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**TRANSURANIC (TRU)
WASTE MANAGEMENT PROGRAM**

**Nuclear Waste Incineration
Technology Status**

July 1981

Rockwell International
ENERGY SYSTEMS GROUP
ROCKY FLATS PLANT

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NUCLEAR WASTE INCINERATION
TECHNOLOGY STATUS

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ABSTRACT

The incinerators developed and/or used for radioactive waste combustion are discussed and suggestions are made for uses of incineration in radioactive waste management programs and for incinerators best suited for specific applications. Information on the amounts and types of radioactive wastes are included to indicate the scope of combustible wastes being generated and in existence. An analysis of recently developed radwaste incinerators is given to help those interested in choosing incinerators for specific applications. Operating information on U.S. and foreign incinerators is also included to provide additional background information. Development needs are identified for extending incinerator applications and for establishing commercial acceptance.

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SUMMARY

The Transuranic Waste Systems Office (TWSO) at Rocky Flats has the responsibility of providing assistance to DOE in coordinating development of technology for management of transuranic waste. The objective of this report is to provide a technical assessment of the status of radwaste incineration and define areas where additional technology development may be required.

In the past, incineration has been used both to reduce the waste volume and to convert combustible material to an ash which can be processed for actinide recovery. Two incinerators; one at LANL and one at Rocky Flats, have each operated for about 25 years in plutonium recovery operations. Many of the early incineration systems required extensive modification to improve performance or to achieve operational status. Information on the incinerators installed for radwaste use in the U.S. and foreign countries is provided in the appendices of this report. While some of these systems provided a valuable function and burned large volumes of waste, operation of many of the units was terminated because of operational problems and high maintenance requirements. Identification of the problems led to an extensive incinerator development and demonstration effort within DOE during the last decade.

This report includes a discussion of the need for radwaste incineration, the status of demonstration of the more recently developed combustion systems, an assessment of the incinerators for specific types of waste or areas of application, and identification of additional development needs.

A listing of the amounts of waste presently in storage and estimates of waste generation for the next 20 years for both defense operations and the commercial nuclear industry is presented in Selection 2.0, Waste Categorization and Quantities. For DOE, the presently available burial and storage capacity exceeds the projected accumulated volumes of TRU and LLW waste through the year 2000. However, two sites, LANL and ORNL, will have

generated more TRU waste volume than the retrievable storage capabilities presently available at those sites. The projected commercial waste volume generated by the year 2000 (4,800,000 m³), will exceed the presently available storage capacity (3,647,000 m³). Recent political actions and actions by some burial site operators may further reduce burial capacity and cause increased interest in incineration of these wastes. Other factors which will have an impact on the need for incineration of radwaste are increased costs of transportation and storage and the need to reduce hazards associated with transportation and storage of combustible materials.

The use of incineration in radwaste applications is somewhat more restrictive than a typical commercially available combustion system for municipal waste. Factors such as radiation protection for operators and maintenance personnel, containment of radioactive materials and nuclear criticality protection result in a more complex system design. Nine of the combustion systems recently developed for radwaste in the U.S. are discussed in Section 3.0, Incineration Technology. The nine systems are as follows:

- Acid Digestion - HEDL
- Agitated Hearth - RFP
- Controlled Air - LANL
- Cyclone Drum - MF
- Electric Controlled Air - SRL
- Fluidized Bed - RFP
- Molten Salt - RI
- Rotary Kiln - RFP
- Slagging Pyrolysis - INEL

While most of these units have undergone pilot and/or demonstration scale testing with suspect radwaste, three units; Agitated Hearth, Rotary Kiln, and Slagging Pyrolysis, have been designed for production operations based on information from the non-nuclear industrial applications. Each of the nine incineration systems were chosen for development or application

because they offered solutions to incineration problems at specific sites and appeared to be well suited in general for nuclear applications. The Acid Digestion unit, Electric Controlled Air, and Fluidized Bed Incinerators were specifically developed to accommodate high levels of fissile material. In selecting the Slagging Pyrolysis unit, the ability to accommodate unsorted waste with high concentrations of noncombustible was an important consideration. The use of commercially available incineration technology was important in selection of the Controlled Air and Agitated Hearth Incinerators. A low capital investment was a major objective of the Cyclone Drum Incinerator and in situ neutralization of acid gases was important to selection of the Molten Salt and Fluidized Bed systems. The operating characteristics of each of these systems is summarized in Table 3-1. The solid waste capacities of these systems vary from a low of 5 kg/hr for the Electric Controlled Air to a high of 850 kg/hr for the Slagging Pyrolysis. Some of the units have also been demonstrated suitable for combustible liquid processing. Although most of these systems have undergone extensive TRU waste testing with various feed components, there are two areas in need of additional development activity if they are to be used for incineration of wastes with B- γ activity. The ability of the offgas treatment systems to remove fission products will need to be demonstrated. Also remote operation and maintenance of the incinerator will have to be demonstrated if the system is to be used with high levels of B- γ activity.

A commercialization program for the Controlled Air Incinerator has been initiated which will include evaluation of fission product removal in the offgas system. Complete remote operation and maintenance has not been demonstrated for any of the nine combustion systems.

When an incineration system is being selected for a given application, the first considerations are that the unit can safely process the waste components at the desired capacity and produce the desired objectives of volume reduction and product form. The installed capital cost and the cost of operation and maintenance are secondary factors which can be used as

selection criteria among the systems which are technically suitable for a given application.

Capital cost information was obtained for each of the systems as installed (or projected installations). These costs were adjusted to 1979 dollars and are presented in Table 3-2. Some caution should be used with these estimates because considerable differences exist in the degree of instrumentation, nuclear criticality control and support equipment or facilities included in the cost figures. To obtain a more direct comparison of capital cost, each system was also estimated for a 45-kg/hr capacity using the 0.6 power rule. The installed capital cost for 45-kg/hr capacity varied from a low of \$1,100,000 for the Cyclone Drum Incinerator to a high of \$10,100,000 for the Electrical Controlled Air Incinerator. Selection of incinerators best suited for specific wastes and waste type is discussed in Section 4.0, Incinerator Selection.

Each of the nine combustion systems has been identified as a preferred candidate for one or more specific applications. Presented in Figure 4-1 and 4-2 is the waste incineration selection matrix for TRU and LLW respectively. For each site and waste specific application, one or more incineration systems have been identified as suitable candidates. Factors used in identifying preferred candidates were the waste component composition, activity level, fissile material content, capital cost, desired capacity, and final product form. Information on operating and maintenance cost for the systems were not available for this report and could become major factors in selection of a process for a specific site.

The incineration technology appears to be well developed for most of the TRU applications. Further development for TRU waste should be undertaken only for well defined specific needs. Commercialization of the technology is needed and is expected to require some experimental testing or demonstration in addition to a considerable amount of consulting and design review work. This is presently being pursued for the Controlled Air

Incineration system and may be needed for other systems. An effort should be made to obtain and document the nuclear safety and operating information on the systems suitable for higher levels of fissile material content waste.

1.0 INTRODUCTION

1.1 Purpose and Scope

Nuclear operations of all kinds produce a variety of wastes. These wastes have been principally managed either by disposing of them in shallow land burial or by placing them into interim storage awaiting further processing and/or disposal. A significant portion of these wastes are combustible, ranging, on the average, from 25 to 50 volume percent, depending on the operation. Incineration of these combustibles could be of benefit to nuclear waste management. This report examines the status of incineration technology within the Department of Energy (DOE) for treating combustible nuclear wastes. Waste incineration processes are described briefly along with a summary of current development status and potential applications. Existing and projected future nuclear waste volumes are discussed along with a discussion of the impact that incineration could have in reducing these waste volumes.

1.2 Nature of the Problem

Nuclear wastes are categorized and classified in a number of ways. The most common system has three principal categories; high level waste (HLW), low level waste (LLW), and transuranic waste (TRU). High level waste results from processing of irradiated reactor fuel. It is, by definition, the raffinate waste from the first cycle of fuel reprocessing. It contains the vast majority of the fission products in the fuel and a small amount of transuranic elements. However, the TRU content is high enough that the waste should be isolated from mans environment for a long period of time. High level waste exists either as liquids or solidified sludges and salt cakes, and is not a combustible waste stream. All combustible wastes fall into the LLW or TRU category. Transuranic wastes are defined as waste materials contaminated with transuranic elements or ^{233}U in amount producing 10 nCi/gm or more of alpha activity. The remainder of the wastes are classified as LLW.

Long-term management plans call for HLW and TRU to be isolated from the biosphere in mined geologic repositories. These wastes are currently held in interim storage. Complete specifications for TRU waste forms acceptable for such geologic isolation are not yet available. Preliminary specifications suggest that over a given percentage of combustibles may not be acceptable and that wastes may have to be chemically inert. The ash resulting from incineration can be readily converted into very inert forms. These potential requirements provide the major impetus to development of incineration technology for TRU wastes. Additional benefits of incineration of TRU wastes include large volume reduction factors and elimination of fire and gas generation potential.

Low level waste is managed by disposal in shallow land burial. Low level waste with high specific activity is also being placed in intermediate depth storage (approximately 50 m). This is a satisfactory management method for low level waste including combustibles, but the availability of burial space, especially for wastes from commercial and institutional sources, is rapidly diminishing. The volume reduction provided by incineration of combustible LLW would greatly ease this capacity problem.

2.0 WASTE CATEGORIZATIONS AND QUANTITIES

2.1 Waste Categories

Wastes contaminated with radioactivity have been classified into many categories in the past with the results generally reflecting the primary interest of the persons or agency making the classification. Some of the historical categorizations are:

- 1) DOE and commercial;
- 2) newly generated, stored, and buried;
- 3) TRU and LLW;
- 4) contact handled and remote handled, reflecting beta-gamma activity;
- 5) combustible and non-combustible; and
- 6) material content, such as paper, rags, or plastics.

