, tubing, and bottles. PVC added as 3- and 4-inch pipe.

(c) Metals added as cable, 1 to 5 inch pipe, and 1/4- and 1/2-inch bar and plate. Glass added as miscellaneous labware and large blocks of vitrified soil.

waste is considered a difficult waste for an incinerator to process because it contains a large fraction of noncombustibles, PVC, and some composite materials typical of failed equipment. The Type 3 waste is considered a difficult waste for a shredder to process because it contains a high loading of metals and electric motors. The five waste types were shredded separately. Type 1 waste was prepared from a mixture of shredded GPT, SAC, and HEPA filter wastes as shown in Table 5. This waste has a low noncombustible fraction (~33%) and is expected to be an average TRU feed material to the incinerator. The same Type 1 waste composition was used in all incinerator tests and a different Type 2 composition (Table 5) was tried at each of the incinerator facilities.

FIGURE 2. Simulated SAC Waste Ready for Shredding Tests

TABLE 5. Incinerator Feed Makeup

Waste Constituent	Makeup Composition, wt%			
	Type 1	Type 2A	Type 2B	Type 2C
GPT	25	-	4	-
SAC	23	-	8	-
Wood HEPA	43	20	50	35
Metal HEPA	9	80	30	15
Type 2	-	-	8	50
Trace Mixture(a)	0.58	-	-	-

(a) Composition of trace mixture given in Table 6.

Prior to the incineration tests, nonradioactive tracers (Ce, Cs, Mo and Sr) were added to the shredded Type 1 wastes to provide information on the volatility behavior of radionuclides during incineration tests. Table 6 shows the weight fraction for significant elements that could be present in the TRU wastes from a commercial reprocessing facility. These concentrations are too low to be detectable using reasonable chemical analysis techniques; therefore the tracers were added in the larger concentrations shown in the last column of Table 6.

TABLE 6. Estimated Radionuclide Content of Commercial TRU Wastes

Radionuclide	GPT/SAC, g/kg Waste		Filters, g/kg Waste		Type 1 Trace, ^(a) g/kg Waste
	Darr (1983)	U.S. DOE (1979)	Darr (1983)	U.S. DOE (1979)	
Cs	7×10^{-4}	1×10^{-5}	9×10^{-2}	9×10^{-4}	0.32
Mo	6×10^{-4}	2×10^{-5}	7×10^{-2}	1×10^{-3}	0.23
Sr	2×10^{-4}	4×10^{-6}	2×10^{-2}	3×10^{-4}	0.39
Zr	6×10^{-4}	2×10^{-5}	8×10^{-2}	1×10^{-3}	--
Rare Earths	1×10^{-2}	5×10^{-5}	1.7	4×10^{-3}	0.54 as Ce
Actinides + U	18	3.5×10^{-2}	35	1.4	--
Waste Generation Rate	12 kg/MTU	196 kg/MTHM	13 kg/MTU	22 kg/MTHM	

(a) The tracers were added as an aqueous slurry of $\text{Sr}(\text{NO}_3)_2$, MoO_3 , CsNO_3 , and a rare earth nitrate mixture consisting primarily of cerium.

**EVALUATION OF
TREATMENT TECHNOLOGIES**

EVALUATION OF TREATMENT TECHNOLOGIES

A literature search and site visits were conducted to identify current generation shredder and incinerator technologies. Incineration concepts have been evaluated extensively at DOE sites since the early to mid 1970s. On the other hand, shredding is just beginning to see application at DOE sites as an incinerator feed pretreatment technology. In this section, shredders and incinerators are reviewed and evaluated with respect to their applicability to commercially generated TRU wastes. The testing program described in subsequent sections was based on this preliminary evaluation and screening of treatment technologies.

SHREDDER TECHNOLOGY

The recommended treatment strategy (Ross et al. 1985) calls for shredding of GPT, SAC, and HEPA filters as pretreatment for the incineration step. Shredding reduces the size, increases the surface area, and improves homogeneity of the incinerator feed material resulting in a suitable feed stock for the incinerator. By shredding the wastes, some incinerators are able to process a higher fraction of noncombustibles. This is necessary when it becomes difficult to separate combustibles from noncombustibles, which is the case with HEPA filters. In addition to incinerator feed pretreatment, the metal shredder will be used to size reduce some CH failed equipment for the batch metal melter process.

Shredder technology can be divided into low-speed and high-speed categories. High-speed shredders such as hammer mills, grinders, and flail mills have been evaluated by Darnell and Aldrich (1983) of EG&G Idaho for incinerator feed pretreatment. These units act to pulverize the waste to a size far smaller than is required for incinerator feed. While this is an advantage for some applications, it is not a particular advantage for TRU waste. The advantages and disadvantages of high-speed shredders are listed in Table 7. Because the one advantage, smaller particle size, is not a significant benefit for the TRU waste application, high-speed shredders were eliminated from further consideration for commercially generated TRU wastes. This was also the conclusion reached by Darnell and Aldrich concerning INEL TRU wastes.

TABLE 7. Advantages and Disadvantages of High-Speed Shredders

<u>Advantages</u>	<u>Disadvantages</u>
• Waste is reduced to a much smaller size than possible with low-speed shredders.	• Equipment requires extensive maintenance. • More respirable fines are generated than with low-speed shredding. • Power requirements are considerably higher than for low-speed shredder of equivalent capacity. • Reportedly are susceptible to dust explosions. • High capital cost. • Occupy larger volume than low-speed shredder with equivalent capacity.

Although the low-speed shredder is a relative newcomer to the market, several government laboratories (including INEL and SRL) have selected them for pretreating incinerator feed (Darnell and Aldrich 1983, Charlesworth and McCampbell 1985). Shredding is achieved by two counter-rotating shafts with cutter wheels and spacers (see Figure 3). One shaft typically rotates faster than the other, which improves the shredding efficiency, prolongs the cutter wheel life by distributing the wear, and improves the tendency of the cutters to self clean. The cutter wheels contain one or more teeth (often referred to as hooks or knives) that intermesh with the cutter wheels on the adjacent shaft (as shown in Figure 3). Waste is drawn down through the wheels and is torn apart. A comb is used on the noncutting side of the cutter shafts to prevent waste from falling through the voids between the cutter wheels. Low-speed shredders are designed to automatically reverse the cutter shaft's normal rotation when an unshreddable obstruction is encountered, then reverse again and resume shredding. The shredded particle size can be reduced by adding more teeth to each cutter wheel, by reducing the wheel width, or by periodically reversing and then resuming cutter rotation.

Manufacturers of low-speed shredders use either an electric or hydraulic drive motor to turn the cutter shafts. Darnell and Aldrich (1983) determined

FIGURE 3. Cutter Wheel Configuration of a Typical Low-Speed Shredder

that the electric type of drive system was superior for radioactive waste applications. Advantages and disadvantages for each type of drive are listed in Table 8. Considering these advantages and disadvantages, electrically powered shredders are preferred for TRU waste applications. Higher maintenance associated with electric drive motor reversals can be obviated by reducing the amperage limit at which reversals occur or by oversizing the unit so that reversals will not occur during normal shredding operations.

Slow-speed shredding technology is developed to the point that application to TRU wastes would be relatively straight forward. System capacity and product particle size should be verified with simulated wastes. Also, consideration should be given to remote installation, remote feeding of wastes, and removal of nonshreddable items.

TABLE 8. Advantages and Disadvantages of Hydraulic and Electric Drives for Low-Speed Shredders

Final Drive Motor	Advantages	Disadvantages
Hydraulic	• Hydraulic motors have better shock loading protection in the event of encountering an unshreddable item. • Reversals are faster (~3 sec) • The power unit can be separated a substantial distance from the shredder.	• Oil spills and leaks are common with hydraulic units. • Power units are bulky and require considerable space. • A more educated maintenance force is required. • Hydraulic hoses between shredder subsystems is undesirable, particularly in remote applications • Up to one third more horsepower is required due to energy losses to the hydraulic drive. • The presence of hydraulic oil may add a fire hazard to a remotely operated system (although nonflammable oils are available).
Electric	• Power units are much smaller and require less horsepower. • Less maintenance is required due to the absence of hydraulic pumps and motors. • Small to medium sized electric shredders are typically less expensive than equivalent hydraulic units.	• Reversal times are slower (~10 sec). Unit must pause upon contacting a nonshreddable item to permit the motor to come to a complete stop before reversing. • Reversals provide more wear and tear on an electric motor than on hydraulic motors.

INCINERATOR TECHNOLOGY

The U.S. Department of Energy (DOE) has sponsored research, development, and demonstration of radioactive waste incineration (Perkins 1976, Bordiun and Taboas 1980, Ziegler 1982). The published work from these studies provides an excellent data base for comparing and screening incinerator systems for use with TRU combustible wastes from commercial reprocessing and fuel fabrication. Table 9 presents a summary of U.S. DOE radioactive waste incinerators. The incinerator treatment systems include acid digestion, controlled air, cyclone, fluidized bed, rotary kiln, single hearth, and slagging pyrolysis.

TABLE 9. Summary of U.S. DOE Radioactive Waste Incinerator Treatment Systems

Incinerator Type	DOE Site	Feed Capacity	Intended Application	Status
Acid Digestion	HEDL	10 kg/h	Pu recovery from TRU combustibles.	Decommissioned
Controlled Air	LANL	45 kg/h	Volume reduction of TRU combustibles (LL & Haz. solid and liquid wastes also tested, licensed for PCB).	Testing with newly generated TRU.
Controlled Air	SRL-SWIFT ^(a)	180 kg/h	Vol. reduction of suspect LL wastes, <1 mR/h surface.	FY-85 hot operation.
		40 gal/h	Purex solvent	
Controlled Air	SRL-PWI ^(b)	10 kg/h	Vol. reduction of solid alpha waste, <10 ⁶ nCi/g.	FY-85 cold testing.
Controlled Air	INEL-WERF ^(c)	180 kg/h	Vol. reduction of all INEL LLW, <10 nCi/g.	Fully operable by mid FY-85.
Cyclone	Mound	35 kg/h (for one station)	Vol. reduction of dry TRU waste. Modified for liquid feed.	Used for LLW incineration.
Fluidized Bed	RFP	82 kg/h	Pu recovery from TRU combustibles.	Operational on actual waste.
Rotary Kiln	RFP	40 kg/h	Vol. reduction and Pu recovery for solid and liquid TRU waste of low to high activity.	Decommissioned
Rotary Kiln	INEL-PREPP ^(d)	230 kg/h	Permit certification of retrievable TRU waste for WIPP (high loading of noncombustibles present).	Production unit installation in progress (FY-86 cold testing).
Single Hearth	RFP	55 kg/h	Vol. reduction of solid and liquid trace activity TRU.	Decommissioned
Slagging Pyrolysis	INEL	100 kg/h	Permit certification of buried and stored TRU waste at INEL for WIPP disposal.	Canceled

(a) SWIFT - Suspect Waste Incinerator Facility Test.

(b) PWI - Plutonium Waste Incinerator.

(c) WERF - Waste Experimental Reduction Facility.

(d) PREPP - Process Experimental Pilot Plant.

Of these incinerators, the acid digestion, cyclone, fluidized bed, single hearth, and slagging pyrolysis systems were eliminated from further consideration without additional testing and evaluation. The bases for elimination are as follows:

- Acid Digestion - The presence of noncombustibles, as would be the case with composites such as shredded HEPA filters, greatly

complicates operation. The recovery of Pu from the wastes, although a major advantage of this system, is not applicable to commercial TRU wastes. Noncombustible solids accumulate in the digestion chamber and must be removed periodically. Classification to separate the noncombustibles prior to processing is not probable since HEPA filter adhesives are affixed to the frames and to the media. Also, the acid recovery system utilizes a centrifuge, which is a high maintenance item. This, with the concentrated sulfuric and nitric acids, would make remote operation difficult. The process has been operated on a pilot scale; however, no production-scale testing has been performed. The R&D and engineering study requirements required to adapt the acid digestion technology are considered above average compared to the other processes.

- Cyclone Incineration - This unit was designed as a simple and reliable batch incinerator for volume reduction of CH TRU wastes (Klingler 1981). The benefits disappear when the unit is considered for RH wastes such as HEPA filters. High inlet air flows required to create the cyclone action results in high ash carryover to the off-gas system. The complexity of the secondary waste treatment processes is increased due to the ash carryover. The ash is removed from scrub liquid by a vertical leaf filter. Remote operation and maintenance of the leaf filter and a drum changeout system would be difficult.
- Fluid Bed - The presence of noncombustibles increases the complexity of the fluid bed incinerator operation. Noncombustible solids, such as metals, and glass, accumulate in the bed media and must be routinely removed. This increases the complexity of the secondary waste treatment processes and makes remote operation difficult. For this reason, the fluid bed is not well suited for the application and can be eliminated as an initial processing option.
- Single Hearth - These incinerators are typically large units used for burning sewage sludge. Although they are common commercially, no single hearth unit has been demonstrated on a production scale with radioactive wastes. The R&D and engineering study requirements

necessary for development of this incinerator places the single hearth incinerator at a disadvantage to the other U.S. DOE units. A rabble arm on a rotating shaft is used for mixing the wastes during the high-temperature combustion cycle and for removal of the ash during the ash discharge cycle. This makes the unit more difficult to remotely maintain than other units such as the controlled air or rotary kiln incinerators.