Each of these categories can be further subdivided as follows:

A. Source of Generation

1. DOE

Weapons Production
Energy Research

2. Commercial

Power Generation
Fuel Fabrication
Research and Industrial Applications

3. Institutional

Hospitals
Universities

B. Time of Generation

1. Present Generation
2. Future Generation
3. Stored-Retrievable
4. Buried

C. Alpha Activity

1. TRU (>10 nCi/gram activity from TRU elements)
 High Fissile Content (glove box generated waste)
 Low Fissile Content (non-glove box generated waste)
2. LLW (<10 nCi/gram)

D. Beta-Gamma Activity

1. Contact Handled (<200 mR/hr surface radiation)
2. Remote Handled (>200 mR/hr surface radiation)

E. Material Content

1. Paper
2. PVC Plastic
3. Other Plastic
4. Rubber
5. Wood
6. Organic Resins
7. Filters
 Cartridge
 HEPA
8. Leaded gloves
9. Organic Liquids

- 10. Carbon
 - Graphite
 - Filter Media

- 11. Cloth
- 12. Leather
- 13. Biological Wastes
- 14. Scintillation Vials

2.2 Waste Inventories and Storage Capabilities

To evaluate the volume of nuclear waste available for processing, one has to consider the amount that presently exists in storage, the amount currently being generated, and finally estimating the amount that will be generated in the future. Each of these categories will be discussed in the following sections of this report.

2.2.1 Existing Inventory¹

Combustible waste generated from the early atomic energy research, development, and production operation were placed in ground burial. In 1970, the transuranic contaminated wastes were placed in retrievable storage, and in the future the transuranic waste will be placed in a permanent repository. As the waste storage methods become more sophisticated, waste volume reduction methods become more attractive. However, each of these storage conditions, as well as the present generation of defense and commercial waste, represent considerably different processing requirements. For example, although INEL has several times the volume of stored TRU waste relative to SRP, the waste at SRP contains twice the number of curies that are stored at INEL.

2.2.1.1 DOE Buried Wastes, TRU, and LLW

In 1970, the AEC (now DOE) initiated a new policy directing that newly generated TRU wastes be segregated and stored so that they could be retrieved intact and in an uncontaminated condition for at least 20 years. Prior to this policy, TRU waste and LLW were routinely placed in shallow land burial. The volumes of buried TRU waste at major DOE sites are shown in Table 2-1. Volumes of LLW buried at major DOE sites are shown in Table 2-2. Records of waste burial are not as precise as those for storage, and hence the uncertainties are much higher. The volumes shown are best estimates of the initially buried waste volume. They do not

TABLE 2-1 ESTIMATED BURIED TRU WASTE VOLUME AT MAJOR DOE SITES

Site	Volume Buried* m ³
Hanford Site	225,000
Idaho National Engineering Laboratory (INEL)	57,000
Los Alamos National Laboratory (LANL)	11,500
Nevada Test Site (NTS)	5,700
Oak Ridge National Laboratory (ORNL)	6,300
Pantex Plant	30
Sandia National Laboratories (SNL)	10
Savannah River Plant (SRP)	27,000
Estimated Total Buried TRU Waste:	330,000 m ³

*Excludes about 11 million m³ of TRU and Fission Product contaminated soils resulting from liquid waste disposal, containing over 200 kg of Pu (mostly Hanford). In addition, there are about 3 million m³ of contaminated soils resulting from accidental discharges of spills; the amount of this soil that is contaminated with over 10 nCi/g of transuranics is under investigation.

TABLE 2-2 ESTIMATED BURIED LLW VOLUME AT DOE SITES

Site	Volume Buried Prior to FY 80 m ³
Hanford Site	464,800
INEL	117,000
LANL	115,300
NTS	57,020
ORNL	192,000
SNL	1,336
SRP	336,500
Others	436,900
Total	1,760,856

include any soil contaminated through the rupture or corrosion of containers in the ground, which is estimated to be approximately 1.4 times the initial buried waste volume. Exhumation would likely require repackaging, which would affect volume and handling requirements.

2.2.1.2 DOE Wastes 1970 to 1980

Table 2-3 gives the inventories of contact handled and remotely handled TRU waste held in retrievable storage at major DOE sites. In addition, there are usually small quantities in staging areas at various other site awaiting shipment to one of the major storage sites.

TABLE 2-3 RETRIEVABLY STORED TRU WASTE AT MAJOR DOE SITES	
Site	Stored Inventory m ³
CONTACT HANDLED (CH)	
Hanford Site	8,000
INEL	40,000
LANL	3,500
NTS	240
ORNL	400
SRP	2,400
Estimated Total Stored CH TRU Waste:	~54,500 m ³
REMOTELY HANDLED (RH)	
Hanford Site	<20
INEL	20
LANL	70
ORNL	790
Estimated Total Stored RH TRU Waste:	~900 m ³
Total	55,400 m ³

2.2.1.3 Waste at Commercial Sites to 1980

DOE facilities and commercial TRU waste generators have shipped wastes to five of the six commercial waste disposal sites in the United States. (Barnwell, South Carolina, has always prohibited the burial of TRU waste.)

In the past, no regulation required separation of TRU waste from the other wastes buried at the commercial sites. However, the TRU content and the total volume of the buried waste is known. The TRU content ranges from 3.6 kg at West Valley, New York, to 69.1 kg at Maxey Flats, Kentucky. Of the 668,000 m³ of buried waste, 363,000 m³ is suspected to contain transuranics and only 20% of this volume is expected to contain greater than 10 nCi/g TRU. Since February 1980, there has been no commercial site licensed to receive TRU waste for burial.

Table 2-4 lists the commercial disposal sites, volumes of buried waste, volumes of wastes which may contain TRU, and Mass of TRU elements present.

TABLE 2-4 ESTIMATED WASTE AT COMMERCIAL BURIAL SITES AS OF JANUARY 1, 1980

Site	Buried Volume Total m ³	Suspect TRU m ³	Mass of TRU Elements kg
Barnwell, South Carolina	269,300	0	0
Beatty, Nevada	73,898	58,054	14.3
Maxey Flats, Kentucky	135,287	135,287	69.1
Richland, Washington	35,844	16,238	23
Sheffield, Illinois	86,701	86,701	13.4
West Valley, New York	66,521	66,521	3.6
Total	667,551	362,801	123.4

2.2.2 Projections of Future Inventory¹

Table 2-5 and 2-6 give the projected rates of TRU waste and LLW generation respectively at DOE facilities in the next 20 years, based on scheduled operations, research, and facilities decontamination. Uncertainties are large, because of the difficulty in projecting both weapons production schedules and research activities very far into the future. Furthermore, even when trends are correctly forecast, the amounts generated in any single year can vary greatly from the average because of the startup or completion of research projects, the decontamination of equipment or facilities, and accidents that may generate TRU waste.

TABLE 2-5 PROJECTED ANNUAL DOE TRU WASTE GENERATION

Site	Average Generation Rate 1980-2000 (m ³ /yr)
CONTACT HANDLED (CH)	
Argonne National Laboratory (ANL)-East	180
Battelle, Columbus Laboratories (Battelle-C)	40
Bettis Atomic Power Laboratory (Bettis)	<10
Hanford Site	470
INEL	110
LANL	550
Lawrence Livermore National Laboratory (LLNL)	25
Lovelace Biomedical and Environmental Research Institute	<1
Mound Facility (MF)	560
ORNL	70
Paducah Gaseous Diffusion Plant	1
Rocky Flats Plant (RFP)	1,700
SNL	5
SRP and Laboratory	150
Projected Annual CH TRU Waste Generation:	≈3,900
REMOTELY HANDLED (RH)	
ANL-East	10
Hanford Site	<740
INEL	5
LANL	10
ORNL	75
SNL	3
Projected Annual RH TRU Waste Generation:	≈800
Projected Total Annual DOE TRU Waste Generation:	≈4,700 m ³

TABLE 2-6 PROJECTED ANNUAL DOE LLW GENERATION

DOE Field Office	Average Generation Rate 1980-2000 m ³ /yr
Albuquerque	15,520
San Francisco	4,030
Chicago	2,450
Idaho	4,750
Nevada	1,360
Oak Ridge	7,990
Pittsburgh N.R.	2,450
Richland	12,940
Savannah River	16,110
Schenectady N.R.	1,700
Total	69,300

Figures 2-1 and 2-2 show the existing inventory of DOE TRU waste and LLW respectively, and the inventory projected to accumulate between now and the year 2000, assuming that current, or similar, management practices continue to that time. The horizontal line represents the buried waste; the sloping line shows the growth in total inventory from increases in waste. When a permanent repository becomes available, the inventory of stored TRU waste will cease growing and will gradually diminish. The volume of buried waste would be reduced if exhumation began at any of the sites. The total volume could be further reduced by processing the waste. The bulk of the remotely handled TRU waste volume projected for the next 20 years will be generated by the Fast Flux Test Facility (FFTF) at Hanford, Washington.

At the present time, DOE has authority and responsibilities only for the management of government generated wastes and to provide generic support to commercial waste management technology. In the future, it is possible that commercial waste may have to be managed by the DOE. In this event, commercial waste would be handled in the same manner as DOE waste. Should spent fuel be reprocessed, the volume of waste to be managed will depend on the number and the capacity of commercial nuclear power plants. Several fuel cycles and a wide range of nuclear power capacities are possible. The once-through uranium cycle, which is now used in U.S. commercial power reactors, requires no spent fuel reprocessing, and therefore, minimizes waste generation. The uranium recycle and the uranium-plutonium recycle fuel cycles do involve reprocessing and generate TRU waste and LLW.

The NRC is likely to require permanent isolation of newly generated commercial TRU waste. The volumes of commercial TRU generation, which may require retrievable storage followed by processing and disposal, are projected in Figure 2-3. The upper estimate assumes spent fuel reprocessing, and is based on the maximum nuclear power capability likely to existing in the United States by the year 2000. The lower estimate assumes a once-through uranium cycle and represents wastes from expected decontamination of commercial facilities, research, and commercial uses of transuranics. Projected volumes of commercial LLW are shown in Figure 2-4.

Figure 2-1 Inventory of TRU waste at DOE sites.

Figure 2-2 Inventory of LLW at DOE sites

Figure 2-3 Projected volumes of stored commercial TRU waste.

Figure 2-4 Projected volumes of commercial LLW

The capacity of the commercial burial sites may not, however, be the most significant factor in continued commercial LLW disposal. Recently the South Carolina state government mandated a 25% reduction in waste volume accepted in 1981 and a 50% reduction in 1982 at the Barnwell disposal site. Incineration of combustibles would result in far more effective utilization of this reduced capacity.

Usable commercial capacity may be further reduced due to a recently passed initiative in the state of Washington, the location of the Hanford disposal site. This initiative bans the receipt of any waste generated outside the state, unless the generating state has joined in a regional compact with Washington State starting in mid 1981. This initiative will likely force a larger burden on the other two sites, again emphasizing the need to use the capacity at those sites as effectively as possible. Implementation of commercial waste incineration could result in a reduction in commercial waste volume. It is difficult to exactly assess the percentage of commercial waste that is combustible, but a figure of 50% could be used to estimate the waste volume reduction possible through incineration. The volume reduction obtained by incineration is dependent on the degree of compaction of the feed stream and on the product form required. If immobilization of the ash is required for transportation and storage, the weight and volume reduction may be less.