- Slagging Pyrolysis - This unit is designed to produce a cast slag waste product rather than ash. In order to produce a molten slag, certain portions of the incinerator must be designed to operate at 1500°C as opposed to the 1000° to 1200°C temperatures of more conventional incinerators. This introduces additional complexities to the design, increases the system cost, and would likely reduce the reliability of a remotely operated system. The slagging pyrolysis process was not given serious consideration in the TRU Strategy Study (Ross et al. 1985) because of previous unresolved problems (Tait 1983).

The controlled-air and rotary-kiln incinerators are being developed for both TRU and LLW applications and deserve further consideration for commercial TRU waste applications. A study at INEL (Hedahl 1982a) concluded that the controlled-air and rotary-kiln incinerators were preferred for incineration of INEL combustible TRU waste. Proof of principal tests were then conducted to determine which incinerator was best suited for processing the INEL wastes. Incinerator feed for the tests contained between 40 and 90% noncombustibles (based on projected INEL waste compositions). For this application, the rotary kiln was selected for further development. Additional engineering tests and evaluations were then conducted on the rotary kiln and its off-gas system before the process design was completed (Pattengill et al. 1982, Hedahl 1982b).

The feed composition and characteristics of commercially generated TRU wastes and the remote operating requirements are significantly different from that of INEL waste application. The anticipated noncombustible weight fraction of the commercial TRU waste is 34%, somewhat lower than the INEL noncombustible

fraction. The INEL wastes that were tested contained up to 90% noncombustibles, were all contact handled, and were not pretreated by shredding prior to the incinerator proof-of-principle tests. These differences would have an impact on the ash and residue characteristics and could impact final selection of a reference process for commercial TRU wastes. Testing of both the controlled-air and rotary-kiln incinerators has been conducted for the commercial waste application. A more detailed description of these incinerators and a discussion of several off-gas treatment options are listed in the following sections.

Controlled-Air Incinerators

Controlled-air systems use two chambers to achieve complete combustion. Wastes are charged to the first chamber where they are burned at near stoichiometric conditions. This results in a low turbulent combustion environment which minimizes entrainment of fly ash. Products of partial oxidation and volatilization flow into the second chamber where excess air and supplemental heating are added to achieve complete combustion.

Four controlled-air incineration systems are either operable or soon to be at U.S. DOE sites (refer to Table 9). The unit at LANL is gas heated and has operated for the longest time, with development beginning in 1973 and testing beginning in 1978 (Neuls et al. 1982). Two other gas-fired units, one at SRL (SWIFT) and the other at INEL (WERF) are of very similar design, only with larger capacity. The SRL-PWI incinerator is electrically heated and deviates more from the standard design in order to accommodate high alpha wastes (Charlesworth and McCampbell 1985). The two basic types of controlled-air incinerators are described in more detail below.

1. Gas Heated - Wastes are typically charged at regular intervals to the primary incineration chamber using a ram feeder or a top loading chute. Figure 4 shows a flow diagram of the LANL gas-heated controlled-air incinerator which uses a ram feeder. A system of guillotine doors are used to help maintain an air balance on the unit during feeding. The INEL controlled-air incineration is of a similar design to that at LANL but uses a top loading chute for introducing waste. Underfire air is introduced from beneath the hearth in the

FIGURE 4. LANL Gas-Heated Controlled-Air Incineration System

primary chamber to maintain a slightly richer than stoichiometric oxygen level and to burn out any fixed carbon in the ash. Combustion temperatures in the primary chamber range from 800 to 1000°C. A nominal temperature of 1100°C is maintained in the secondary chamber with 200 to 300% excess air. Supplemental heating to both the primary and secondary combustion chambers is supplied by diesel or natural gas burners. Once the wastes are charged into the unit, the burners operate on demand, supplementing the waste heat content to maintain the desired temperatures. Ash is removed at the end of each incineration run by an internal ash discharge ram. The ram moves along the incinerator floor pushing the ash to a gravity dropout port. Ash removal systems are available which permit continuous ash removal operation as opposed to batch ash removal operation.

2. Electrically Heated - Figure 5 shows a flow diagram of the SRL-PWI controlled-air incineration system. Wastes are accurately metered to the primary chamber of the electrically heated incinerator through two stages of low-speed shredders and a waste compactor pump. For this application, the compactor pump is coupled with a variable speed drive and serves as a feed metering device. The primary chamber has a woven wire mesh conveyor belt which slowly moves waste material through the incinerator to a gravity ash dropout point. Residence time is controlled by the belt speed. Combustion air is introduced at the ash discharge end of the incinerator and travels counter current to the waste direction. Off gases exit near the feed port and pass to the secondary chamber where excess air is added to complete the combustion process. Heating in both chambers is provided by electric glowbars.

Rotary-Kiln Incinerators

The rotary kiln has been tested at INEL on simulated TRU wastes (Pattengill 1982). It is especially efficient for incinerating difficult to burn wastes because the kiln rotation constantly exposes new surfaces of waste material to the oxidizing atmosphere. Kiln incineration systems usually operate at 800 to 1000°C and include a secondary combustion chamber to improve the

FIGURE 5. SRL-PWI Electrically-Heated Controlled-Air Incinerator System

overall oxidation efficiency, wherein temperatures run about 1250°C. Other inherent design features include continuous ash removal and controllable residence time (by adjusting rotation rate and/or inclination).

The INEL-PREPP facility includes a rotary-kiln incinerator as the primary means of volume reduction. A flow diagram of the INEL-PREPP system is shown in Figure 6. The rotary kiln was chosen over a controlled-air incinerator because the range of expected waste characteristics required a system with processing flexibility (Hedahl 1982a). Also, the kiln's high efficiency in oxidizing wastes yields an ash that is easily wettable for grouting, which is an integral part of the PREPP process.

While kiln rotation improves combustion efficiency, it also creates operational and maintenance problems. The seal between the rotating kiln and the stationary ends is critical for containment of radionuclides and is difficult to maintain. Rocky Flats points to sealing troubles as being one factor in their decision to decommission their rotary kiln. INEL has designed a triple

FIGURE 6. INEL-PREPP Rotary Kiln Incineration System

pressurized seal for the PREPP facility. With the seal pressurized and the kiln operating at a slightly negative atmosphere, a positive flow of gases from the seal into the incinerator will be maintained but fine solids may still migrate into the seal causing abrasive wear and eventual seal failure. The tumbling action of wastes accelerates refractory wear leading to a difficult and costly replacement project; there is no current method to rebrick a kiln remotely.

All rotating elements of the rotary kiln require frequent maintenance making it one of the more maintenance-intensive incinerator options. The PREPP design has provided for drive maintenance by extending the kiln drive shaft through the wall, placing the drive motor and gear box outside the radioactive area. However, the rotating seals will require contact maintenance for adjustment and repair, and the tires, trunnion, and bull gear require remote lubrication.

Feed to the kiln may be either continuous or semi-continuous. Whatever the feeding methods, it is essential to introduce the feed far into the kiln to prevent solids from falling back into the seal. The INEL-PREPP kiln utilizes a vibratory slip conveyor and a shuttle car system to transfer shredded waste into the kiln.

Rotary kiln incinerators are normally fired concurrent with the feed stream and the firing rate controlled by the temperature of the discharge gases. Long waste retention time in the kiln tends to smooth out fluctuations in heat loading from changes in feed rate or heat content. Since the residence time for gases is only a few seconds, very rapid and stable control can be maintained.

Off-Gas Treatment Systems

Both wet and dry off-gas treatment systems can be used with the controlled-air incinerators or the rotary kiln. Following are general descriptions of treatment systems used in current incinerator designs.

The controlled-air incinerator at LANL has a wet off-gas system consisting of a quench column, venturi scrubber, packed column absorber, and HEPA filters (see Figure 4). Both controlled-air incinerator units at SRL and the one at

INEL are equipped with dry off-gas systems. Off gases from the SRL-PWI incinerator are cooled by air dilution prior to sintered-metal and HEPA filtration (see Figure 5). The sintered metal filters are of a blow-back type and contain a coating of lime to neutralize HCl and SO₂ in the off gas. Dilution air is added to further cool the off gases prior to final HEPA filtration. The SRL-SWIFT off-gas system resembles that of the SRL-PWI unit except cooling is done by both a spray quench and air dilution. These dry systems were selected to reduce secondary waste treatment difficulties and reduce HCl corrosion problems associated with burning Cl-containing wastes such as PVC. Off gases from the INEL-WERF controlled-air incinerator are cooled first by air dilution, then by passing through an air-to-air heat exchanger, and finally by a second air dilution. Gases are then passed through one of two parallel bag houses and final HEPA filters. Unlike the LANL and SRL incinerators, the INEL-WERF unit is not designed to process PVC wastes. Water and chloride, which are present as combustion products, tend to condense out as HCl at cool points in the off-gas system, causing corrosion (Waters and Volodzko 1983). Another factor in not incinerating PVCs is that when neutralized to a salt, essentially no volume reduction is obtained.

The rotary kiln at INEL-PREPP uses a wet scrubbing system consisting of a quencher, variable throat venturi, wave plate separator, mesh pad mist eliminator, gas reheater, prefilters, HEPA filters and an induced draft blower (see Figure 6). Depending on the composition of the waste, the scrubbing solutions may become quite corrosive. Destruction of wastes containing halogens, such as PVC and contaminated oils, creates off-gas corrosion problems as it would in a controlled-air incinerator off-gas system.

SHREDDER TESTS

SHREDDER TESTS

Low-speed shredders from different manufacturers were tested using GPT, SAC, HEPA filters, Type 2 and Type 3 simulated wastes (refer to Table 4). The objectives of the tests were to:

- Confirm that low-speed shredding can be used to effectively size reduce simulated commercial TRU waste.
- Generate a shredded waste material suitable for use during the incineration tests.
- Evaluate the process for adaptability to remote radioactive operations and identify potential process problems.
- Develop specifications of a reference shredding system to be used for subsequent testing and development.

The waste material was initially divided into two identical lots; one to be shredded at Shredding Systems, Inc. in Wilsonville, Oregon, and the other to be shredded at Shred Pax Corp. in Wood Dale, Illinois. These two companies are considered major manufacturers of low-speed electric-drive shredders.

The subcontractor performing the electrically heated controlled-air incineration test determined that the shredded wastes were too large to process in the small pilot-scale incinerator they were using. As a result, arrangements were made with a local shredder manufacturer (Saturn Shredder Division of MAC Corp., Grand Prairie, Texas) to reshred the waste material. Even though the shredders used by Saturn were hydraulic drive and not the preferred electric drive, the shredding results as they are available are included with the electric drive shredder results.

The remainder of this section contains descriptions of the shredders and the test results.

SHREDDER DESCRIPTIONS

The shredder systems that were tested and their cutter configurations are listed in Table 10. The first two test units were actually the same model 1600 machine manufactured by Shredding Systems with different cutter configurations. Figure 7 shows the Model 1600 unit with its 100 hp electric drive motor. This unit is a test model and is not currently being marketed, although it is representative of other shredders on the market. The cutter wheels used were 48.9 cm diameter, 5.1 cm wide, and had one tooth on each wheel with a height of 5.1 cm. The tooth height determines how much material is gripped and shredded with each rotation of the wheel. The first test unit had a 2+2+2 cutter configuration (2 cutters, 2 spacers and 2 cutters). Each cutter tooth was offset from the adjacent tooth in what is termed a "single-spiral" alignment. The tooth offset is such that it takes the full length of the cutter shaft to make one revolution in the cutter tooth positions. With a single-spiral configuration, only one tooth at a time shreds the waste material. Theoretically the entire shaft force is applied to each cutting tooth as it contacts the waste.

TABLE 10. Shredder Test Unit Comparison

Test Unit No.	Shredder Model	Power Unit	Infeed Opening, m	Configuration	Cutter Tooth		Cutter Wheel		Shaft Speed, rpm		Tooth Force, Newtons/1000	
					#/Wheel	Ht, cm	Wth, cm	Dia, cm	Fast	Slow	Fast	Slow
1	1600 ^(a)	100 hp Electric Drive	1.27 x 0.91	2+2+2 Single Spiral	1	5.1	5.1	48.9	26.7	21.1	109	138
2	1600 ^(a)	100 hp Electric Drive	1.27 x 0.91	1+1+1 Single Spiral	1	5.1	5.1	48.9	26.7	21.1	109	138
3	AZ-80 ^(b)	80 hp Electric Drive	1.60 x 0.84	1+1+1 In Line	3	6.0	4.7	47.0	25.0	21.7	97	112
4	AZ-80 ^(b)	80 hp Electric Drive	1.60 x 0.84	2+2+2 Single Spiral	1 & 3	6.0	4.7	47.0	25.0	21.7	97	112
5	AZ-80 ^(b)	80 hp Electric Drive	1.60 x 0.84	1+1+1 Single Spiral	1	6.0	4.7	47.0	NA ^(c)	NA	NA	NA
6	36-22 ^(d)	75 hp Hydraulic Drive	0.91 x 0.56	1+1+1 Single Spiral	2	3.2	1.9	27.3	83.6	53.6	37	58
7	52-32 ^(d)	150 hp Hydraulic Drive	1.32 x 1.02	1+1+1 Single Spiral	2	5.4	3.8	43.2	47.7	23.5	83	115

(a) Model 1600 manufactured by Shredding Systems, Inc., Wilsonville, Oregon.

(b) Model AZ-80 manufactured by Shred Pax Corp., Wood Dale, Illinois.

(c) Shaft speed and tooth force data on test unit 5 is not available.

(d) Models 36-22 and 52-32 manufactured by Saturn Shredder Division of MAC Corp., Grand Prairie, Texas.

FIGURE 7. Model 1600 Electric Drive Shredder (Manufactured by Shredding Systems)

Test unit number 2 (Table 10) was set up using a 1+1+1 single spiral configuration. This configuration requires more power for shredding a given item but it produces a smaller particle size.

Test units 3, 4 and 5 (Table 10) are model AZ-80 shredders manufactured by Shred Pax. The units are equipped with two 40 hp electric motors which transfer power into a single gear box. Figure 8 shows one of the AZ-80 test units. Cutters on the AZ-80 shredders were all 47.0 cm diameter, 4.7 cm wide and had teeth 6.0 cm high. Test unit 3 had a 1+1+1 in-line configuration with three teeth per cutter wheel. Unit 4 had a 2+2+2 single-spiral configuration with a combination of cutter wheels which had one or three teeth each. Test unit 5 had a 1+1+1 single-spiral configuration with one tooth per cutter wheel.

FIGURE 8. Model AZ-80 Electric Drive Shredder (Manufactured by Shred Pax)

Test units 6 and 7 (Table 10) are both hydraulic drive shredders manufactured by Saturn Shredders. Each unit has a 1+1+1 single spiral cutter configuration with two teeth per cutter wheel. The model 36-22 (test unit 6) had a single 75 hp electric motor and hydraulic pump which power a final hydraulic drive motor. The model 36-22, shown in Figure 9, is a smaller and lighter duty shredder than the others tested. It uses 27.3 cm diameter cutter wheels which are 1.9 cm wide. The combination of the narrow dual tooth cutter wheels and 1+1+1 configuration, results in a shredded product with a much smaller particle size than achievable using the other shredder test units. The model 52-37 shredder (test unit 7) had two 75 hp electric motors and pumps which power a single hydraulic drive motor. The cutters are 43.2 cm diameter and 3.8 cm wide.

FIGURE 9. Model 36-22 Hydraulic Drive Shredder
(Manufactured by Saturn Shredders)

The actual shredding power is determined by the tooth force exerted by the faster shaft and by the cutter configuration. Tooth force is dependent on drive unit power, cutter wheel diameter, and shaft rpm. The last four columns of Table 10 show the shaft rpm and tooth force of the different shredder test units. The model 1600 has the highest tooth force at 109,000 newtons (N) on the fast shaft compared with 97,000 N for the AZ-80s, 83,000 N for the model 52-32 and 37,000 N for the model 36-22.

TEST RESULTS

Shredder performance was determined by measuring throughput rate, number of reversals, and particle size for the different types of simulated TRU wastes. A portion of the waste material was shredded a second time to provide

data on two-stage shredder systems. In all cases, where two stages of shredding was performed, the first unit had a 2+2+2 configuration and the second unit had a finer 1+1+1 configuration. Table 11 presents the throughput data and number reversals per 100 kg of waste for each combination of first and second stage shredders.

General Process Trash

Three different first stage shredders were tested using simulated GPT waste. Test unit 1 is considered the better performer since no cutter reversals occurred during the testing. The AZ-80 unit 4 experienced 1.4 reversals per 100 kg but had the highest net throughput of 80 kg/min. Several factors causing the reversals on unit 4 were: greater tooth height, narrower cutter wheel width (thus more teeth per shaft), lower net tooth force, and the presence of several three-tooth cutter wheels. Test unit 3 exhibited the most reversals at 14 per 100 kg of GPT. The in line configuration along with three tooth cutter wheels distributes the power out over many teeth. Since several teeth may contact a waste item at one time, this unit is much more likely to reverse. Second stage shredding of the GPT by test unit 5 was no problem as a throughput rate of 76 kg/min was maintained with no reversals.

Sample and Analytical Cell Wastes

Shredding of the SAC waste was more difficult, primarily because of the metal present in the waste. Test unit 1 experienced 1.6 reversals per 100 kg while test unit 4 had 6.7 during first-stage shredding. The causes for the difference in reversals are the same as those given above for the GPT wastes. Second-stage shredding of SAC was less difficult than the first stage, however, test units 2 and 5 both experienced some reversals (see Table 11).

Wood-Framed HEPA Filters

Wood-framed HEPA filters were shredded using test units 1, 4 and 5. No cutter reversals occurred during any of these tests; however, feeding of the filters to the shredders was difficult. The wood-framed HEPAs tended to ride on the cutter wheels and spacers without being gripped and shredded. In order to complete the shredding process, it was necessary manually reposition the filters on the cutter teeth. Even with this manual repositioning, the

TABLE 11. Shredder Performance Comparison

Waste Material	First Stage				Second Stage			
	Shredder (Model)	Cutter Wheel Configuration	Throughput Rate, kg/min	Reversals per 100 kg	Shredder (Model)	Cutter Wheel Configuration	Throughput Rate, kg/min	Reversals per 100 kg
GPT	Test Unit 1 (1600)	2+2+2 Single Spiral	60	0	None	--	--	--
GPT	Test Unit 4 (AZ-80)	2+2+2 Single Spiral	80	1.4	Test Unit 5 (AZ-80)	1+1+1 Single Spiral	76	0
GPT	Test Unit 3 (AZ-80)	1+1+1 In Line	19	14	None	--	--	--
SAC	Test Unit 1 (1600)	2+2+2 Single Spiral	70	1.6	Test Unit 2 (1600)	1+1+1 Single Spiral	80	1.7
SAC	Test Unit 4 (AZ-80)	2+2+2 Single Spiral	40	6.7	Test Unit 5 (AZ-80)	1+1+1 Single Spiral	126	1.0
Wood HEPAs	Test Unit 1 (1600)	2+2+2 Single Spiral	ND ^(a)	0	None	--	--	--
Wood HEPAs	Test Unit 4 (AZ-80)	2+2+2 Single Spiral	ND	0	Test Unit 5 (AZ-80)	1+1+1 Single Spiral	ND	0
Wood HEPAs	Test Unit 5 (AZ-80)	1+1+1 Single Spiral	ND	0	None	--	--	--
Metal HEPAs	Test Unit 1 (1600)	2+2+2 Single Spiral	50	4.1	Test Unit 2 (1600)	1+1+1 Single Spiral	20	4.4
Metal HEPAs	Test Unit 4 (AZ-80)	2+2+2 Single Spiral	34	9.3	None	--	--	--
Type 2	Test Unit 1 (1600)	2+2+2 Single Spiral	75	2.7	Test Unit 2 (1600)	1+1+1 Single Spiral	62	1.6
Type 2	Test Unit 4 (AZ-80)	2+2+2 Single Spiral	19	18	None	--	--	--
Type 3	Test Unit 1 (1600)	2+2+2 Single Spiral	25	1.2	None	--	--	--

(a) Wood HEPA filters had to be manually repositioned at regular intervals to facilitate shredding. No throughput data is reported as it was dependent on the manual repositioning, and not the shredder capacity.

shredding was very slow. A feeding assist device such as a top press should be incorporated if wood-framed filters are to be routinely shredded. This same feeding problem was encountered by Darnell and Aldrich (1983) during shredding of plywood boxes. They successfully designed and tested a device which holds the box upright and rotates it across the top of the shredder cutter wheels.

Metal-Framed HEPA Filters

Gripping of the metal-framed HEPA filters by the shredder teeth was no problem. The filters required more power to shred as indicated by the high level of reversals (4.1 per 100 kg with test unit 1 and 9.3 per 100 kg with unit 4). One reason the reversals occurred was because the shredders tried to process the filters too quickly. Second-stage shredding of the metal HEPAs using test unit 2 resulted in 4.4 reversals per 100 kg, still quite high. The processing rate could be slowed down by reducing the tooth height and by decreasing the shaft rpm. Another approach would be to program the shredder to cycle forward and reverse at intervals that are frequent enough to eliminate the high-torque situations that cause normal reversals. When this is done, the partially shredded filter would be kicked back up on top of the cutter wheels during the reversal and then shredded a little more during the forward cycle. Because the filter repositions itself each time it is kicked up, the shredded particle size would be smaller. Programmed reversal cycles are commonly used with hydraulic drive shredders because the hydraulic drives can be quickly and easily reversed. Electric drive shredders could incorporate the automatic reversals, however extra wear and tear on the electric motor would occur due to the repeated on-off cycles.

The metal-framed HEPA filters that were shredded had been used previously as off-gas filters during nonradioactive testing of the large-scale in situ vitrification process (Buelt et al. 1985). During the shredder tests, some of the dust contained on the load filters was released. A method for fixing contaminants prior to shredding, such as a water or chemical spray, appears to be needed to reduce or eliminate the dusting problem.

Type 2 Wastes

The Type 2 waste material (waste judged difficult to incinerate) was batch fed to test units 1 and 4 in 208 L (55 gal.) drums. Test unit 1 has 2.7 reversals per 100 kg while test unit 4 was highest at 18 reversals per 100 kg. The frequency of reversals is attributed to the high metals loading of the Type 2 material. Second stage shredding using test unit 2 was somewhat easier with only 1.6 reversals per 100 kg.

Type 3 Wastes

Test unit 1 was used to process the difficult to shred Type 3 material. The items were manually fed, one at a time, into the shredder. The only reversals occurred when a 1/4 hp vacuum pump was shredded. Had the Type 3 waste been batch fed to the shredder, the reversals would have been much higher than the 1.2 per 100 kg observed. No Type 3 material was tested using an AZ-80 shredder as the manufacturer believed it would result in unacceptable wear and tear on the equipment. This judgment was made after the high frequency of reversals was observed while processing Type 2 waste with test unit 4.

Fragment Size Analysis

Fragment size was determined by randomly selecting ten pieces of each major waste component (i.e. paper, cloth, wood, metal, filter media, etc.) from the shredder product and measuring the length, width, and thickness of the fragments. The mean dimensions and standard deviation of the fragment size was calculated from these measurements.

Table 12 presents the fragment size analysis of the shredded wastes. Several observations regarding the effects of shredder configuration and single or dual stage operation on the resulting waste fragment size have been made. Wastes that are shredded one time are typically long and narrow. The mean length of the fragment is proportional to the distance between teeth on the cutter wheel and the width corresponds closely to the width of the cut. The cut width for a 2+2+2 configuration is two times the width of the cutter wheel. The shredded fragment thickness for the simulated TRU wastes during this study was more a function of the original material thickness than anything else.

Materials, which were both flexible and durable such as cloth and polyethylene sheeting, had shredded fragment sizes well above the mean values shown in Table 12. Both low-strength materials, such as paper, and rigid materials, such as wood and metal, had average fragment sizes below the mean value.