2.2.3 Capacities and Effect of Incineration¹

Table 2-7 shows the amounts of wastes accumulated by 1980, the projected generation rates, the estimated accumulated volume by 2000, and the total capacities of present sites for stored DOE TRU waste, DOE LLW, and commercial LLW. The capacity for DOE to store TRU waste is sufficient for well over 50 years at present generation rates, except for selected sites such as ORNL, which would fill if transportation of TRU wastes was not allowed. If expansion of DOE LLW and commercial waste sites into presently available areas is allowed, these wastes also have enough room for burial through the year 2000.

TABLE 2-7 SUMMARY OF WASTE VOLUMES

Waste	End of 1980 Volume m ³	Average Generation Rate m ³	Volume By 2000 m ³	Capacity m ³
DOE TRU	55,400	4,700	149,400	750,000
DOE LLW	1,847,000	69,300	3,233,000	>5,000,000* ²
Commercial Waste	761,000	≈202,000* ¹	4,800,000	3,647,000* ³

*¹Predicted rate is actually not linear.

*²Exact volume not defined since several sites have significant undeveloped capacity.

*³Commercial capacity if expansion is allowed will be 15,000,00 m³.

Radioactive waste inventories represent an extremely heterogeneous group of liquid and solid materials with physical and chemical properties varying over a wide compositional range.

Estimates of the percentage of combustibles, by volume, generally range from 25 to 50%. These estimates vary from site to site and also depend on estimated compaction factors and whether volumes "as generated" or "after compaction" are used. One estimate² of fuel cycle solid waste volume distribution at SRP showed 72% low level plus TRU combustibles.

An example of the effect of incineration on stored TRU waste volumes is shown in Figure 2-5. The effect of incinerating only the newly generated combustible waste and for incinerating both newly generated and previously stored combustible wastes are shown. For these lines, 25% of the wastes are assumed to be combustible and a reduction factor of 20:1 is assumed for storage of ash and off-gas treatment products as compared to the original combustible waste volume. The stored waste is assumed to be incinerated over a 20-year period. A fourth line on Figure 2-5 shows the effect of incinerating newly generated and stored TRU waste if 50% of the waste volume is assumed to be combustible.

Figure 2-5 Effect of Incinerating DOE TRU wastes.

The total capacity of storing TRU waste over the period 1980-2000 is adequate. The capacity remaining at the seven major DOE storage sites is more than 745,000 m³, and exceeds 10⁷ m³ if undeveloped, but accessible, storage areas are included. The volume of TRU waste that will be generated between now and the year 2000, even the volume projected by high estimates, is less than 500,000 m³. Thus, even if the DOE becomes responsible for commercial TRU waste and the high estimate of TRU waste generation from uranium-plutonium recycle proves to be correct, additional storage sites would not be required. This conclusion excludes political considerations, and depends on the assumption that storage space is interchangeable, i.e., that storage space at NTS can be used as easily a storage space at Hanford. A look at the capacity of individual sites, however, does show an impending shortage of space at ORNL (see Table 2-8).

TABLE 2-8 RETRIEVABLE STORAGE CAPACITY FOR TRU WASTES (1980)

Site	Projected Storage Rate m^3/yr	High-Estimate	Present Available Capacity m^3
		20-Year Capacity Needed m^3	
Hanford Site	1,200	30,000	285,000
INEL	2,600	65,000	270,000
LANL	580	14,600	12,350
NTS	25	600	175,000
ORNL	150	3,800	1,200
Pantex Plant	1	2	100
SRP	150	4,500	6,350
Total	4,700	118,500	750,000

The DOE has always intended the retrievable storage of TRU waste to be an interim measure, pending the availability of a permanent repository. Retrievable storage can be continued, however, until DOE policy changes or environmental analyses dictate otherwise. If necessary, waste in weakened containers could be repacked to extend storage life. The burial grounds containing TRU waste are routinely monitored, and no hazard exists to ground water aquifers. This practice will continue until the environmental impacts of long-term management options for the buried waste are evaluated. The DOE plans to implement long-term waste management practices as soon as the technology is demonstrated and the environmental impacts are evaluated.

3.0 INCINERATION TECHNOLOGY

3.1 Background

Incineration is defined as the act of burning to ashes or the procedure of heating organic substances with free access to air until only ashes remain. There are essentially two types of incineration. These are burning with an open flame where an excess of oxygen is supplied, and starved air incineration where less than the stoichiometric amount of oxygen is supplied. The different incinerator types now in use come from attempts to improve the contact between air and combustibles, alternate ways of heating the materials to combustion temperature, and various ways of treating the off gases. Acid digestion is a special case where an oxidizing agent other than air is used.

Open flame burning is the oldest form of incineration used by man. Open pit and natural draft burning are simple examples of this technique. Improvements to open pit burning induce more complete incineration by increasing the contact between the oxidizing air and the combustibles. These improvements include open grates which allow the air to flow up through the combustibles or stirring mechanisms in the agitated hearth, multiple hearth, and moving grate type incinerators. Agitation is supplied by a continuous tumbling action in a rotary kiln incinerator. The fluid bed and molten salt incinerators use the agitation of the air moving through the bulk medium.

Partial pyrolysis (decomposition and release of combustible gases) is achieved in starved air incineration by sealing the incineration chamber and controlling the amount of air fed into the chamber. Pyrolysis incinerators produce ash with a larger carbon content than with open burning, but have the advantage of less ash in the off-gas stream. The pyrolysis incinerators often have one or more secondary chambers where excess air is added to burn the pyrolysis gases. The controlled air and electric air units are operated close to stoichiometric or slightly substoichiometric

air in primary burning chambers followed by excess air in the secondary burning chambers.

Many methods can be used to heat the combustibles to a temperature at which incineration can take place, but there are two general classes. These are direct fired incinerators and indirectly fired incinerators. In a direct fired incinerator oil, gas, or some other fuel is burned in the chamber to bring the incinerator up to operating temperature and to supplement the trash burning if required. The agitated hearth, controlled air, cyclone drum, and rotary kiln incinerators use this type of firing. The indirectly fired incinerators are heated from outside the combustion chamber. The electric controlled air and acid digestion units use indirect heating. The fluidized bed and molten salt incinerators use a combination of these.

Many of the differences in incineration units are prompted by different ways of treating the off-gases. For instance, the fluidized bed and molten salt incinerators neutralize acidic off-gases in the bed materials. They have dry off-gas systems using sintered metal or bag filters. Most incinerators must use wet scrubbing systems to remove the acidic gases from the off-gas stream. These usually include a caustic scrubber to neutralize the acidic gases. All radioactive waste incinerators also include one or more stages of HEPA filtration for final particulate removal.

3.2 Previous Experience

A wide range of incineration systems have been installed for radioactive use in the U.S. and foreign countries. While some of these systems have been successful in processing large volumes of waste and serving a needed function, many problems in operation and maintenance have been identified.

3.2.1 Benefits and Problems

The incineration of radioactive wastes was begun in the U.S. in the early 1950's in what was then the Atomic Energy Commission (AEC) weapons facilities. Private companies engaged in fuel fabrication launched incineration activities at about the same time. Incineration has proven to be a successful method to reduce both the volume and weight of bulky combustible wastes. Volume reductions of 40 to 1 and weight reductions of 10 to 1 are both common in various incineration methods. The earlier incinerators were relatively simple in design, with most featuring one or two combustion chambers that were either natural gas or electrically heated to temperatures ranging from 800° to 1200°C. Some, such as the LANL basket incinerator, were small capacity units designed for plutonium recovery operations. The LANL unit was operated very successfully for this application for a period exceeding 25 years, with only one major rebuilding operation. Other larger units, such as the 20-kg/hr Rocky Flats incinerator, burned large volumes of radwaste, but did require a relatively high amount of maintenance. The long operating history of these units have proven the value of incineration for (1) weight and volume reduction, (2) elimination of flammable and/or pyrophoric materials, and (3) conversion of bulky combustibles to a form amenable to actinide recovery operations.

Operation of the early incinerators was not without problems, and many units were modified or completely replaced to improve performance or to achieve operational status. Some of the early units were of a small scale, designed for minimal throughputs of recoverable wastes. These small units were generally more successful than larger units designed for greater capacities of wastes of diverse material content.

Problems with these early units were varied, but most of the problems were in the areas listed below:

- 1) Contamination containment
- 2) Equipment corrosion

- 3) Short refractory life
- 4) Mechanical failures
- 5) Incomplete combustion
- 6) Off-gas cleanup
- 7) Criticality control
- 8) Fires and explosions
- 9) Operational complexities
- 10) Maintenance complexities

The problems associated with nuclear waste incineration were, in many cases, the same as those associated with other industrial or municipal incineration operations. It became obvious, however, that these problems grew in magnitude when radioactive contamination containment and criticality control were added to the incinerator requirements. Other problems proved to be a result of the nature of the material content of the individual radwastes. Common examples of this type of problem were:

- 1) The high ratio of PVC plastics (≈ 40 wt/%) in radwastes that decompose to HCl during incineration. This has been a significant factor in the high metal corrosion rates in many incinerators.
- 2) Leaded gloves, lead tape, and small pieces of lead shielding in the combustible wastes form glassy compounds that attack refractory and reduce the life.
- 3) Many radwaste combustibles have been exposed to acids and/or solvents and become pyrophoric by the time they reach an incineration process. This fact has contributed to fires and explosion problems in sorting and feeding areas. The presence of acid on combustibles also adds to the metal corrosion problems.
- 4) The radioactivity of the waste necessitates a containment system that is not necessary in other conventional incineration operations. The containment system contributes to mechanical complexities, sealing complexities, cooling problems, and maintenance difficulties.

- 5) The possibility of a criticality excursion is another concern unique to nuclear waste incineration. Many prohibitive design and operational restraints must be imposed to insure a critically safe operation.

Finding solutions to these problems has been the focus of recent research on radwaste incinerators.

3.2.2 Radwaste Incinerators

The major incinerators used by both DOE (AEC and/or ERDA) and commercial companies are listed below. Additional information on these incinerators is tabulated in Appendices A and B.