TABLE 12. Shredded Waste Size Analysis

Sample Number	Waste Material	Shredding History		Mean Size L x W x H, cm
		First Stage	Second Stage	
1	GPT	Test Unit 1 (1600)	None	52 x 13 x 1.0 (27 x 6.8 x 0.8) ^(a)
2	GPT	Test Unit 3 (AZ-80)	None	22 x 5.5 x 0.9 (17 x 2.9 x 0.7)
3	GPT	Test Unit 2 (1600)	Test Unit 6 (36-22)	15 x 3.4 x 0.2 (9.4 x 1.9 x 0.1)
4	SAC	Test Unit 1 (1600)	Test Unit 2 (1600)	15 x 5.3 x 0.4 (6.8 x 1.7 x 0.5)
5	SAC	Test Unit 2 (1600)	Test Unit 7 (52-32)	7.8 x 2.5 x 0.6 (4.8 x 1.3 x 0.6)
6	SAC	Test Unit 4 (AZ-80)	Test Unit 5 (AZ-80)	29 x 6.4 x 1.2 (29 x 4.4 x 1.1)
7	Wood Filters	Test Unit 1 (1600)	None	18 x 6.4 x 0.4 (10 x 2.2 x 0.2)
8	Wood Filters	Test Unit 5 (AZ-80)	None	12 x 5.5 x 0.5 (4.7 x 2.0 x 0.2)
9	Wood Filters	Test Unit 1 (1600)	Test Unit 6 (36-22)	7.3 x 2.0 x 0.3 (5.2 x 0.9 x 0.4)
10	Wood Filters	Test Unit 4 (AZ-80)	Test Unit 5 (AZ-80)	9.8 x 6.1 x 0.4 (3.5 x 2.2 x 0.2)
11	Metal Filters	Test Unit 4 (AZ-80)	None	15 x 7.3 x 2.4 (8.4 x 6.8 x 3.6)
12	Metal Filters	Test Unit 1 (1600)	Test Unit 2 (1600)	9.5 x 4.2 x 0.4 (4.4 x 1.8 x 0.8)
13	Type 2	Test Unit 4 (AZ-80)	None	25 x 5.9 x 1.3 (20 x 3.5 x 1.1)
14	Type 2	Test Unit 4 (AZ-80)	Test Unit 7 (52-32)	10 x 3.2 x 0.8 (4.8 x 1.4 x 0.6)
15	Type 2	Test Unit 1 (1600)	Test Unit 2 (1600)	20 x 3.7 x 0.8 (11 x 1.7 x 0.6)

(a) Numbers in parenthesis are standard deviations of 30 or more pieces.

The effects of cutter configuration on shredded fragment size is readily apparent in GPT samples 1 and 2 (refer to Table 12). The length of the average fragment was 52 cm using shredder unit 1 which had a single tooth wheel and the length was reduced to 22 cm using unit 3 which had three teeth per wheel. The average width of sample 1 was 13 cm and for sample 2 was 5.5 cm, corresponding closely with the cut widths of 10.2 and 4.7 cm for the respective shredders.

Shredding the waste through a second stage reduces both the mean fragment size as well as the standard deviation of the waste size. The GPT Sample 3 (see Table 12) which was processed by both shredder units 2 and 6, had an average fragment size of 15 x 3.4 x 0.2 cm, which is significantly smaller than the GPT pieces produced by one-stage shredding (samples 1 and 2).

During the initial shredding of the SAC wastes, it became apparent that some of the long narrow pieces of wood and metal were standing on end and dropping through the shredder cutters without adequate shredding. Figure 10 shows some of these pieces after processing by test unit 1 which had a 2+2+2 configuration. Similar long pieces were also observed after shredding by test unit 4 which also had a 2+2+2 configuration. Upon shredding the SAC through a second stage, the fragment size was reduced such that the average length ranged

FIGURE 10. Larger Metal and Wood Pieces of SAC Waste after Shredding by Test Unit 1

from 7.8 to 29 cm long. The smallest size shredded SAC waste was produced by test unit 7 which had a 1+1+1 single spiral configuration and two cutter teeth per wheel.

The wood-framed HEPA filters were reduced quite nicely by a single stage of shredding (Table 12 samples 7 and 8). The frames were made of either plywood or pressed wood, which tended to fracture into shorter pieces than wooden boards present in the GPT, SAC and Type 2 waste materials. Second stage shredding by test units 5 or 6 reduced the mean fragment length to between 7.3 and 9.8 cm. Figure 11 shows wooden HEPAs after shredding by test unit 1 and after dual shredding by both test units 1 and 6 (samples 7 and 9 in Table 12).

FIGURE 11. Wood Framed HEPA Filters Processed by (a) Single Stage Shredding (Test Unit 1) and (b) Dual Stage Shredding (Test Units 1 and 6)

Upon shredding, pieces of metal-framed HEPA filters will remain basically the same size through subsequent incineration and cementation processes because 85% of the filters are noncombustible. It is important, therefore, to reduce the fragment size by shredding to that which is acceptable by both the incineration and cementation processes. An acceptable size for the cementation process is currently undefined. Single-stage shredding of metal-framed filters by test unit 4 produced a product with an average length of 15 cm (sample 11 Table 12). Dual shredding by units 1 and 2 resulted in a smaller mean fragment length of 9.5 cm (sample 12 Table 12).

Two stages of shredding makes the particle size more uniform as indicated by the standard deviation of the particle sizes of the Type 2 waste material (see Table 12 samples 13, 14 and 15). One stage of shredding by test unit 4 resulted in an average fragment length of 25 (± 20) cm. Dual shredding with test units 4 and 7 produced a fragment length of 10 (± 4.8) cm and dual shredding with units 1 and 2 produced a fragment length of 20 (± 11) cm. By using two stages of shredding, the standard deviation of the particle length was reduced to about 1/2 of the average length. This occurs because the longer pieces which are produced during the first shred tend to lie down flat in the hopper during the second stage shred and are segmented into multiple short lengths.

INCINERATOR TESTS

INCINERATOR TESTS

Three incinerators, the electrically heated controlled-air, gas-heated controlled-air, and gas-heated rotary kiln were tested using simulated TRU waste compositions (refer to Table 4). The objectives of the tests were to:

- Confirm that incineration can be used to effectively process simulated commercial TRU waste.
- Generate a low-carbon ash and residue for product characterization tests and follow-on cement immobilization tests.
- Evaluate the process for adaptability to remote radioactive operations and identify potential process problems.
- Select a reference incinerator system for further testing and development.

Testing of the electrically heated controlled-air, gas-heated controlled-air, and rotary kiln incinerators was performed by off-site contractors. Each incinerator was operated for two test periods; one with average (Type 1) and the other with difficult (Type 2A, B or C) incinerator feed. Incineration parameters were selected to yield the most complete combustion, producing a low-carbon ash. The intent of these tests was not to optimize the process, but rather to confirm that the technology is applicable for commercially generated TRU wastes. Follow-on tests will be required for process optimization.

All simulated wastes were preshredded for the tests as described previously in the Shredder Tests section. A portion of the wastes were shredded twice using similar sized shredders to reduce the mean particle size of the incinerator feed. Trace quantities of Ce, Cs, Mo and Sr (refer to Table 6) were added to the shredded waste to follow their volatility behavior during incineration.

Off gases were analyzed in triplicate during feeding of both the average and difficult incinerator feeds. Off-gas data were taken in accordance with EPA methods described in 40 CFR Part 60. A summary of the off-gas analyses that were performed are listed below:

- Stack velocity - EPA Method 1
- Stack gas flow - EPA Method 2
- CO₂, O₂ and CO - EPA Method 3
- Moisture content - EPA Method 4
- Particulate loading - EPA Method 5
- NO_x - EPA Method 7
- SO_x - EPA Method 8 or combined Methods 5 and 8
- CO - EPA Method 10 (Gas-Heated Controlled-Air Incinerator test only)
- Cl⁻ - Combined EPA Methods 5 and 8

Upon completion of the tests, the incinerator subcontractors supplied off-gas system samples and residue product to PNL for subsequent analysis. A final test report was also prepared by each subcontractor. These reports contain incinerator specifications, off-gas analysis results, a summary of the incinerator operating performance and a log of all incinerator operating data.

The remainder of this section contains a more detailed discussion of the test equipment, procedure, and results of the three incineration tests.

ELECTRICALLY HEATED CONTROLLED-AIR INCINERATOR

A pilot-scale incinerator manufactured and operated by Shirco, Inc. of Dallas, Texas, was used for this test. This same unit was used earlier by SRL during development of their PWI process (Charlesworth and Hill 1985).

Equipment Description

The process equipment consists of a conveyor feed system, a pyrolysis chamber with a moving conveyor, an afterburner and a liquid scrub system. Figure 12 shows a schematic of the Shirco pilot-scale incineration process equipment and Figure 13 shows a picture of the test unit.

The feeding conveyor consists of a hopper with a variable speed conveyor belt used to meter the waste to the incinerator. Wastes drop off of the belt into the front end of the primary chamber through a sealed feed chute, with a 7.6 x 30.5 cm opening at the inlet to the incinerator. The feed system design

FIGURE 12. Electrically Heated Controlled-Air Test Incinerator Schematic

FIGURE 13. Electrically Heated Controlled-Air Test Incinerator

allows the waste to be dropped at an even rate, uniformly across the width of the conveyor belt in the primary chamber. During operation, waste material is fed to the incinerator at feed rates up to 10 kg/hr.

The primary chamber used for pilot testing is a scaled-down model of production-size furnaces (refer to Figure 5 for internal detail). It consists of a feed module, two combustion modules (zones) containing silicon carbide heating elements, and a discharge module. Heating elements deliver up to 20 KVA to each of the two furnace zones and 20 KVA to the secondary chamber. The primary chamber has a steel skin and measures 0.91 x 1.1 x 4.3 m.

A 41-cm wide conveyor belt woven of 315 SS wire is used to transport the waste material from the feed end to the ash discharge end of the incinerator. The belt width is wider than the feed inlet port, which prevents waste from falling over the edge. The belt moves on a series of rollers, which have bearings that are serviceable from the outside. The drive roller is powered by a variable speed motor that allows the waste residence time to be controlled from 10 to 60 minutes. At the feed end of the incinerator, there is a pneumatically operated belt-centering mechanism that is set to pinch the belt from the sides once every minute, assuring that the belt remains in the center of the roller system. The center to center distance between the end rollers is 3.35 m and the effective belt length from the feed drop point to the discharge end is 3.05 m. Ash residue from the process discharges into a sealed rectangular cross-section hopper. The hopper is flanged to the furnace discharge chute to permit ash removal.

The combustion gas flow through the system is counter-current to the waste material flow. Combustion air is provided to the furnace endplate by means of a pressurized line from an air compressor, with flowrate measured by a vertical flowmeter. Air supplied by a centrifugal fan is injected through the ports along the furnace length. Pyrolysis products generated in the primary chamber pass through an electric infrared secondary chamber where they are combusted at a nominal setpoint temperature of 980°C. Standard EPA gas sampling ports are located in the secondary chamber exhaust. Emissions were sampled from these ports as described earlier.

Combustion gases pass from the secondary chamber through the insulated off-gas line directly to a venturi scrubber which quenches the hot off-gas and removes the particulates. The gases then pass into the bottom of a spray tower that has two spray nozzles axially located at different heights within the column. Off-gases exit through the top of the column into a blower and out the stack. The off-gas system uses a fresh water scrub solution for both the venturi scrubber and the spray tower.

Instrumentation and controls include independent temperature controllers for the heated zones and secondary chamber, thermocouples connected to a multi-point chart recorder and LED display to monitor the thermal profile in the incinerator. Also included are belt speed controls and watt-hour meters to record power consumption. The scrubber system is instrumented with water flowmeters for both the venturi scrubber and spray tower.

Test Description

During a preliminary shakedown operation of the pilot system, it was found that due to the large particle size, the waste would bridge in the feed chute and cause plugging. As a result, it was necessary to reshred the waste material to a smaller size. The Saturn Shredder Company was contracted to reprocess the nonmetal waste using a shredder with a 1.9 cm cutter wheel width (test unit 6 Table 10) and to reprocess the metal-containing waste by a shredder with a 3.8 cm width cutter (test unit 7).

The reshredded waste was blended using a manual drum mixer. The appropriate percentages of each waste component was placed into a 303 L (80 gal.) drum, which was then rotated several times to obtain a partial mix. Tracer material was slurried in about 200 ml of water and poured in with the waste as it was being tumbled. The tumbling was continued for several minutes, after which the waste was ready for the incinerator.

The Shirco pilot incinerator required approximately 45 minutes to heat up to process temperatures of 700°C in Zone 1 and 870°C in Zone 2. Temperature setpoints were then selected on the panel mounted controllers for the desired

furnace zone and afterburner temperatures. When the furnace reached a predetermined temperature, the gas scrubber water flow was turned on along with the induced draft fan that exhausts the system.

Simulated Type 1 waste material (refer to Table 5) was fed at rates ranging from approximately 5 to 9 kg/hr. The feed conveyor belt speed was set to obtain the desired feed rate. An operator monitored the conveyor to assure that the correct amount of material was on each flight. This resulted in a continuous and consistent feed rate. Excessively large pieces of metal or fabric were periodically encountered. Pieces that were judged large enough to cause bridging were separated out and not fed to the incinerator. The difficult to incinerate Type 2A waste material (Table 5) was fed at 6.9 kg/hr during the last day of operation.

Combustion air for oxidation of the waste solids in the primary combustion chamber was input through end ports as described previously. In an attempt to decrease the fixed carbon content in the ash, the combustion air flow was increased at several intervals through the first day of operation. Due to limitations of the compressed air system, this flow was later decreased and additional air was added from a blower through ports in the furnace side.

It was not necessary to add combustion air to the secondary chamber during this test program. The air leakage into the secondary chamber around its glow-bars was sufficient to sustain a complete combustion process. This was based upon residual oxygen measurements made down stream of the secondary combustion chamber. For the pilot test program, furnace draft was measured in the furnace discharge module. To minimize air in-leakage and control the pyrolysis process, the exhaust system was adjusted to eliminate smoke emissions from the material feed inlet. This was done by manually positioning the scrubber venturi butterfly damper. The setting remained substantially constant for each test condition. Thus, the draft was primarily adjusted while reaching steady state for each condition. At the end of each of the different operating conditions, the entire ash hopper was emptied. The residue was weighted and its volume measured. After completion of feeding both Type 1 and Type 2 wastes, the incinerator was allowed to cool, was opened up, and residual ash and residue was removed.

Operating data for the three incinerators tested are presented in Table 13. The electrically heated controlled-air unit was operated for five test periods (A-1 through A-5) using Type 1 waste material and one test period (A-6) using Type 2A waste material. The incinerator conveyor speed was adjusted to provide a 0.5 hr residence time during all test periods except A-5 in which it was adjusted to 1.0 hr. At one point during operation, the drive roller began to slip, causing the conveyor to stop. The conveyor was restarted manually by applying a wrench to the pinch roller shaft. The pressure between

TABLE 13. Incinerator Operating Data Summary

Test Period	Feed Type	Feed Rate, kg/hr	Run Time, hr	Residence Time, hr	Temperature, °C			Secondary Chamber
					Primary Chamber		Exhaust	
					Feed End	Mid Section		
Electrically Heated Controlled-Air Incinerator								
A-1	1	8.7	13.9	0.5	880 (13)(a)	735 (18)	>970 (200)	940 (13)
A-2	1	5.1	1.6	0.5	880 (13)	735 (18)	>970 (200)	940 (13)
A-3	1	7.2	17.1	0.5	880 (9)	770 (31)	>970 (152)	920 (21)
A-4	1	6.5	12.1	0.5	880 (10)	755 (10)	>975 (72)	930 (9)
A-5	1	4.6	3.9	1.0	880 (11)	710 (25)	685 (104)	895 (18)
A-6	2A	6.9	8.5	0.5	875 (8)	750 (35)	945 (27)	865 (39)
Gas-Heated Controlled-Air Incinerator								
B-1	1	66	7.0	2.0 to 9.0	---	860 ^(b) (81)	---	980 (59)
B-2	2B	66	6.2	2.2 to 8.2	---	895 ^(b) (77)	---	980 (34)
Rotary Kiln Incinerator								
C-1	1	57	1.5	1.5	605 (45)	400 (75)	290 (30)	NA ^(c)
C-2	1	54	7.2	1.5	800 (84)	620 (83)	420 (22)	NA
C-3	2C	68	4.2	1.5	775 (84)	685 (82)	465 (28)	NA

(a) Numbers in parenthesis are standard deviations of multiple readings.

(b) Gas fired controlled-air incinerator equipped with single primary zone.

(c) Not applicable since rotary kiln incinerator did not have a secondary chamber.

the drive and pinch rollers was increased which solved the slippage problem. Current production model incinerators of this design are equipped with pneumatic cylinders that automatically maintain the desired pressure between the drive and pinch rollers.

Temperatures during these tests averaged from 710 to 770°C in the zone nearest the residue discharge end and from 875 to 880°C in the zone nearest the feed end. Although the system could operate at higher temperatures, these ranges prevented melting of glass materials into the woven wire conveyor, which would be detrimental to the continuous movement of the conveyor. At the primary chamber exhaust port, where the wastes are actively burning, temperatures averaged up to and above 970°C. Secondary chamber temperatures were lower, ranging from 865 to 940°C.

During operation, a small portion of the ash and residue fell off the conveyor belt. Most of the incinerator residue was discharged into the ash hopper with only 1.0 wt% remaining in the primary chamber.

Off-gas emission sampling, as described earlier, was performed in triplicate during feeding of both waste types. The furnace system was operated until a steady state condition was achieved before sampling was initiated. As several different sets of operating parameters were tested during feeding of Type 1 waste, environmental samples were taken during the period thought to be producing the lowest carbon ash.

GAS-HEATED CONTROLLED-AIR INCINERATOR

The gas-heated controlled-air incinerator tested is a production model 500-TE manufactured by Ecolair Environmental Control Products (ECP), Inc. of Charlotte, North Carolina. The test unit is owned by Bowman Gray School of Medicine in Winston-Salem, North Carolina and is used for disposing of pathological wastes. The incinerator is of a recent design, fabricated in 1983, and first put into operation in April of 1984. Descriptions of the equipment and the test are presented in the remainder of this section.

Equipment Description

The 500-TE unit is a dual chamber incinerator heated by either diesel fuel or natural gas. It is designed for semicontinuous (ram) feeding and batch ash discharge (continuous ash discharge models are available). It has a rated capacity of 180 kg/hr for pathological wastes. A schematic of the system is shown in Figure 14 and a picture is presented in Figure 15. The unit is equipped with a hydraulic system which powers a ram feeder, a refractory-faced guillotine charge door, an ash discharge ram, and an ash slide gate.

Both primary and secondary chambers are lined with refractory brick and contains dual fuel burners. There are two air blowers associated with each chamber; one provides air to the gas burner and the second provides combustion air to oxidize the wastes. The blowers and the burners all operate automatically to maintain the desired temperature and to control the air balance within the incinerator during the feed cycle. The gas residence time is approximately 11 seconds in the primary chamber and two seconds in the secondary chamber.

The incinerator is not equipped with an off-gas treatment system for air pollution control, as it meets the existing Federal Emission Code without off-gas treatment. Two ports were placed on the stack to permit environmental analysis of the off gas during the test. No blower is used to remove the off gases because natural convection provides the draft.

The incinerator is equipped with a control system that permits either automatic or manual operation. To begin the automatic feed cycle, the waste is dropped into a ram charge area and the top door closes. The charge door into the incinerator then opens, the ram pushes the waste material into the incinerator chamber and partially retracts to allow the charge door to close, a water spray cools the ram and it returns to its original position, and the top door opens to permit the next waste drop. This feed cycle takes about one minute to complete. The primary chamber burner automatically shuts off while the guillotine door is open to prevent smoke from exiting the open charge door.

FIGURE 14. Gas-Heated Controlled-Air Test Incinerator Schematic

FIGURE 15. Gas-heated Controlled-Air Test Incinerator

Test Description

Prior to testing, the incinerator was cleaned out, with all ash from prior incinerations removed. As the incinerator had been used for some wastes that contained short lived low-level radioisotopes (liquid scintillation vials, animals with microspheres, etc.), it was checked for both gamma and beta contamination. A survey of the primary chamber and entrance to the secondary chamber showed that no radiation above background was present.

The feed materials were loaded into cardboard boxes that measured 42 x 42 x 52 cm and had a tare weight of 0.91 kg. Compositions for Type 1 and Type 2B wastes were tested (see Table 5). Because the incinerator was charged batchwise, it was judged less important for the wastes to be intimately mixed as they were during the electrically heated controlled-air tests. As a result, the shredded wastes were loaded into the cardboard boxes without mixing. Trace elements were slurried with approximately 200 ml of water and were poured on top of the Type 1 wastes.

The incinerator was started up and allowed to warm up for a period of 45 minutes to 60 minutes before feeding was initiated. Boxes of waste with a net weight of 15 kg each were charged to the incinerator every 15 minutes during each of the two test periods. Ash and residue was allowed to accumulate in the primary chamber until completion of each run. After each feed period was completed, an automatic two-hour shut-down sequence was initiated. The incinerator was maintained at operating temperatures during this period to ensure that the last waste charged was completely combusted.

The gas-heated controlled-air incinerator was operated during test periods B-1 and B-2 as shown previously in Table 13. The residence time for the waste charges ranged from 2 to 9 hours with Type 1 waste and 2.2 to 8.2 with Type 2B waste. The variable residence time is due to the semicontinuous feeding and the batch mode of ash removal, in which all residue remains in the primary chamber until after the incineration burn is completed.

At one point during feeding of Type 1 material, a circuit breaker tripped on one of the automatic control circuits and had to be reset. This caused the incinerator to momentarily shut down. Upon initiating the auto start sequence,

the stack smoked for about 2 minutes until the burners and combustion air blowers were on and operating normally. The smoking condition could have been prevented had the incinerator been restarted manually.

Temperatures in the primary chamber of the gas-heated controlled-air incinerator averaged from 860 to 895°C, essentially the same as in the feed end of the electrically heated unit (see Table 13). The secondary chamber was maintained somewhat hotter, at 980°C.

The incinerator was allowed to cool for at least 36 hr after each test before the residue was removed. An access door on the end of the primary chamber was opened so that the ash removal process could be viewed. First the ash slide gate was opened and then the automatic ash discharge ram was cycled several times to discharge the residue into 208-L (55 gallon) barrels. The slide gate was apparently warped and could only be opened about half way. This caused some difficulty in discharging the residue, especially the larger pieces of metal. After the automatic removal process was completed, the inside of the incinerator was manually swept out to remove all the remaining ash.

The ash discharge ram effectively removed 80 wt% of the incinerator residue after testing; however, the remaining 20% had to be removed manually. The removal efficiency could be increased significantly by using an alternate primary chamber design. The test incinerator had a rounding bottom that permitted the residue to remain on the sloped walls after the discharge ram was cycled. Ecolair has manufactured primary chambers with a flat bottom and square sides, which would permit much better discharge efficiencies than experienced with the test unit.

ROTARY KILN INCINERATOR

The rotary kiln incineration system was built and operated by Colorado School of Mines Research Institute (CSMRI) in Golden, Colorado. This is the same test unit used by INEL during the rotary-kiln proof-of-principle tests conducted prior to design of the PREPP incineration system (Hedahl 1982a).

Equipment Description

The process equipment consists of a ram feed unit, rotating kiln, cyclone dust separator with spray quench, baghouse dust separator and a final induced-draft blower (see Figures 16 and 17). The ram feed system consists of a hopper on top of a 61-cm diameter ram shaft. The ram is hydraulically driven and has

FIGURE 16. Rotary-Kiln Test Incinerator Schematic

FIGURE 17. Rotary-Kiln Test Incinerator

a stroke of 2.3 m. The rotary kiln incinerator has a 0.91-m (3 ft) ID, a 1.2-m (4 ft) OD, a 9.1-m (30 ft) effective length, and a 10.7-m (35 ft) actual length. The kiln is operated in a concurrent gas-firing mode with an 0.8° slope. The kiln drive uses a chain-driven ring sprocket and a variable-speed drive unit. The rotational speed of the kiln is adjustable from approximately 0.5 to 3 rpm, but was operated at 1 rpm for the test. The kiln is supported by five sets of rollers along its length. During operation, the incinerator residue is discharged from the kiln into a refractory-lined end housing where it drops into a 208 L (55 gallon) drum.

Temperatures inside the kiln are monitored at five locations using thermocouples. A pair of continuous copper rings mounted around the kiln and a pair of graphite contacts mounted on the support structure are used to transmit the thermocouple signal from each sensor on the moving kiln to a temperature recorder.

The burner system consists of a 7.6-cm main burner and a 5.1-cm pilot burner with natural gas as fuel. Both burners are positioned at the feed end of the incinerator above the ram feeder tube. The position of the pilot burner tip is located below and behind the main burner tip, crossing at an angle to the axis of the main burner. The burner gas flow rates are controlled manually, however automatic systems are available.

Off gases exit from the end of the kiln into a 0.91-m diameter by 1.52-m tall cyclone. Gases are then routed through a 0.61-m diameter by 11.3-m long pipe that is used for effluent sampling. Gases then pass vertically through a water quench section of pipe and into a baghouse. During operation, the residue from the cyclone and from the baghouse is dropped into 208-L (55 gal) drums. The baghouse contains 36 nylon bags that are 3.7-m long and 11-cm diameter. It is equipped with a pulse air blow-back system for periodic unloading of the filters. Cleaned gases then pass through an induced-draft blower and to the stack.

Test Description

The rotary kiln was preheated for 4.75 hr using the main and pilot burners prior to the introduction of Type 1 feed waste material. The temperature at

the start of feeding was 550°C near the burner end of the kiln. The temperature of the entire kiln rose steadily to 927°C during the test due to the additional heat input of the combustible waste. The kiln was fed the Type 1 waste material batchwise every 10 minutes. The waste was loaded directly into the charging chute without using a box as was done during the gas-heated controlled-air incinerator test. A feed rate of 80 kg/hr was tried for the first two batch charges but was then reduced to 54 kg/hr after excessive smoke, flame out of the primary burner, and minor draft fluctuations were observed. The system effectively handled the 54 kg/hr feed rate (batches of 9 kg every 10 min). Each batch was prepared by weighing out the correct amounts of waste material (refer to Table 5) in the ram cylinder, pouring the tracer (slurried with approximately 200 ml of water) over the batch, and then activating the plunger to charge the batch into the kiln.