United States Radwaste Incinerators³

Argonne National Laboratory - single chamber, gas fired
ARHCO - dual chamber, moving grate
Babcock and Wilcox - single chamber
Babcock and Wilcox - dual chamber, gas fired
Nuclear Fuel Division
Bettis Atomic Power Laboratory - single chamber, cyclone air feed
Douglas United Nuclear - natural draft, open bit burning
G.E. Atomic Power Equipment Dept. - Triple chamber, gas fired
G.E. Nuclear Fuel Plant - vortex burner, gas fired
Goodyear Atomic Corp. - dual chamber, gas fired
Gulf General Atomics - dual chamber, gas fired
Kerr-McGee Nuclear Corp. - dual chamber, gas fired
Knolls Atomic Power Laboratory - single chamber, pure O₂
LANL - single basket, electrically heated
Metals and Controls-----
Mound Facility - single basket, electrically heated
National Lead of Ohio - dual chamber, gas fired
Nuclear Fuel Services - dual chamber, gas fired
ORNL (K-25) - dual chamber, gas fired

ORNL (Y-12) - single chamber, gas fired
Pratt and Whitney Aircraft-----
RFP - dual chamber, gas fired
Shippingport Atomic Power Station - cyclone air feed
United Nuclear Corp. - single chamber, gas fired
U.S. Army Nuclear - dual chamber, cyclone air feed
Defense Laboratory
Westinghouse Nuclear - dual chamber, excess air burner
Fuel Division
Yankee Rowe Atomic Electric Co. - cyclone air feed

During the same time period that the U.S. radwaste incinerators were being developed and becoming operable, a number of foreign countries were also launching incineration projects. Foreign counterparts paralleled U.S. experience in that many units required modifications and/or rebuilding to achieve operational status or increase throughput. Maintenance was generally high, but still the advantages of incineration were sufficient to spur the continuation of operations. A list of past and present foreign radwaste incinerators follows. These incinerators are further described in Appendix C.

Foreign Radwaste Incinerators⁴

United Kingdom

Harwell, Berkshire - single chamber, gas fired
Windscale, Cumberland - four chamber, electrically heated

France

Cadaroché Nuclear Study Center - dual chamber
Fontenay-Aux-Roses (CEN-FAR) - dual chamber, oil and propane
fired
National Center for Scientific Research - dual chamber, oil fired
(CNRS), Strasbourg, Cronenbourg

Marcoule Center of Plutonium Production - triple chamber, gas fired, Bagnols-sur-Ceze
Center of Nuclear Studies - dual chamber, Genoble (CEN-G)

Belgium

Belgium Nuclear Center - triple chamber, gas fired, Mol (CEN)
Belgium Nuclear Center - slagging type, dual chamber, Mol (CEN)

Republic of Germany

Karlsruhe Nuclear Research Center - dual chamber, electrically preheated,
Julich Nuclear Research Center - dual chamber, controlled air.
Nukem, Hanau Ger. - agitated pyrohydrolysis

India

Bhabha Atomic Research Center - dual chamber, oil fired, Trombay

Japan

Japanese Atomic Energy Research Institute - dual chamber, oil fired (JAERI), Tokai
Oarai Research Establishment - four chamber, oil and gas fired (JAERI), Oarai

Canada

Chalk River Nuclear Laboratories - dual chamber, gas fired (CRNL), Ontario

Most of the U.S. and foreign incinerators listed were patterned after commercial industrial units in use at the time. Modifications were necessary, of course, to provide for alpha, gamma, and neutron containment; removal of radioactive particulate from off-gases; and criticality safety. From the record of modifications and rebuilding operations, it became apparent that many conventional incinerators were not well suited to radwaste incineration. Consequently, people in DOE and industry began

formulating incineration systems specifically for nuclear wastes. Some systems were based on a proven commercial system, while others were completely new designs. All attempted to provide the unique requirements for radwaste incineration as an integral part of the design. In the U.S. there were several such incinerators designed and tested in the 1970's that are now ready for practical application. Most of these units were funded by DOE and built and tested in DOE facilities; however, two strictly commercial designs are also being considered for nuclear applications. A list of these radwaste specific incinerators is shown below:

- Atomics International Molten Salt - original design
- HEDL Acid Digestion - original design, chemical oxidation
- INEL Slagging Pyrolysis - Andco-Tarrax modified commercial design
- LANL Controlled Air - Environmental Control Products modified commercial design
- Mound Facility Cyclone Drum - original design
- RFP Fluidized Bed - original design, catalytic combustion
- RFP Rotary Kiln - Raymond/Bartlett-Snow modified commercial design
- RFP Agitated Hearth - Envirotech modified commercial design
- SRP Controlled Air - Environmental Control Products modified commercial design
- SRP Electric Controlled Air - original design

These incinerators, except the SRP controlled air, are discussed in the next section. The SRP unit is patterned after the LANL controlled air incinerator and will possess the same general characteristics, excepted for a greater capacity.

3.3 Characteristics and Capabilities of Recently Developed Incinerators

The operating characteristics of the incinerators most recently developed and studied for specific application to radwaste (listed in the last section) are discussed in this section. A brief comparison of the

TABLE 3-1
PROCESS CHARACTERISTICS OF RECENTLY DEVELOPED TRU INCINERATION SYSTEMS

	ACID DIGESTION	AGITATED HEARTH	LANI CONTROLLED AIR	CYCLONE DRUM	ELECTRIC CONTROLLED AIR	FLUIDIZED BED	MOLTEN SALT	ROTARY KILN	SLAGGING FLYASH SYSTEMS
INCINERATION	HEDL	RFP	LANI	MOUND	SRL	RFP	NONE INSTALLED AT NUCLEAR SITE	RFP	PLANNED FOR INHL
Process Description	Waste is chemically oxidized in sulfuric acid containing a small percent nitric acid. Acid is evaporated to produce revidun product.	Waste is batch fed into primary chamber. Residue is raked by rotating rabble arm. Final offgas combustion in separate afterburning chamber.	Waste is decomposed in starved air primary chamber. Volatiles and particulate are final burned in secondary chamber.	Waste is burned in steel storage drum with air injected in spiral pattern to cool drum walls. Continuous feed option is available.	Waste is decomposed in starved air primary chamber. Volatiles and particulate are final burned in secondary chamber.	Waste is fed to fluidized bed of Na_2CO_3 granules for partial combustion. Volatiles are final oxidized in fluidized bed of catalyst granules.	Combustion in bed of molten Na_2CO_3 . No second stage combustion. Ash is contained in solidified salt cake upon cooling.	Waste is charged into inclined, horizontal kiln that is rotating. Final offgas combustion in separate afterburning chamber.	Stacked kiln concept. Waste loaded in top drying zone, descends into pyrolysis zone, descends into melt zone, to be discharged as molten slurry.
Unique Capabilities	Produces soluble inorganic sulfate and oxide residue for Pu recovery. Acid recycle.	Positive agitation of waste for complete combustion. Automatic ash discharge system.	Features commercial equipment. Little ash is entrained in offgas.	Provides capability to incinerate waste in storage drum, without sorting or pretreatment.	Electrically heated. Slow gas flows entrain little ash in offgas.	Neutralization of acids in fluidized bed of Na_2CO_3 . Dry offgas system. No refractories.	Neutralization of acids in molten bed of Na_2CO_3 . Dry offgas system, if possible.	Positive agitation of waste for complete combustion. Automatic ash discharge system.	Produces slag-type residue that requires no further fixation. Will accept noncombustibles.
Design Capacity (kl/hr)	10	70	45	27	5	82	50	41	850
Operating Temperatures	250°C	800-1000°C	800-1100°	1100-1300°C	400-1000°C	500-600°C	800-900°C	800-1000°C	800-1650°C
Raw Materials Required	Sulfuric acid, nitric acid, scrubber caustic.	Scrubber caustic.	Scrubber caustic.	Scrubber caustic.	Scrubber caustic.	Na_2CO_3 and Cr_2O_3 catalyst.	Na_2CO_3 and Na_2O_4 .	Scrubber caustic.	Bark, coal, and soil (possibly Na_2CO_3).
Auxiliary Heat Required	Second chamber and acid evaporator are electrically heated.	Fuel oil fired for heatup and as needed during operation.	Gas fired for heatup and as needed during operation.	Fuel oil fired for heatup. None during operation.	Electrically heated.	Heatup with electrically heated air and methanol fuel. None during operation.	Propane fired for heatup. May require coke to maintain temperature.	Fuel oil fired for heatup and as needed during operations.	Fuel oil fired for heatup and as needed during operation.
Waste Pretreatment	Sort out noncombustibles. Double, fine shredding.	Size reduce to less than 1 ft ³ .	Sort out noncombustibles.	None required for in-drum batch burning.	Sort out noncombustibles. Medium shredding.	Sort out noncombustibles. Coarse and fine shredding.	Sort out noncombustibles. Extra fine shredding.	Size reduce to less than 1 ft ³ .	Sort and blend in coal and bark. Size to <2 ft.
Waste Feed System	Ram feeder.	Ram feeder.	Ram feeder.	None.	Ram feeder.	Screw feeder.	Pneumatic feeder.	Ram feeder.	Mech. arm feeder.
Product Removal System	Residue slurry intermittently air-lifted from reaction chamber.	Ash raked out by rabble arm at finish of batch run.	Gravity ash dropout and pneumatic transport.	Ash remains in drum. Can be removed by vacuum transfer.	Batch gravity discharge.	Continuous gravity discharge to screw conveyor.	Periodic draining of salt-ash mixture.	Continuous ash removal by rotation of inclined kiln.	Periodic draining of slag product.
Product Form	40% mineral ash, 60% sulfates.	Low carbon, mineral ash.	Low carbon, mineral ash.	15% carbon, mineral ash.	5% carbon, mineral ash.	47% mineral ash, 50% Na_2CO_3 - NaCl - Na_2O_4 , 12% carbon, 11% catalyst.	25% mineral ash, 60% Na_2CO_3 , and 15% NaCl .	Low carbon, mineral ash.	Metallic oxide mixture.
Offgas System	Two packed scrubbers, acid fractionator for recycle, HEPA filters. HCl vent.	Two-stage venturi scrubbing, HEPA filters.	Quench column, venturi scrubber, packed column scrubber, HEPA filters.	Deluge tank, venturi scrubber, demister, HEPA filters.	Venturi quench, fibrous-bed scrubber, packed bed contactor, HEPA filters.	Cyclone separators, sintered metal filters, HEPA filters.	Mist eliminator, water cooler, bag filters, HEPA filters.	Two-stage venturi scrubbing, HEPA filters.	Spray dryer, sintered metal filters, H_2O_2 reactor, HEPA filter.
Materials of Construction	Glassed lined steel.	Refractory lined steel.	Refractory lined steel.	Steel drum, refractory lined header.	Refractory lined steel.	316/304 stainless steel.	Refractory lined steel.	Refractory lined steel.	Refractory lined steel.
Criticality Control	Geometrically safe.	Administrative.	Administrative.	Administrative.	Administrative.	Administrative.	Administrative.	Administrative.	Administrative.

nine units is presented in Table 3-1, that gives the reader a quick review of each unit's operation. The following sections discuss each incinerator separately. This discussion treats the waste handling capabilities (including capacity), acceptable waste size, and ability to handle various waste types. The ability to handle varying radioactivity levels and allow actinide recovery, and the remotability are also discussed. Major advantages and disadvantages are then listed and potential applications of each incinerator are given.

3.3.1 Acid Digestion (HEDL)^{5,6,7}

Solid Waste Capabilities

The process has been demonstrated with paper, rags, wood latex rubber, Hypalon rubber, Neoprene rubber, PVC plastic sheet, ion exchange resins, and polyurethane plastic sheet. Fluorinated wastes cause corrosion to the glass lined equipment.

Capacity

The original processing rate was about 3.0 kg/hr, but a new high-rate digester has been added to increase the capacity to 10 kg/hr.

Waste Size

Waste must be shredded to approximately 1/2 in. size prior to ram feeding into the digester. Double shredding is some times required to avoid stringy material. The shredder will accept waste up to 1 ft by 2 ft in size.

Noncombustibles

Waste is hand sorted to remove noncombustibles prior to shredding. An air classification system is employed to remove tramp metal from the

shredded waste. Small pieces of metal that may inadvertently reach the digester are slowly dissolved into the acid; acid-resistant materials must be periodically removed.

Moisture Content

The unit can accommodate damp combustibles. Free water would be undesirable in the waste shredding area.

Acid Producing Solids

The system is resistant to acids produced by PVC plastic, etc. Not all acids are recovered in the off-gas scrubbing system, however, and some nitric and hydrochloric vapors are vented to the atmosphere.

Volatile Solids

The low temperature operation (250°C) does not promote volatilization, and most volatile materials will be decomposed and dissolved into the acid system.

Liquid Waste Capabilities

The processing of organic liquids by acid digestion is somewhat limited because the noncombustible and volatile liquids vaporize and leave the digester with the off-gas. Vacuum pump oil and tri-n-butyl phosphate have been digested, but normal paraffin hydrocarbons are not processed at present.

Capacity

Unknown.

Acid Producing Liquids

Unknown.

Aqueous Liquids

The process can accept water and aqueous waste and a capacity of 20 kg/hr of water has been demonstrated.

Radioactive Waste Capabilities

Design Potential

The system was designed to process TRU and LLW containing plutonium ranging from very low levels to kilogram quantities.

Nuclear Safety

The facility at HEDL is designed in dimensions safe for multi-kilogram quantities of plutonium. Administrative control is utilized to hold the actual fissile material inventory below 2 kg.

Degree of Automation

The equipment is housed in glove boxes for alpha containment. Waste is removed from drums and placed into an airlock on the feed preparation box. It is then hand sorted in the glove box to remove noncombustibles. The combustibles are then thrown into the shredder for size reduction followed by air classification for tramp metal removal. The prepared feed is then placed in a conveyor that transfers it to the feed hopper for the ram extruder. The system is operated from a separate control room. Dried residue must be removed from an evaporator and bagged out of a glove box for subsequent plutonium recovery or storage.

Actinide Recovery

When plutonium contaminated combustibles are processed by acid digestion, the resulting residue contains aqueous-soluble plutonium sulfate. The plutonium sulfate has been found to be quite soluble in 7M HNO_3 . Once into solution, it can be purified by ion exchange and subsequently converted to PuO_2 by oxalate precipitation and calcination.

Major Advantages

- Designed to process high levels of fissile content waste.
- Soluble residue for actinide recovery.
- Low temperature operation.

Major Disadvantages

- Maintenance of glass lined equipment.
- Small feed size requires shredding.
- Acid gases are vented to atmosphere.
- Adaptable for limited number of organic liquids.

Potential Applications

The acid digestion system has been demonstrated for processing most forms of solid waste, but it is quite limited in the number of organic liquids it can decompose. The fact that the process can be designed in geometrically favorable dimensions makes it valuable for processing wastes containing high levels of plutonium. Subsequent recovery of actinides is also enhanced by the soluble nature of the sulfate residue it produces. In addition, the system will tolerate a large variety of solids, including glove box gloves. At the present stage of development, the system is best suited to small volume waste streams, but by sacrificing critically safe dimensions it could be scaled up considerably. The glass lined equipment is vulnerable to fluoride attack, so fluorinated wastes must be excluded.

Since this unit is operated in a glove box system, no remote operating techniques have been tested and a very extensive development program would be required to adopt the process to a remote operation. However, since it is essentially a liquid process, it could offer some advantages for remote hot cell type operations.

3.3.2 Agitated Hearth (RFP)⁸

Solid Waste Capabilities

The unit at RFP is not yet in operation. The projected use for this incinerator is the burning of LLW, essentially suspect waste from production areas of the plant. The materials in this type of waste would consist mainly of paper, polyurethane, PVC plastic, latex rubber gloves, and cloth.

Capacity

The design capacity is 70 kg/hr.

Waste Size

The only size restriction is that imposed by the ram feeding system, which will accept waste packages approximately 1 ft³ in size.

Noncombustibles

The incinerator will tolerate small noncombustibles, but large items must be removed prior to feeding.

Moisture Content

The system should tolerate relatively wet solids, since the waste is tumbled over the hearth by rotating rabble arms.

Acid Producing Solids

High acid waste or high concentrations of PVC plastic may cause corrosion damage to the metal rabble arms in this unit. Acids in the off-gas will be neutralized in the caustic scrubbing system.

Volatile Solids

Operating temperatures of 800 to 1000°C will promote volatilization of some waste materials. The formation of lead compounds on the incinerator and afterburner refractory lining presents the greatest potential problem.

Liquid Capabilities

The RFP unit will not be equipped for burning liquids because of nuclear safety concerns. In applications that do not involve fissile materials, this type of incinerator could be equipped to spray organic liquids into the combustion chamber.

Capacity

Unknown.

Acid Producing Liquids

Acids from burning chlorinated hydrocarbons would not be desirable because of the presence of metal components in the incinerator.

Aqueous Liquids

If no fissile materials were present, some aqueous liquids could be sprayed into the combustion chamber along with auxiliary fuel. Some waste chemicals could prove to be damaging to metal parts and refractories.

Radioactive Waste Capabilities

Design Potential

The RFP unit is a commercial design for processing non-glove box generated waste. Only LLW that has been drum counted and determined to have no more than background radioactivity will be burned.

Nuclear Safety

Nuclear safety will be achieved by administrative control of materials being charged to the incinerator. The unit will be batch operated, with a period of time at the end of the run when ash is raked out of the unit by the rotating rabble arms. The system as installed does not incorporate the necessary criticality safety features for processing glove box generated waste with high levels of fissile material.

Degree of Automation

Wastes will be dumped into a glove box for hand sorting to remove large noncombustibles. The sorted waste will be fed via a ram feeder in 2.3-kg increments over a 5-hour period. Ash will be automatically raked to a dump port at the end of the run. No other hand operation is required except for the removal and replacement of the ash collection drum.

Actinide Recovery

The unit will produce refractory oxides in the ash that are relatively difficult to dissolve for actinide recovery.

Major Advantages

- Little waste pretreatment requirements.
- Mechanical agitation of waste during combustion.
- Automatic ash removal.

Major Disadvantages

- Maintenance of mechanical equipment in the combustion chamber
- Will accommodate only low levels of fissile materials

Potential Applications

The agitated hearth incinerator has not been demonstrated in a nuclear waste application; however, the intended use at RFP appears to take advantage of the strong points of the system. With no particular criticality precautions designed into the system, it will best be utilized to burn a large volume, LLW stream. The fact that it will tolerate a moderate amount of noncombustibles is advantageous in that intensive hand sorting can be eliminated. Acid producing waste and lead contaminated wastes should be avoided to decrease the possibility of metal corrosion and refractory degradation. The unit is installed in a canyon for semi-remote operation. However, because of anticipated maintenance problems with refractories and metal corrosion, it is not a strong candidate for remote hot cell type operation.

3.3.3 Controlled Air (LANL)^{9,10}

Solid Waste Capabilities

The controlled air process has been tested with various cellulosic compounds, polyethylene plastic, PVC plastic, latex rubber gloves, and cartridge filters.

Capacity

The LANL unit has been demonstrated at the design feed rate of 45 kg/hr.

Waste Size

The main ram feeder will accommodate packages up to 1.7' x 2.7' x 3.3'. Physical constraints in the feed preparation glove box line limit the package size entering the main ram to 1' x 2' x 2'.

Noncombustibles

Waste is X-rayed prior to incineration to detect any large noncombustible items within the packages. Large noncombustible items are sorted out; small noncombustibles are tolerated.

Moisture Content

The unit should tolerate relatively damp solids since it is gas fired; there is no provision for agitation of damp materials within the combustion chamber resulting in longer combustion times and more supplemental fuel being required.

Acid Producing Solids

Large amounts of acidic materials may affect some corrosion damage to the steel incinerator shells and other head end equipment if they are consistently burned. Acids are neutralized in the off-gas scrubbing system on the tail end of the process.

Volatile or Low Melting Solids

Operating temperatures of 800 to 1100°C is sufficient to volatilize some metals and metal compounds. Deposition of corrosive lead compounds on refractories may shorten refractory life if lead containing materials are burned.

Liquid Waste Capabilities

The LANL unit has not been demonstrated for incineration of organic or aqueous liquids; however, the unit is presently being modified to test liquid and resin combustion. At present, all waste is x-rayed to detect any liquids within the boxed waste.

Capacity

Unknown. Unit has not been tested with liquids.

Acid Producing Liquids

Incineration of chlorinated hydrocarbons or other acid producing liquids could present corrosion problems.

Aqueous Liquids

The incinerator is presently being modified to accommodate liquid feeds.