The kiln and cyclone products from Test 1 were collected at two different times during the test (periods C-1 and C-2 Table 13). The first collection was made following 3 hr of feeding in order to allow observation of the products. The product from the first period represented feed for the first 1.5 hr because residence time was measured at 1.5 hr (time required for waste to travel the length of the kiln). The product from the remainder of the Test 1 was collected continuously during the balance of the test and during the kiln drain period.

The procedure for feeding Type 2C waste (test period C-3) was similar to the test procedure followed for the Type 1 testing except that the kiln was heated for over 7.7 hr prior to initial feeding. The kiln was fed the Type 2C waste in 11.3 kg batches every 10 min resulting in a feed rate of 68 kg/hr.

The kiln temperature at the start of feed of Type 2C was 555°C near the burner end of the kiln. Due to the longer preheating period, the temperatures were approximately 170°C hotter further down the kiln than for the previous startup. The incinerator system temperatures all began to rise steadily as soon as feed was introduced to the system. Temperatures during the latter portion of this test approached 980°C near the feed end of the kiln (refer to Table 13 for average kiln temperatures).

During both tests, the kiln temperature profile was logged continuously on a strip chart recorder while pressures and other operating data were recorded approximately every one half hour on a log sheet. The objective was to reach a steady-state temperature; however, due to the relatively short duration of the tests, the kiln temperatures were still climbing at the end of each test.

The ram feed system and kiln drive system performed well during all test periods. The kiln operation could be improved by increasing the burner size in the primary chambers to facilitate a faster warm-up cycle. Also, the system should be built tighter to permit better control over the combustion air flow.

Upon completion of each test, the residue, cyclone product, and baghouse product were collected. Samples were also taken of the quench liquid. The weights and volumes of each product were also measured.

TEST RESULTS

Results of the three incinerator tests are compared in this section. Data pertaining to residue characteristics, off-gas characteristics, and trace element behavior are presented and discussed.

Residue Characteristics

Weight and volume reductions achieved during the incinerator test periods are presented in Table 14. Weights and volumes for the incinerator residue and off-gas particulate are also presented. The electrically heated controlled-air incinerator had the highest average weight and volume reductions (4.1 and 10.8, respectively) which were nearly double those achieved with the gas-heated controlled-air and rotary kiln incinerators. These high net reductions are somewhat misleading and should be lower. A portion of the metal in the electrically heated incinerator feed was sorted out due to limitations of the shredder used for the additional feed size reduction. Some metal was also removed prior to the incineration test due to the size limitation imposed by the incinerator feed chute. By removing a fraction of the metal (which does not undergo weight or volume reduction during incineration) the apparent reductions increase as they are more dependent on the combustible fraction of the waste. The reshredding operation also increased the packing factor of the

TABLE 14. Incinerator Weight and Volume Reductions

Test Period	Feed		Incinerator Residue		Off-Gas Particulate (b)		Total Product		Net Reduction	
	Wt, kg	Vol, ^(a) L	Wt, kg	Vol, L	Wt, Kg	Vol, L	Wt, kg	Vol, L	Weight	Volume
Electrically Heated Controlled-Air Incinerator										
A-1 & 2	129.3	580	35.8	84.9	0.28	1.40	36.1	86.3	3.6	6.7
A-3	122.5	549	27.2	37.4	0.26	1.30	27.5	38.7	4.5	14.2
A-4	79.4	356	14.5	14.6	0.17	0.85	14.7	15.5	5.4	23.0
A-5	18.1	81.2	5.1	4.7	0.04	0.20	5.1	4.9	3.5	16.5
A-6	<u>59.0</u>	<u>258</u>	<u>15.4</u>	<u>22.4</u>	<u>0.15</u>	<u>0.75</u>	<u>15.6</u>	<u>23.2</u>	<u>3.8</u>	<u>11.1</u>
TOTAL A:	408	1824	98	164	0.9	4.5	99	169	4.1	10.8
Gas-Heated Controlled-Air Incinerator										
B-1	460.4	1960	169.6	234.0	6.4	32.0	176.0	266.02	2.6	7.4
B-2	<u>408.5</u>	<u>1370</u>	<u>210.5</u>	<u>269.0</u>	<u>11.9</u>	<u>59.5</u>	<u>222.4</u>	<u>328.5</u>	<u>1.8</u>	<u>4.2</u>
TOTAL B:	869	3330	380	503	18.3	91.5	398	595	2.2	5.6
Rotary Kiln Incinerator										
C-1	81.6	347	25.8 ^(c)	33.4	5.63	28.2	31.4	61.6	2.6	5.6
C-2	402.8	1710	149.6 ^(c)	148.0	27.8	139.0	177.4	287.0	2.3	6.0
C-3	<u>294.8</u>	<u>989.0</u>	<u>108.9^(c)</u>	<u>96.2</u>	<u>6.4</u>	<u>32.0</u>	<u>115.3</u>	<u>128.2</u>	<u>2.6</u>	<u>7.7</u>
TOTAL C:	779	3046	284	278	39.8	199	324	477	2.4	6.4

(a) Volumes calculated from feed densities.

(b) Weights calculated from off-gas particulate loadings. Volumes calculated using density of 0.20 kg/L, which is measured density of bag house particulate during test period C-2.

(c) Rotary kiln residue weight includes weight of cyclone product.

metal noncombustibles, which further increases the net volume reduction. The average weight and volume reductions measured during the gas-heated controlled-air and rotary kiln incineration tests are approximately equal, as any differences are within the standard deviation of the data.

Table 15 presents the chemical analysis of the incinerator ash. Of prime interest is the fate of aluminum (Al) from the HEPA filter separators. The presence of Al metal in a cement waste form promotes an undesirable hydrolysis reaction, which generates H_2 gas. A significant fraction of the ash is Al, ranging from 11.7 wt% in the electrically heated controlled-air residue to

TABLE 15. Chemical Analysis of Incinerator Ash^(a)

Element	Electrically Heated Controlled-Air, wt%	Gas-Heated Controlled-Air, wt%	Rotary Kiln, wt%
Al	11.7	15.0	37.7
B	1.43	1.40	0.97
Ba	0.79	0.83	0.70
Ca	7.13	5.40	1.90
Ce	0.20	0.32	0.13
Cr	0.08	0.36	0.06
Cs	0.09	0.08	0.06
Cu	0.09	0.27	0.13
Fe	1.90	8.20	4.91
K	0.60	1.03	0.44
Li	0.03	0.02	0.02
Mg	1.03	1.01	0.42
Mn	0.03	0.09	0.04
Mo	0.15	0.17	0.13
Ni	0.03	0.12	0.03
P	0.57	1.00	0.27
Pb	0.16	1.11	1.03
Si	10.0	9.73	5.85
Sr	0.15	0.24	0.12
Ti	0.73	0.82	0.28
Zn	2.63	0.97	1.22

(a) Numbers shown are average values of three sample analysis. The noncombustible residue (i.e. metals, glass, etc.) was separated from the ash prior to analysis. Cs was analyzed by flame atomic absorption. All other elements were analyzed by inductively coupled argon plasma atomic emission spectroscopy.

37.7 wt% in the rotary kiln residue. None of the incinerators effectively oxidized the Al as HCl solubility tests revealed that over 95% is in the metal form. Other elements which were predominant in the incinerator ash include B, Ca, Fe, Si, and Zn. It is likely that these elements are present as oxides; however, an analysis of chemical form was not made.

High concentrations of unburned carbon in the ash is undesirable, as the ability of the residue to become wetted in the cementing process is hindered. The incinerator ash carbon content shown in Table 16, was lowest at 1.9 wt% for the gas-heated controlled-air incinerator, probably due to the prolonged residence time characteristic of this unit. No carbon analysis was performed on the off-gas filter particulate collected during this test due to the small size of sample. Ash from the electrically heated controlled-air incinerator test contained the highest level of residual carbon at 11.0 wt%. This is probably due to the short residence time (~0.5 hr) used during the test period. The carbon content of the off-gas particulate that passed through the secondary combustion chamber was lower at 3.1 wt%. Incinerator residue from the rotary kiln ash contained 6.7 wt% carbon while the off-gas particulate contained 29 wt%. The quantity of unburned carbon in the rotary kiln ash is likely due to the lower operating temperature of the kiln compared to that of the two controlled-air incinerators (refer to Table 13). The tumbling action within a kiln promotes entrainment of the lighter carbonaceous material as indicated by the extremely high carbon content of the off-gas particulate. The carbon

TABLE 16. Residual Carbon Analysis of Incinerator Product^(a)

Incinerator Product	Electrically-Heated Controlled-Air, wt%	Gas-Heated Controlled-Air, wt%	Rotary Kiln, wt%
Ash	11.0	1.9	6.7
Off-Gas Particulate	3.1	ND ^(b)	29

(a) Numbers shown are average values of three sample analysis. The non-combustible residue (i.e. metals, glass, etc.) was separated from the ash prior to analysis. Carbon analysis was performed by thermal decomposition and oxidation of the carbon followed by gas chromatograph analysis for CO₂.

(b) There was insufficient sample on the off-gas particulate filters to perform carbon analysis.

content of the off-gas particulate would have been substantially lower had the rotary kiln incinerator been equipped with a secondary combustion chamber.

The ash residue from the electrically heated controlled-air incinerator test is characterized by small chunks of carbonized wood as well as chunks of unfused and fused Al. Much of the unfused Al remained with the larger metal fraction when the ash was separated from the metal. The residue generated during the gas-heated controlled-air test contained clinkers of fused Al and fused glass media from the HEPA filters. Rotary kiln residue contained the Al clinkers but no significant quantities of fused glass filter media.

Off-Gas Characteristics

Off-gas analyses were performed in triplicate during test periods A-4, A-6, B-1, B-2, C-2 and C-3. Table 17 presents the results of these analyses, showing off-gas flow, excess air, water vapor, gas composition and normalized releases. Test periods A-4, B-1 and C-2 will be used for purposes of comparing the three incinerators because all three test periods used a common Type 1 waste material. The other three test periods (A-6, B-2 and C-3) cannot be used for direct comparison since the Type 2 feed composition was different for each period.

The normalized off-gas flow during the electrically heated controlled-air test ranged from 10 to 12 dscm/kg of waste feed. The flow during testing of the gas-heated unit was three times higher, ranging from 32 to 36 dscm/kg due to the additional gases introduced by the gas burners. Flows were highest at 75 to 93 dscm/kg during the gas-heated rotary kiln tests. Excess air was lowest for the gas-heated controlled-air incinerator (138% excess air for test period B-1) as it was equipped with the most automated burner and combustion air control system. The lower O_2 concentration and higher CO_2 and water vapor concentrations (see Table 17) during period B-1 correlate with the lower excess air level during this period. The CO level was less than 0.1 vol % during both controlled-air tests; however, the CO averaged 0.57 vol % during operation of the rotary kiln (period C-2) primarily because the kiln was not equipped with a secondary combustion chamber.

TABLE 17. Incinerator Test Off-Gas Characteristics

Test Period	Feed Type	Off-Gas Flow	Excess Air, %	Water Vapor, %	Gas Composition, dry vol%			Normalized Release, g/kg Waste			
		dscm/kg Waste ^(a)			O ₂	CO ₂	CO	Cl ⁻	SO ₂	NO _x	Particulate
Electrically Heated Controlled-Air Incinerator											
A-4	1	10.6 (0.6) (b)	312 (55)	5.42 (0.54)	16.1 (0.6)	3.13 (0.12)	<0.1 -	1.67 (0.07)	0.91 (0.25)	1.81 (0.90)	2.16 (0.21)
A-6	2A	12.0 (0.4)	780 (110)	4.83 (0.30)	18.6 (0.3)	2.23 (0.29)	<0.1 -	1.75 (0.77)	1.10 (0.40)	0.92 (0.48)	2.52 (0.94)
Gas-Heated Controlled-Air Incinerator											
B-1	1	32.0 (2.0)	138 (70)	10.2 (2.1)	12.0 (2.3)	6.5 (1.4)	0.007 (0.010)	19.0 (1.8)	2.8 (1.2)	4.6 (2.7)	13.9 (2.3)
B-2	2B	36.1 (1.2)	119 (40)	10.4 (0.4)	11.5 (1.9)	6.6 (1.5)	0.001 (0.001)	18.1 (7.3)	1.63 (0.39)	6.3 (1.7)	29.1 (8.1)
Rotary Kiln Incinerator											
C-2	1	92.6 (0.5)	343 (69)	5.72 (0.15)	16.7 (0.6)	1.94 (0.55)	0.57 (0.38)	0.19 (0.25)	8.2 (1.4)	14.3 (0.8)	69 (11)
C-3	2C	74.6 (0.2)	200 (33)	2.68 (0.75)	14.7 (0.8)	2.22 (0.32)	0.45 (0.13)	0.17 (0.25)	5.5 (1.8)	11.7 (0.7)	21.8 (9.1)

(a) Dry Standard Cubic Meters per kg of waste feed.