Radioactive Waste Capabilities

Design Potential

The unit at LANL was designed to evaluate and demonstrate the incineration of TRU wastes. The LANL Treatment Development Facility where the incinerator is located, is limited to a plutonium inventory of 100 grams.

Nuclear Safety

The LANL incinerator is not critically safe by dimension, so administrative control must be utilized for nuclear safety. Boxed waste is assayed for TRU content prior to incineration by use of a LANL-developed

Multi-Energy Gamma Assay System (MEGAS) installed in the waste pretreatment glove box line. Waste is fed in approximately 6000-gram batches, while a gravity ash dropout collects ash in a hopper for intermittent pneumatic removal. There is no positive removal of ash from the primary chamber hearth until a run is complete; then any remaining residue is removed by vacuum transfer. The system as installed does not incorporate the necessary criticality safety features for processing glove box generated waste with high levels of fissile material. The off-gas scrubbing equipment of the present unit is not safe by dimension but could be redesigned for applications with greater concentrations of fissile materials.

Degree of Automation

The incinerator is operated from a control room with manual feed preparation. Boxed waste is received in 30-gallon drums which are unloaded into the feed preparation glove box. Each box is assayed and x-rayed. If noncombustibles are present, the box is opened, sorted, and resealed prior to insertion into one of two ram feeders. Feeding and control of the incinerator is done from an adjacent control panel. Ash is pneumatically removed from the ash dropout during operation. After a run is completed, the combustion chambers are vacuumed to remove any residual ash deposits.

Actinide Recovery

The process produces refractory oxides that are not as amenable to actinide recovery processes as those produced by the lower temperature combustion processes.

Major Advantages

- Limited airflow in the primary combustion chamber reduces ash entrainment.
- Commercially available equipment.
- Built-in TRU assay and x-ray equipment for waste identification.

- Tolerates small noncombustibles.
- Shredding of feed not generally required.

Major Disadvantages

- A considerable heat of ash remains in the lower chamber of the incinerator, although ash is periodically removed during normal operation.
- Will accommodate only low levels of fissile materials.

Potential Applications

The controlled air system should be useful in processing waste streams containing low levels of TRU elements and relatively large volumes. The 45-kg/hr unit at LANL could easily be scaled up to accommodate greater amounts of waste. The high fired quality of the ash and the possibility for some retention of ash during operation would be a detriment to the processing of recoverable amounts of fissile materials in this unit. The MEGAS assay unit and x-ray equipment on the LANL incinerator is advantageous in maintaining a nuclear safe operation and could be utilized in other incineration systems. High levels of PVC plastics in wastes could eventually present corrosion problems within the system. This unit, as installed at LANL, is a glove box type of operation and semi-remote canyon type operations have not been tested. A considerable development effort would be needed before this system could be considered a strong candidate for remote hot cell type operations.

3.3.4 Cyclone Drum (MF)^{12,13,14}

Solid Waste Capabilities

The cyclone incinerator has been demonstrated with alpha-contaminated wastes from Mound Facility that contain paper, PVC plastic, polyethylene plastic, polypropylene plastic, rubber, cloth, and some tramp metal. In

addition, the system has been tested for burning organic liquids (kerosene) and plastic scintillation vials containing a dioxane-water mixture.

Capacity

Uncompacted waste are burned at a rate of 27 kg/hr; compacted material burns somewhat slower.

Noncombustibles

Noncombustibles in waste will have very little effect on operation of the process in batch operation. The high velocity airflow within the drum will promote combustion of flammable materials, even though there may be a large amount of noncombustibles present. If the system were operating on a continuous basis, noncombustibles would have to be sorted out prior to shredding of the material.

Waste Size

If the system is operated on a batch basis, using each waste drum as a combustion chamber, there is no size restrictions other than those imposed by the storage drum itself. When operating continuously, a stainless steel drum is left in place and waste is pneumatically charged. This mode of operation necessitates the shredding of wastes to a size of approximately 1 in.².

Moisture Content

Ignition of waste in the storage drums has presented some problems in the Mound system. Development work was started on a system in which an electrical arc is used to ignite a liquid fuel. The procedure proved troublesome in the high velocity airflows within the burning chamber. Very wet wastes would not ignite easily in a batch operation, and they would not transfer well pneumatically in the continuous mode; consequently, it

appears that the process may be quite sensitive to high moisture content in wastes.

Acid Producing Solids

The cyclone drum burning system utilizes the cooling effects of the high velocity air flow to cool the walls of the combustion drum, so no refractories are needed in the burning chamber. If acid producing waste is being burned, the combustion drum, the upper combustion chamber (sealed to the top of the drum and used to inject combustion air and exhaust off-gas), and the off-gas header presents a large expanse of metal that is subject to corrosion damage. At operating temperatures of 800-1000°C, the acid gases are extremely corrosive, and under batch operating conditions, temperature cycling may allow condensation of acids in these areas. In addition, there have been problems of acid corrosion damage in the deluge tank and transfer pipe connecting the deluge tank and venturi scrubber.

Volatile and Low Melting Solids

Volatile solids will volatilize at the operating temperature of this system. The refractory lined flue gas header could be subject to lead corrosion.

Liquid Waste Capabilities

Only limited burning of clean kerosene has been conducted at Mound. Results with kerosene were encouraging, but further testing with various organic liquids is needed to determine the overall capabilities of the system.

Capacity

Unknown.

Acid Producing Liquids

The burning of corrosive liquids does not seem advisable in this system considering the corrosion problems already experienced with solid wastes.

Aqueous Wastes

There are no provisions for aqueous waste disposal at the Mound Facility. Aqueous wastes would have to be fed with other solid or liquid combustibles, and the system is not equipped for this at present. Small amounts of a dioxane-water mixture have been burned in tests with scintillation vials.

Radioactive Waste Capabilities

Design Potential

The cyclone incinerator was designed for volume reduction of TRU wastes at DOE facilities and waste burial sites. There are no provisions for burning wastes of higher TRU concentrations than can be safely stored in a 210-l steel drum.

Nuclear Safety

The system is not geometrically safe, so nuclear safety must be maintained by administrative means if fissile materials are present in the waste. The system as installed does not incorporate the necessary criticality features for processing glove box generated waste with higher levels of fissile material. Some fly ash is transferred to the scrubbing system by the off-gas stream, but there is no positive ash removal system until the unit is shut down. Ash is then removed from the drum by vacuum transfer.

Degree of Automation

The system is hand operated, but the basic principle of the process eliminates much of the waste handling. If the unit is batch operated, a barrel of waste is attached to the upper combustion chamber and ignited. No dumping, sorting, or size reduction is necessary. No other contact operation is needed until the drum is removed for vacuum ash removal.

Actinide Recovery

The high operating temperature (1100-1300°C) will produce refractory oxides that are less soluble than those from lower temperature processes. The process cannot handle large amounts of fissile isotopes at present, however, because of nuclear safety considerations.

Major Advantages

- Simplicity of design.
- Low capital cost.
- No waste pretreatment (with batch operation).
- Low waste handling requirements.

Major Disadvantages

- Subject to acid corrosion
- High particulate loading in off-gas stream.
- Relatively high carbon content in ash.
- Will accommodate only low levels of fissile materials.

Potential Application

The cyclone incinerator has very distinct advantages and disadvantages that make the correct application especially important. Equipment corrosion has been a problem, and will continue to be troublesome when burning

acid producing wastes. However, the simplicity and modular construction of the system are conducive to easy replacement of relatively inexpensive equipment if necessary. The lack of criticality protections, such as continuous ash removal, etc., would appear to make the burning of LLW desirable. Because of simplicity, low waste handling requirements, the system seems especially adaptable to remote operation. However, the unit is presently installed in a glove box type of operation and no remote operating and maintenance techniques have been tested. Incineration of LLW at a power plant would appear to be a good application for this process.

3.3.5 Electric Controlled Air (SRL)^{12,15}

Solid Waste Capabilities

The SRL unit is designed for the incineration of small quantities of solid waste consisting of cellulose, PVC plastic, polyethylene plastic, and rubber.

Capacity

Design capacity is 5 kg/hr.

Waste Size

Waste is packaged in 250-gram batches in 4-in. by 9-in. long paper bags prior to feeding. Any waste larger than the bag size has to be shredded before packaging.

Noncombustibles

Small noncombustible items could be tolerated by the system; however, noncombustibles would have to be sorted out of wastes that require shredding for size reduction.

Moisture Content

This process should accept relatively wet waste since it does not rely on waste heat value to maintain operating temperature. Moist waste will, of course, decrease capacity.

Acid producing Waste

The incinerator is completely constructed of prefabricated ceramic components, which consist of a horizontal primary combustion chamber and nine vertical alumina afterburner tubes. This equipment should be impervious to acid attack at the 700 to 1000°C operating temperature. Off-gas leaving the afterburner tubes passes into a three-stage scrubbing system, which removes particulate and neutralizes acid gases.

Volatile and Low Melting Solids

Operating temperatures of this unit are conducive to the volatilization of applicable metals. The ceramic components will be subject to degradation if wastes with high lead content are consistently burned.

Liquid Waste Capabilities

There are no provisions for the burning of organic or aqueous liquids in this system; the unit was specifically designed for solid waste.

Radioactive Waste Capabilities

Design Potential

The SRL unit has been designed for burning waste contaminated up to 10^5 times the nominal 10 nCi/g threshold value or about 10^{-2} grams radioactive isotopes/gram of waste.

Nuclear Safety

The incinerator is small and will not accommodate large quantities of wastes, but primary criticality control will be administrative. There is no positive ash removal system; however, most ash will be transported to an ash pit (at the outlet of the primary combustion chamber) by the addition of waste. Some retention of fly ash must be expected in the series of afterburner tubes.

Degree of Automation

The planned incineration system will be hand operated. Waste will be presorted and shredded, if necessary, for packaging in the 4-in. by 9-in. feed bags. Ash must be periodically removed from the ash retention chamber for storage or immobilization. The unit will require periodic complete cleanouts to prevent any buildup of fissile isotopes.

Actinide Recovery

The unit will operate at 1000°C, which is sufficient to form refractory oxides that are difficult to dissolve in recovery operations.

Major Advantages

- Electrically heated primary chamber may improve operational safety.
- Limited airflow in the primary chamber reduces ash entrainment.

Major Disadvantages

- No positive ash removal system during operation.
- Retention of fly ash in afterburner tubes.

Potential Applications

Many of the basic concepts for the electric air incinerator were derived from the Windscale, England incinerator. The English incinerator has burned high level TRU type waste for a number of years. The SRL unit was specifically designed for the same purpose. The electric heating was chosen over auxiliary fuels such as oil or gas to insure a high degree of safety in the production model. It appears that this unit will be used to its best advantage in burning a relatively high level, low volume TRU waste. Fly ash buildup could prove troublesome in the afterburner tubes. This and waste prepackaging requirements would present problems in a remote operated version of the process. In addition, the presence of lead in the waste could contribute to erosion of the all-ceramic unit.

3.3.6 Fluidized Bed (RFP)^{16,17}

Solid Waste Capabilities

Fluidized bed incineration has been demonstrated with a large variety of waste solids that include paper, polyethylene, PVC plastics, latex rubber gloves, wood, leaded rubber gloves, organic resins, cartridge filters, waste chemicals, HEPA filters, and protective clothing.

Capacity

Based on a heat release of 1,500,000 Btu/hr, the demonstration unit will burn approximately 82 kg/hr of average solid waste.

Waste Size

Waste is double shredded to achieve a 1/4- to 1-in. size for continuous feeding via a screw conveyor. The primary shredder will accept waste up to a 2-ft³ size for initial shredding.

Noncombustibles

Large noncombustibles must be removed prior to shredding. An air classification system between the two shredders removes small noncombustibles, and very fine noncombustibles are automatically removed from the fluidized bed by means of a screw conveyor.

Moisture Content

The unit will tolerate relatively wet solids. Materials containing 50 weight percent moisture have been burned.

Acid Producing Solids

Acids produced during the decomposition of materials such as PVC plastic are neutralized as they are formed in the bed of fluidized sodium carbonate granules.

Volatile Solids

The low operating temperature of 550°C reduces the potential of volatilizing materials such as lead, while the sodium carbonate bed prevents the formation of volatile lead, iron, and phosphorous chloride compounds.

Liquid Waste Capabilities

The process has burned naptha solvents, trichloroethylene, tributyl phosphate, waste chemicals, and waste oils. It has also been demonstrated at a 99.9999% efficiency for combustion of Polychlorinated Byphenyls (PCB)-solvent mixture.

Capacity

Based on a heat release of 1,500,000 Btu/hr, the demonstration unit will burn about 50 ℓ /hr of combustible liquids.

Acid Producing Liquids

Acids produced by burning materials such as chlorinated solvents are neutralized in the bed of sodium carbonate.

Aqueous Liquids

The system will accept moderate amounts of aqueous acid or basic wastes with the addition of an auxiliary fuel such as methanol or kerosene. No provisions have been made on the present unit for processing waste slurries.

Radioactive Waste Capabilities

Design Potential

The present unit was designed for incineration of TRU and LLW wastes contaminated with ^{239}Pu in concentrations up to 10^{-3} grams/gram of waste.

Nuclear Safety

The unit is not geometrically safe; consequently, administrative control is necessary for nuclear safety. However, since the system does not require an aqueous scrubbing system the potential for nuclear criticality is greatly reduced. Waste is fed continuously and ash is continuously removed from the off-gas stream by cyclone separation and sintered metal filtration. Ash is continuously removed from the system by a screw conveyor.

Degree of Automation

The equipment is housed in a canyon arrangement for alpha containment. Waste barrels must be opened and attached to a glove box. Once the drum is attached, the waste is emptied, sorted, and fed into the primary shredder

by glove box contact operation. Incineration operation is monitored and controlled from a separate control room. No other hand operation is required except the removal and replacement of ash drums that are automatically filled by a screw conveyor.

Actinide Recovery

Low temperature operation produces low fired ash amenable to recovery operations. Spiked amounts of plutonium oxide and plutonium nitrate were successfully recovered from incinerator ash by a water wash and nitric acid leaching technique.

Major Advantages

- In situ neutralization of acids.
- Low temperature combustion that eliminates refractories.
- Agitation of waste in fluidized bed during combustion.
- Dry off-gas system.
- Continuous ash removal.
- Low fired ash for actinide recovery.
- Designed to process high levels of fissile content waste.

Major Disadvantages

- Small feed size requires double waste shredding.
- Catalyst usage for off-gas afterburning.
- Some insoluble catalyst in ash.

Potential Applications

The fluidized bed has successfully burned a large variety of waste solids and liquids. The in situ neutralization of acids makes the process a leading candidate for waste streams containing large quantities of acid producing solids or liquids. The system has proven especially good for

liquids burning, and the waste shredding system could be eliminated for this application. Ion exchange resins could also be burned without pretreatment. The system should produce low fired oxides amenable to actinide recovery applications. The process can be operated on a small scale in geometrically safe vessels for actinide recovery operations or on larger scales for high throughput of TRU wastes. Easy unit replacement and the lack of high maintenance refractories makes the process a good candidate for remoting. Since the process is installed in a canyon, some remote operating techniques have been tested.

3.3.7 Molten Salt (RI)^{18,19}

Solid Waste Capabilities

The molten salt incineration process was developed by Rockwell International for burning various radioactive wastes. The system has burned paper, polyethylene, PVC plastic, latex rubber gloves, organic ion exchange resin, and leaded Hypalon glove box gloves, film, and various waste chemicals.

Capacity

The process has been demonstrated on a bench scale of 0.2 kg/hr and a pilot scale of 50 kg/hr.

Waste Size

Waste is pneumatically injected into the molten salt bed. In order to accomplish this, the particle size of the waste must be reduced to approximately 1/2 in. A hammermill was used for waste size reduction at RI, but double shredding should offer comparable sizing capability.

Noncombustibles

Waste is sorted prior to shredding to remove noncombustibles that would damage a shredder. Small tramp metal will slowly be oxidized in the molten sodium carbonate, but other insoluble noncombustibles will slowly build up in the molten salt. This would necessitate a complete cleanout eventually.

Moisture Content

The molten salt process will not tolerate any free water in waste feed; consequently, wastes must be relatively dry or predried prior to processing. In addition, moist waste would be difficult to pneumatically transfer into the incinerator.

Acid Producing Solids

Waste is combusted in a bed of molten sodium carbonate and sodium sulfate, which immediately neutralize any acids formed during combustion.

Volatile or Low Melting Solids

Sodium chloride, which is formed in the molten salt bed, tends to volatilize at the operating temperature of 800-900°C, and must be removed in the off-gas cleanup system. Lead, which does not volatilize in this system, reduces to metal that forms a pool at the bottom of the salt bed.

Liquid Waste Capabilities

The system has been tested with organic liquids that include kerosene, tributylphosphate, and various pesticides. The process has been proposed for any organic waste, including high-sulphur oils, etc.

Capacity

Unknown.

Acid Producing Liquids

The process is designed to neutralize acids formed during the combustion of either solid or liquid wastes. Wastes are injected beneath the surface of the molten salt to insure the neutralization of acid gases before they reach the surface of the melt.

Aqueous Liquids

The system will not tolerate any free water; consequently, no aqueous wastes could be processed by this method.

Radioactive Waste Capabilities

Design Potential

A 45-kg/hr system was designed for processing buried wastes at INEL. A molten salt system has been designed to process wastes with plutonium in concentrations up to 8.8×10^{-4} gram Pu/gram waste, and could be scaled down to a size that would be geometrically safe for much higher Pu concentrations.

Nuclear Safety

The process could be operated on a small scale with geometrically safe equipment; however, larger capacities such as the 45-kg/hr unit would require administrative control for nuclear safety. There is no means of continuous ash removal, but ash would be removed in the periodic drainings of spent salt. Tests have shown that 99 percent of the plutonium in waste is retained in the melt.

Degree of Automation

The process has been essentially hand operated in tests thus far. Waste must be finely shredded for pneumatic feeding; consequently, wastes must be sorted to remove noncombustibles that would damage shredding equipment. Draining of spent salt has also been conducted as a hand operation thus far. Tests with Pu contaminated waste were conducted in a glove box that necessitated bagout procedures for salt, wastes, etc.

Actinide Recovery

Although the system operates at a temperature of 800-1000°C, it produces a soluble form of plutonium for recovery. The actinides and other metallic oxides are separated from the spent salt by a water wash procedure in which the salt is dissolved and the oxides remain as an insoluble residue. Rockwell has reported Pu recovery rates of 90 to 98 percent in nitric and hydrochloric acid leaching of the residues.

Major Advantages

- In situ neutralization of acids.
- Agitation of waste in molten salt bed during combustion.
- Tolerates some noncombustibles such as metal and glass.
- Automatic separation of lead from salt-ash residue.

Major Disadvantages

- Small feed size requires extensive waste shredding.
- Sodium chloride entrainment in off-gas.
- Will not tolerate free water in waste.

Potential Applications

This process features in situ neutralization of acids produced during combustion of PVC, etc. It will tolerate most forms of nuclear wastes, including leaded dry box gloves and other lead bearing wastes. Lead from wastes forms a pool at the bottom of the salt bed that can be drained separately from the salt itself. These two features would be valuable in burning wastes containing high concentrations of acid producing wastes and/or lead bearing wastes. Wet solids and aqueous liquids cannot be processed by this system, and care must be exercised to avoid accidental feeding of wet materials. On a small scale, the process could be designed critically safe for high levels of TRU elements. Maintenance of refractories and other high temperature valves and equipment might prove to be difficult under remote operating conditions.

3.3.8 Rotary Kiln (RFP)⁸

Solid Waste Capabilities

The rotary kiln incinerator at RFP has not been tested for burning nuclear wastes as yet; it is scheduled for startup in 1981. It was designed to burn cellulose, polyethylene and PVC plastics, rubber, organic resins, wood, and polypropylene cartridge filters.

Capacity

Design capacity is 41 kg/hr.

Waste Size

The rotary kiln is 6 ft in diameter and could burn quite large size waste, but the ram feeder will accept waste packages of only approximately .1 ft³ in size.

Noncombustibles

The kiln will tolerate any amount of noncombustibles as long as they fall within the size limitations of the ram feeder and the ash discharge port.

Moisture Content

The system should accept relatively wet solids, since the unit is oil fired and the waste undergoes a tumbling action in the rotating kiln.

Acid Producing Solids

The unit is refractory lined and has a minimal amount of metal exposed to the corrosive environment and elevated operating temperatures. However, some acid corrosion of the steel outer tube or head end feeding equipment can be expected. A caustic scrubbing system will neutralize acids in the off-gas.

Volatile or Low Melting Solids

The refractory lined kiln is subject to degradation by low melting and glass forming materials such as lead. Some materials will volatilize at the operating temperature of 800 to 1000°C.