(b) Numbers in parenthesis are standard deviations of three or more samples.

Normalized release data for Cl^- , SO_2 , NO_x and particulate, expressed as g/kg waste, are presented in the last four columns of Table 16. The Cl^- releases were significantly higher during the gas-heated controlled-air incineration tests as were the SO_2 and NO_x releases during the rotary kiln testing. Reasons for this behavior are not readily apparent. Particulate releases were lowest at 2.2 g/kg waste during the electrically heated controlled-air test, were somewhat higher at 13.9 g/kg during the gas-heated controlled-air incinerator test, and were highest at 69 g/kg during the rotary kiln test. Low particle releases during the electrically heated controlled-air incinerator tests are attributed to the low level of turbulence in the primary chamber. Additional gas flow and turbulence generated by the gas burner in the gas-heated controlled-air incinerator is believed to be responsible for the higher particulate release. The highest release associated with the rotary kiln is attributed to the rotating action of the kiln in conjunction with the increased gas flow introduced by the gas burner system.

Trace Element Behavior

The distribution of trace elements in the incinerator product and off-gas particulate is presented in Table 18. Elements considered nonvolatile (Ce and Sr) are listed separately from those that have semivolatile tendencies (Cs and Mo). Concentrations of the nonvolatile Ce and Sr in the ash and off-gas particulate were averaged and used to calculate trace element material balances for the test periods A-4, B-1 and C-2. The total trace element material balance was lowest at 39% for test period A-4 but was much more reasonable at 71% and 75% for test periods B-1 and C-2, respectively. The high unaccountability during operation of the electrically heated controlled-air incinerator is not understood and tends to diminish the usefulness of that data. It is important to note, however, that essentially all the trace element material detected during the electrically heated test was in the residue.

Despite the less than ideal material balances, it appears that the bulk of the nonvolatile trace materials detected during the two controlled-air tests were present in the ash, with less than 1% showing up in the off-gas particulate. In contrast, the rotary kiln off gas contained 20% of the nonvolatile trace elements added to the feed. This illustrates the bulk off-gas solids

TABLE 18. Distribution of Trace Elements in the Incinerator Product and Off-Gas Particulate

Element	Trace Element Distribution, % of Initial Added										
	Test Period A-4 (Electrically Heated Controlled-Air)			Test Period B-1 (Gas-Heated Controlled-Air)			Test Period C-2 (Rotary Kiln)				
	Ash	Off-Gas ^(a)	Total	Ash	Off-Gas ^(a)	Total	Ash	Cyclone	Subtotal	Off-Gas ^(a)	Total
Nonvolatiles:											
Ce	37.9 (9.5) ^(b)	0.0 (0.0)	37.9 (9.5)	68.9 (6.9)	0.0 (0.0)	68.9 (6.9)	26.7 (9.0)	22.6	49.3 (9.0)	16.4 (10.2)	65.7 (9.6)
Sr	39.1 (3.3)	0.0 (0.0)	39.1 (3.3)	71.7 (8.1)	0.8 (0.7)	72.5 (8.8)	36.3 (10.9)	25.1	61.4 (10.9)	23.1 (6.3)	84.5 (8.6)
Average	39	0.0	39	70	0.4	71	32	24	55	20	75
Material Balance: ^(c)			39			71					75
Semivolatiles:											
Cs	28.8 (6.1)	0.3 (0.1)	29.1 (6.2)	28.2 (1.9)	4.1 (2.7)	32.3 (4.6)	21.5 (5.5)	14.8	36.3 (5.5)	28.4 (31.5)	64.7 (18.5)
Mo	37.9 (6.0)	0.4 (0.1)	38.9 (6.1)	49.3 (4.3)	3.1 (1.5)	52.4 (5.8)	36.3 (15.5)	21.5	57.8 (15.5)	25.1 (1.6)	82.9 (8.6)

(a) Off-gas analysis are of particulate collected on filters during environmental testing.

(b) Numbers in parenthesis are standard deviations of three samples.

(c) The net material balance is based on the accountability of Ce and Sr in the incinerator product and off-gas particulate.

carry-over associated with the tumbling action of a rotary kiln, which is not observed with a controlled-air type of incinerator.

The semivolatile components (Cs and Mo) were detected primarily in the ash during the electrically heated controlled-air test with less than 1% in the off-gas solids. This indicates good retention and is probably a result of the relatively short residence time (0.5 hr) during the test period. For the gas-heated controlled-air test, the semivolatiles were depleted in the ash and enriched in the off-gas, probably due to the much longer residence time associated with the batch mode of ash removal. As seen in Table 18, only 0.4% of the nonvolatile elements were detected in the off-gas particulate while 4.1% of the Cs and 3.1% of the Mo were present. A similar volatilization effect was observed during the rotary kiln test, however, physical entrainment was the predominant mechanism for loss of trace element to the off gas. Of the 75% of total trace element accounted for in the rotary kiln test, 55% of the nonvolatiles were present in the ash and cyclone product. The remaining 20% was present in the off-gas particulate, suggesting physical carryover as the mechanism. Some volatilization of Cs is evident since 36.3% was present in the ash and 28.4% was detected in the off-gas particulate.

COMPARISON OF INCINERATOR PROCESSES

COMPARISON OF INCINERATOR PROCESSES

The electrically heated controlled-air, gas-heated controlled-air, and rotary kiln incineration processes were evaluated based on technical merit and system cost. Capital and operating costs were estimated for shredding, incineration, and off-gas treatment operations. The technical merit of each process was judged by a five member panel using the Figure-of-Merit (FOM) process selection methodology. The FOM numbers are viewed as a measure of the overall process effectiveness. Cost-effectiveness ratios were generated using the cost/FOM ratio for each process. These ratios were then used to select a reference shredder and incinerator process for further development.

INCINERATOR ECONOMICS

Capital costs have been estimated for feed shredding, incineration, off-gas treatment, and the portion of the facility occupied by these unit processes. Annual costs were estimated for labor and energy to heat the incinerator. Other fixed operating costs will be similar for the three processes and as such, were not included in the cost analysis. Likewise, the economic comparison does not include the residue handling and cementation portions of the process since they would be the same regardless of the incineration system used.

Capital costs for the process components are based on the equipment requirements listed in Table 19. Due to their mechanical nature, the incineration systems are best suited for remote operation in a hot cell as opposed to a canyon. Hot-cell volumes for the off-gas systems were calculated using the volumes of a pilot-scale and large-scale in situ vitrification off-gas system (Timmerman and Oma 1984, Buelt et al. 1985). To compensate for periodic surges, an overdesign factor of four was used to scale the off-gas system to the required capacity. Cell volumes for the other incinerator subsystems were estimated by taking four times the equipment volume envelope as specified by the manufacturers. The additional volume allows for cell manipulators and an overhead crane required for remote operation and maintenance.

TABLE 19. Incineration System Equipment Requirements Used for Cost Estimate

Incinerator Subsystem	Electrically Heated Controlled-Air		Gas-Heated Controlled-Air		Rotary Kiln	
	Equipment Information	Required Cell Volume, m ³	Equipment Information	Required Cell Volume, m ³	Equipment Information	Required Cell Volume, m ³
Feed System:	• Coarse shredder • Metering pump • Fine shredder	120	• Coarse shredder • Top loading chute	80	• Coarse shredder • Vibrating conveyor • Feed shuttle system	85
Primary Chamber:	• 40 kg/hr Type 1 waste • 90 min residence time • Continuous ash removal • Automatic heater control (no computer)	240	• 40 kg/hr Type 1 waste • 90+ min residence time • Batch ash removal • Automatic burner control (no computer)	110	• 40 kg/hr Type 1 waste • 90 min residence time • Continuous ash removal • Automatic burner control (no computer) • Pressurized kiln seals	180
Secondary Chamber:	• 2 sec residence time • 1100°C mean temperature • 200% excess air • Automatic heater control (no computer)	35	• 2 sec residence time • 1100°C mean temperature • 200% excess air • Automatic burner control (no computer)	70	• 2 sec residence time • 1100°C mean temperature • 200% excess air • Automatic burner control (no computer)	70
Off-Gas System:	• 6.7 scm/min mean flow • Quencher • Venturi scrubber • Condenser • Gas reheater • HEPA filters	60	• 33 scm/min mean flow • Quencher • Venturi scrubber • Condenser • Gas reheater • HEPA filters	200	• 33 scm/min mean flow • Cyclone separator • Quencher • Venturi scrubber • Condenser • Gas reheater • HEPA filters	220
Total Cell Volume:		455		460		555

The electrically heated controlled-air incinerator process requires two stages of feed shredding while the other two incinerators require only one (refer to Table 19). A smaller waste fragment size for the electrically heated unit is needed to promote complete combustion of the wastes for several reasons:

- The wastes are not tumbled or agitated as they are with the rotary kiln. Combustion air must reach the unburned waste by diffusion.
- The residence time is short compared to that of the gas-heated controlled-air incinerator, which has batch ash removal.
- Heat transfer to the waste is by radiation from the glowbars. For most effective heating, the glowbars must be positioned within inches of the woven wire conveyor. This limits the maximum size of waste fragments that can be loaded onto the conveyor.

For the economic comparison, feeding is accomplished using a waste metering pump similar to that demonstrated on the SRL-PWI system (Charlesworth and McCampbell 1985) for the electrically heated controlled-air process. The gas-heated controlled-air process has a top loading chute with airlock doors for feeding while the rotary kiln process uses a vibrating conveyor and feed shuttle system similar to that used on the INEL-PREPP kiln process.

Another basic difference between the incineration processes is the required off-gas capacity. Since the electrically heated unit does not have additional combustion air and combustion gases from a gas burner system, the off-gas flow rate is about one fifth of that required for the two gas-heated incineration processes. This reduces both the equipment costs and facility costs associated with the electrically heated controlled-air process off-gas system. For the cost comparison, the rotary kiln off-gas system has a cyclone as the first stage cleaning device since high particle carryover is a trait of the process.

The capital cost estimates are presented in Table 20 showing the cost breakdown between the facility and process equipment. Cost data for the feed systems and incinerators were obtained from potential manufacturers while the off-gas system costs were derived from actual costs of the in situ

TABLE 20. Capital Costs for Incineration Processes (\$1000)

Capital Component	Electrically Heated Controlled-Air	Gas-Heated Controlled-Air	Rotary Kiln
Facility Cost: ^(a)	5,360	5,420	6,520
Equipment Cost:			
Feed System	280	140	235
Incinerator	800	250	750
Off-Gas System	<u>440</u>	<u>1,150</u>	<u>1,260</u>
Subtotal Equipment	<u>1,520</u>	<u>1,540</u>	<u>2,245</u>
Total Capital Cost	6,880	6,960	8,765

(a) Cost based on \$11,600/m³ hot cell volume. Includes cost of hot cell with manipulators and windows, an overhead crane, operating gallery, rear face gallery, aqueous storage, and cell ventilation. Facility cost does not include those costs which are independent of the process size such as analytical laboratory and offices.

vittrification off-gas treatment systems (Timmerman and Oma 1984). Off-gas system costs were adjusted to the required equipment capacity using the six-tenths-factor rule (Peters and Timmerhaus 1968) and were escalated to 2nd quarter 1985 dollars. Facility costs were based on \$11,600 per cubic meter of hot cell volume plus \$85,000 for one hot cell crane. Facility costs include the hot cell with manipulators and windows, operating gallery, rear face gallery, aqueous storage, and cell ventilation. These costs were based on a 1981 Pacific Northwest Laboratory cost estimate for a Byproduct Recovery Facility and were escalated to 1985 dollars.

To determine equipment and facility size and annual operating costs, the following assumptions are made:

- 38,500 kg of TRU wastes are shredded and incinerated each year.
- Incinerator is operated three shifts per day during waste processing campaigns.
- Incinerator is on line 20% of time and there are 250 working days per year (this corresponds to approximately 40 kg/hr processing capacity).

- Labor direct rates are:
  - \$25/hr for supervisor and engineer
  - \$21/hr for maintenance, operator and radiation technician
- Labor overhead is 110%.
- Capital equipment is costed based on the following information:
  - Equipment life = 15 years
  - Facility life = 30 years
  - Salvage value = 0
  - Real discount rate (i) = 3% per annum (the cost of inflation free money)
  - Present worth factor in year n (pwf_n) = $\frac{1}{(1 + i)^n}$

Table 21 gives the estimated annual labor requirement and operating costs for each incineration process. Annual labor requirements for supervision and operation personnel is judged to be identical for all three processes.

TABLE 21. Annual Labor Requirements and Operating Cost Estimate for Incineration Processes^(a)

Annual Direct Labor, man years	Incineration Process		
	Electrically Heated Controlled-Air	Gas-Heated Controlled-Air	Rotary Kiln
Supervisor	0.6	0.6	0.6
Engineer	0.3	0.2	0.3
Maintenance	1.1	0.8	1.7
Operator	2.4	2.4	2.4
Radiation Technician	0.6	0.6	0.9
Total Labor	5.0	4.6	5.9
<u>Annual Cost, \$1000</u>			
Labor:			
Direct	217	200	255
Overhead (110%)	239	220	281
Incinerator Heating:			
Electricity	7		
Diesel #1		8	8
Total Annual Cost	463	428	544

(a) Fixed operating costs which are the same for all incinerator options are not included. The cost analysis only includes costs judged to have a dependency on the process selected.

Engineering and maintenance personnel requirements are slightly lower for the gas-heated controlled-air process because of lower overall maintenance. Maintenance and radiation technician personnel requirements are highest for the rotary kiln process primarily because the refractory of the kiln requires more frequent replacement than for the two controlled-air processes.

The present-worth method (Peters and Timmerhaus 1968) was used to calculate the costs of the three incineration processes for a 30 year operating period. This was done by applying the facility cost to year zero, the equipment cost to years zero and sixteen, and the operating costs to years 1 through 30. The total cash outlay in each year was multiplied by the present-worth factor and then summed for all the years to generate the present-worth of each incineration process. The present worth cost of the electrically heated controlled-air and gas-heated controlled-air incineration processes were lowest at \$16.3 M and \$16.9 M respectively. Due to both higher capital and operating costs, the present worth of the rotary kiln processes was calculated to be \$20.8 M. These costs are not adjusted for future inflation.

FIGURE-OF-MERIT ANALYSIS

A five-member panel, consisting of the authors and two other technically qualified persons, was established to conduct the FOM evaluation of the incineration processes. The panel members had varied technical backgrounds in areas related to the evaluation including: incinerator testing, radioactive process development, waste form development, off-gas treatment, CH and RH equipment and facility design, and waste form characterization. The FOM evaluation was performed as follows:

- Incineration operating requirements were defined (feed composition, feed rate, etc.).
- A list of evaluation criteria was prepared by the panel members.
- The list was divided into primary and secondary criteria.
- Performance measures used to judge the criteria were defined.
- Panel members independently assigned weights to the primary and secondary criteria. For each set of criteria, the sum of weights is

unity. The individual weightings for each criteria were then averaged to obtain group weightings that were used to generate a FOM model.

- Panel members independently assigned ratings of 1 to 10 for each of the secondary criteria for the three candidate incineration processes.
- A FOM number for each candidate process was calculated for each panel member and for the group as a whole. This was done by multiplying the primary criteria weighting by the secondary criteria weighting and by the group rating for that criteria.
- The FOM model was tested for sensitivity.
- The panel members were given the opportunity to revise their weightings and ratings and a final FOM model was developed.

The finalized FOM model is shown in Table 22 along with the group ratings and FOM values for the three incineration processes. The primary criteria selected were product, equipment and operating considerations. Secondary criteria and the associated performance measures are also shown in Table 22. The maximum possible FOM value a process could achieve using this model is a 10. The FOM numbers derived from the model were 7.0 for the gas-heated controlled-air incinerator, 6.1 for the electrically heated controlled-air incinerator, and 5.8 for the rotary kiln incinerator. The ratings are rather tightly grouped; however, the FOM ratings based on each panel member's individual evaluation were consistently highest for the gas-heated controlled-air process. The individual FOM evaluation results for the five panel members are listed in Table 23. Four of the five panel members ranked the electrically heated controlled-air process second and the rotary kiln process third while one of the panel members reversed this ranking. The difference between the FOM number for the second and third ranked processes is only 0.3 and, as such, they are considered about equal in overall effectiveness.

The electrically heated controlled-air incinerator's strong points are the minimal off-gas treatment requirements, low ash/residue holdup in the primary

chamber, long equipment life, and the ability to process different feed materials (all of these areas received ratings of greater than 8). The main weaknesses of the process were the inability to burn out the residual carbon, the high level of feed pretreatment required, the presence of clinkers in the ash, and the difficulty of remote maintenance (these areas received rankings of less than 5).

The higher rated features of the gas-heated controlled-air incinerator are the complete burnout of residual carbon in the ash and the state of development (several units are operational with both TRU and LL wastes). The process was rated greater than 5.6 for all of the other evaluation criteria and as such, there are no process weaknesses that stand out.

The rotary kiln's greatest strength is its ability to process different feed materials including solids, liquids and sludges with up to 100% noncombustible content. The kiln also received a high rating for feed pretreatment because it can handle relatively large pieces of feed material. The process received ratings of less than 5 for trace element retention in the residue, off-gas treatment requirements, maintenance requirements and personnel exposure. Because of the continual tumbling action associated with kiln rotation, physical entrainment of the ash particles was noted both in terms of a high carryover of semivolatile and nonvolatile trace elements and in terms of a high particulate loading in the off-gas. The high maintenance requirements and high personnel exposures are related to one another. Remote maintenance items add to the personnel exposure associated with that maintenance. The design refractory life for the rotary kiln is estimated to be 2 years as compared to 5 for the controlled-air incinerators. Replacement of the refractory adds to both the remote maintenance requirements and personnel exposures associated with the rotary kiln.

COST EFFECTIVENESS ANALYSIS

The cost effectiveness ratio of each incineration process is calculated by dividing the present worth by the FOM number and then normalizing the ratios such that the most cost effective system has a ratio of unity. Using this technique, the most cost effective incineration process is the gas-heated

TABLE 22. Figure-of-Merit Model for Incinerator Process Comparison

Primary Criteria		Secondary Criteria		Performance Measure	Electrically Heated Controlled-Air			Gas-Heated Controlled-Air			Rotary Kiln		
Description	Weight	Description	Weight		Performance Measure	Rating	FOM Value	Performance Measure	Rating	FOM Value	Performance Measure	Rating	FOM Value
Product Considerations	0.376	Elimination of Combustibles	0.31	Residual Carbon Residual Al Metal	11.0% of ash Most Al as metal	3.2	0.37	1.9% of ash Most Al as metal	8.2	0.96	6.7% in ash Most Al as metal	5.4	0.63
		Net Reduction	0.45	Volume Reduction Weight Reduction	10.8 (larger metal pieces 4.2 sorted from feed)	6.8	1.15	7.4 5.6 2.6	0.95		5.9 5.6 2.3	0.95	
		Trace Element Retention	0.16	Fraction of Trace Element Retained in Residue	Ce/Sr - 39% Cs - 29% Mo - 38% (Material Balance - 39%)	6.0	0.36	Ce/Sr - 70% Cs - 28% Mo - 49% (Material Balance - 71%)	6.6	0.40	Ce/Sr - 55% Cs - 36% Mo - 58% (Material Balance - 75%)	4.0	0.24
		Ash Particle Size	0.08	Presence of Klinkers	Carbon rich wood chunks, most HEPA filter Al spacers unfused	4.4	0.13	Fused Al from HEPA sep- arators and fused glass from HEPA media	6.6	0.20	Fused Al from HEPA separators	6.4	0.19
		TOTAL	1.00										
Equipment Considerations	0.336	State of Development	0.15	Nuclear Systems in Progress	SRL (cold startup FY-85)	6.2	0.31	INEL (operational FY-85) LANL (LL & TRU operation) SRL (LL operation FY-85)	8.0	0.40	INEL (final construction) ORNL (design complete) SRL (initial design)	5.8	0.29
		Feed Pretreatment Requirements	0.13	Feed Particle Size Limits	2 in. max (L+W) (Accurate metering reqd.)	3.8	0.17	18 in. max (L+W)	7.4	0.32	24 in. max (L+W)	8.4	0.37
		Off-Gas Requirements	0.16	Off-Gas Particulate Loading Off-Gas Volume	2.2 g/kg waste 10 scm/kg waste	8.8	0.47	14 g/kg waste 50 scm/kg waste	5.8	0.31	69 g/kg waste 50 scm/kg waste	4.0	0.22
		Product Handling Requirements	0.17	Ash/Residue Holdup	1%	9.4	0.54	20% (Can be reduced by redesign)	5.8	0.33	6% (can be reduced by redesign)	7.2	0.41
		Remote Maintainability	0.28	Number of Major Maintenance Items Inside Cell	(8) Two shredders, feed pump, incinerator conveyor, rollers, belt centering system, ash dropout door, heaters	4.8	0.45	(7) Shredder, air-lock door, charging door, ash discharge ram, ash dropout door, under-fire air ports, burners	7.6	0.72	(11) Shredder, feed conveyor, feed shuttle, air-lock door, charging door, rotating seal, kiln rollers, drive system, ash dropout door, sliding T/C connectors, burners	5.0	0.47
		Equipment Life	0.11	Total System Life Refractory Life	20 yr design 5 yr design (10 yr max)	8.0	0.30	15 to 20 yr design 5 yr design (10 yr max)	7.8	0.29	10 to 15 yr design 2 yr design (10 yr max)	5.6	0.21
		TOTAL	1.00										
Operating Considerations	0.288	Controlability/Safety	0.22	Number of Operators Pressurization Potential Fire Potential	2 for incinerator Possible by overfeeding No combustible fuels used	7.4	0.47	2 for incinerator Possible by overfeeding Fuel line break	7.0	0.44	2 for incinerator Possible by overfeeding Fuel line break	7.0	0.44
		Ability to Process Different Feeds	0.23	Feed Types Noncombustible Limit	Solids & sludges Up to 100%	8.2	0.54	Solids & liquids 50% (depends on waste)	7.0	0.46	Solids, liquids & sludges Up to 100%	9.0	0.60
		Maintenance Requirements	0.33	Number Maintenance Items Percent Downtime		5.4	0.51		7.6	0.72		4.8	0.46
		Personnel Exposure	0.22	Rem/Year		5.2	0.33		7.2	0.46		4.6	0.29
Total	1.00	TOTAL	1.00		TOTAL FOM VALUE		6.1	TOTAL FOM VALUE		7.0	TOTAL FOM VALUE		5.8

TABLE 23. Figure-of-Merit Results for Individual Panel Members

<u>Panel Member</u>	<u>Electrically Heated Controlled-Air</u>	<u>Gas-Heated Controlled-Air</u>	<u>Rotary Kiln</u>
1	5.7	6.0	3.9
2	6.1	6.5	5.4
3	5.5	7.1	6.3
4	6.4	7.5	6.1
5	6.6	7.4	6.5

controlled-air unit with a cost effectiveness ratio of 1.0 followed by the electrically heated controlled-air process with a ratio of 1.2 and the rotary kiln process with a ratio of 1.5. Based on this analysis, the gas-heated controlled air incinerator is judged superior for the commercial TRU waste application and is selected as the reference process for further development.

The three incinerators tested are all excellent pieces of equipment and each has its advantages for different incineration applications. The selection of the gas-fired controlled-air unit only applies to this TRU waste application. The electrically heated controlled-air or rotary kiln systems are likely to be rated superior for other waste applications.

DEVELOPMENT NEEDS

DEVELOPMENT NEEDS

The incinerator FOM and economic analysis shows the gas-heated controlled-air incineration system to be the most cost effective for processing commercially generated TRU wastes. One stage of shredding is adequate feed pretreatment to produce a waste particle size that can be effectively passed through the incinerator. While the initial tests confirmed that the technology is adaptable to the TRU waste treatment application, these tests did not determine processing ranges, optimize the operating parameters, or evaluate the equipment design for remote operation. Several development needs for the shredder and gas-heated controlled-air incineration system are listed below.

- Identify and test methods to fix radioactive contaminants on HEPA filters prior to the shredding process. During the shredding tests, it was noted that a portion of the dust contained on loaded HEPA filters was released.
- Develop and test a mechanical device for feeding wood-framed HEPA filters to the shredder. In order for the shredder teeth to effectively grab the edges of the wood-framed HEPA filters during the shredder tests, it was necessary to manually reposition them at regular intervals.
- Test a shredder that is programmed for periodic automatic reversal cycles. Such a shredder could further reduce the particle size of the wastes and more easily process difficult to shred items such as metal-framed HEPA filters.
- Evaluate the incinerator off-gas treatment requirements and select a reference off-gas treatment system. Both wet and dry designs should be considered as well as the need for fission product sorbers.
- Determine impact of residual Al metal content in the ash on subsequent cementing operations and product performance.
- Establish the operating ranges of the incinerator during independent feeding of each different waste composition (i.e., GPT, SAC, wood framed HEPAs, and metal framed HEPAs).

- Prepare preconceptual and conceptual designs of the integrated shredder, incinerator, and off-gas system.
- Test a prototype shredder, incinerator, and off-gas treatment system with simulated TRU wastes. The shredder should have an optimized cutter configuration. The incinerator should have an improved ram and ash discharge design to reduce the ash/residue holdup within the primary chamber. The system should also have remote design features to permit operation and maintenance by master manipulators and an overhead crane.
- Perform radioactive verification testing of the integrated shredder, incinerator, and off-gas system.

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