Liquid Capabilities

The rotary kiln is equipped to feed both organic and aqueous waste liquids. Provisions have been made to continuously monitor temperatures and detect the presence of flame during liquids incineration.

Capacity

Design capacity is approximately 135 kg/hr of various organic liquid mixtures.

Acid Producing Liquids

Acid producing liquids could present corrosion problems in atomizing nozzles and other metal components in the system.

Aqueous Liquids

The RFP unit is equipped to inject aqueous laboratory wastes. Some wastes may contain glass formers, however, that could be damaging to refractories in the kiln and afterburner.

Radioactive Waste Capabilities

Design Potential

The kiln was designed for burning line generated, high level TRU waste that will be processed for plutonium recovery.

Nuclear Safety

The RFP unit has been approved for incineration of high level TRU waste. Ash removal is continuous and automatic by action of the inclined, rotary kiln. The components of the caustic scrubbing system are either critically safe by dimension or filled with borosilicate Raschig rings for nuclear poisoning.

Degree of Automation

Waste must be packaged in containers suitable for ram feeding to the kiln; no other pretreatment is required. Operation of the incinerator will be monitored and controlled from a separate room. Ash automatically falls on a vibrating screen that separates the ash from noncombustibles (tramp metal). Most of the waste will be transferred to the incinerator sorting glove box by an in-line transfer system, and ash and noncombustibles will

be transported out by the same system. Contact handling will be primarily limited to the waste sorting operation.

Actinide Recovery

The unit is designed to burn wastes containing recoverable amounts of plutonium, but the planned operating temperature of 800-1000°C will produce refractory oxides.

Major Advantages

- Positive, automatic ash removal.
- Little waste pretreatment requirements.
- Tumbling action of waste during combustion.
- Accepts noncombustibles.
- Designed for processing high levels of fissile content waste.

Major Disadvantages

Rotary seal maintenance.

Potential Applications

The RFP unit will be utilized for burning wastes containing recoverable amounts of plutonium. The rotary kiln was selected for this application because it provides a positive, continuous removal of ash with a minimum retention of residues in the combustion chambers. It will tolerate and remove from the system any percentage of noncombustibles that may be charged; consequently, it would be a good candidate for waste streams containing large amounts of noncombustibles. It would be desirable to avoid wastes of high lead content to increase the refractory life of the unit. The system at RFP is relatively automatic, with little waste handling except to load the ram feeder. If seal and bearing maintenance requirements do not prove to be excessive, the rotary kiln should be a

strong candidate for remote operating applications. The unit at RFP is installed in a canyon type system where remote operation will be employed.

3.3.9 Slagging Pyrolysis (INEL)^{20,21}

Solid Waste Capabilities

An Andco-Torrax incinerator is being considered for burning wastes retrievably stored at INEL. The unit under consideration has not been utilized in a nuclear waste application as yet. There is a version of this incinerator being demonstrated for burning municipal refuse in Luxembourg, Belgium. The INEL unit will be designed to accept all kinds of combustibles, most types of noncombustibles, and contaminated soil.

Capacity

The proposed unit will process 850 kg/hr.

Waste Size

There is no size limit for incoming waste except that imposed by the throat of the incinerator, which is 1.4 m in diameter. A rough sizing to approximately 1/2 m in diameter has been proposed for the INEL installation.

Noncombustibles

All types of noncombustibles, including soil, will be accepted by this process with the only limitation being the size restraints of the waste throat.

Moisture Content

The process will accept very wet materials because the wastes must pass through a drying zone as they move down the vertical shaft toward the lower pyrolysis and combustion zones.

Acid Producing Wastes

Acids produced by decomposition of wastes may cause corrosion damage to metal components. In situ neutralization of acids may be accomplished if sodium carbonate is added to wastes that contain PVC plastic. Any excess of sodium carbonate would be incorporated into the slag product..

Volatile or Low Melting Wastes

The high operating temperatures (1650°C) in the combustion/melting zone will volatilize or melt most metals contained in the wastes. The presence of large quantities of lead in wastes buried at INEL could cause deposition problems and refractory degradation in this particular application.

Liquid Capabilities

The INEL incinerator is being designed primarily for stored solid wastes; however, it appears that the system would tolerate a considerable amount of either organic or aqueous liquid wastes along with combustible solids and/or auxiliary fuel.

Capacity

Unknown.

Acid Producing Liquids

Incineration of acid producing liquids such as CCl_4 would present a good opportunity for corrosion of metal components unless a sufficient amount of sodium carbonate was also fed for in situ neutralization.

Aqueous Liquids

A moderate amount of aqueous wastes can be tolerated along with solids or auxiliary fuels.

Radioactive Waste Capabilities

Design Potential

The proposed unit is being designed to burn the majority of the wastes retrievably stored at INEL. Some waste sorting will be required to identify drums containing more than 200 grams of plutonium. Drums that contain greater than 200 grams will be set aside for other processing; all other waste is acceptable for the slagging pyrolysis unit. The unit will require a large amount of additives for supplemental fuel (coal and wood chips) and product slag formers (soil).

Nuclear Safety

Because of the large size of the equipment and the great throughput, nuclear safety must be maintained by strictly administrative methods.

Degree of Automation

Waste will be manually sorted to determine the plutonium content. When high level waste (in excess of 200 gram Pu per drum) is identified, it will be removed from the feed stream. Intact drums will probably be cut open and fed into the vertical drying shaft. Operation and slag removal

will be automatic, and no other hand operations will be required other than disposal of the slag residue.

Actinide Recovery

The basalt-type slag residue produced by this process would be very difficult to process for actinide element recovery. The high fired residue will be insoluble in most acid leach processes.

Major Advantages

- Process will accept unsegregated wastes containing high percentages of noncombustibles.
- Requires very little waste sizing or pretreatment.
- Generates a stabilized residue for storage.
- Slag is continuously discharged.
- In situ neutralization of acids can be incorporated if sodium carbonate is fed with waste.
- Availability of commercial design.

Major Disadvantages

- Large volume of waste in the unit could cause nuclear safety concerns.
- Slag residue is unacceptable for actinide recovery.
- Volume in weight reduction will be less than other systems because of the required additives for slag formation.

Potential Applications

The only slagging pyrolysis incinerator now being considered for nuclear waste is the unit proposed for burning the INEL retrievably stored wastes. Similar units are in use for municipal incineration, where large quantities of waste are converted to a stabilized slag for discard or

reuse. This type of application would appear to be ideal for this incinerator, since the goal is to eliminate the stored waste and produce a stabilized product in a single operation. Refractory damage may be a problem if the large quantities of lead in the buried waste is burned. Remoting of this particular unit will be difficult because of the large size equipment and refractory maintenance.

3.4 Incineration Cost Evaluations

The primary criteria for selection of a suitable incinerator for a given application is that the unit be able to accept the waste to be processed and produce an acceptable product within a safe operation. For a given application several combustion processes may be able to meet the technical objectives; then the capital cost for installation of a unit and the operating cost become important decision factors. It is impossible to provide a complete cost analysis without having the application and the site where the process would be installed well defined.

In an effort to provide some cost comparison for the various processes discussed in this report, data has been assembled on the installed cost of systems funded through TWSO as well as two production units at Rocky Flats and a molten salt process which was purchased for installation at INEL. The costs obtained from each site represent the units "as installed" including design, equipment procurement, and installation direct costs. For each system the cost estimate was adjusted from the year of installation to a common basis of 1979 dollars. There is a wide variance in the degree of instrumentation provided for the units. In the case of the fluidized bed incinerator the cost includes a computer data acquisition and process control system that was installed for research purposes; but this is not required for a typical production operation. The Electric Controlled Air, Fluidized Bed and Rotary Kiln incinerators, and the Acid Digestion unit were all designed to process waste materials from glove box or canyon operations. Geometrical restrictions in the existing digester of the Acid Digestion unit increase the cost compared to that which may be

required for processing waste containing little fissile material. Redundant scrubbing systems and geometrical size limitations employed in the off gas cleaning system for the Rocky Flats Rotary Kiln increased the cost compared to that required for non-glove box generated waste.

The installed cost for the Molten Salt system included a metal building but was not designed to accommodate high concentrations of fissile material. These two factors tended to be off setting in affecting the estimated cost. The equipment was purchased but never installed and the cost figure was based on projected installation.

The Slagging Pyrolysis Incinerator was estimated for a large 850-kg/hr unit to be installed in a new facility. A cost estimate was also obtained for a 63.6-kg/hr unit. These two costs are comparable if one uses an 0.5 power factor to scale the capacity. The cost estimates presented in this report are based on the 63.6-kg/hr unit. The capacity of these units was based on the assumed feed of TRU waste stored at INEL which contains about 30% combustible. If these units were to process combustible category waste only, it is anticipated that the capacity could double and still have sufficient additives to produce a slag product.

The Controlled Air, Agitated Hearth, and Cyclone Drum incinerators were designed to process non-glove box generated waste. Therefore, the units are less complex in terms of criticality control features which tend to reduce the installed equipment cost.

Presented in Table 3-2 are the capacity of each unit and the installed cost.

The cost was also adjusted using the 0.6 power rule to estimate the cost of each unit sized to process 45 kg/hr of combustibles. This represented a scale-up factor of 9 for the Electric Controlled Air incinerator and a scale-down factor of 1.82 for the Fluidized Bed Incinerator. The scale factor for all other units fell within that range and each is

TABLE 3-2
 INSTALLED INCINERATION CAPACITY
 AND ASSOCIATED COSTS
 IN 1979 DOLLARS

<u>System</u>	<u>Capacity (kg/hr)</u>	<u>Installed Cost</u>		<u>Installed Cost/Unit Capacity</u>	
		<u>Installed Capacity (\$1,000,000)</u>	<u>45 kg/hr Capacity (\$1,000,000)</u>	<u>At Installed Capacity (\$1,000)</u>	<u>At 45 kg/hr Capacity (\$1,000)</u>
Cyc, Cyclone Drum	27	0.8	1.1	29.6	24.2
AH, Agitated Hearth	70	1.7	1.3	24.3	28.9
FBI, Fluidized Bed	82	2.3	1.6	28.0	35.6
CAI, Controlled Air	45	2.0	2.0	44.4	44.4
RKI, Rotary Kiln	41	2.6	2.75	63.1	61.1
MS, Molten Salt	45	3.6	3.6	80.0	80.0
AD, Acid Digestion	10	1.5	3.7	150.0	82.2
EAI, Electric Controlled Air	5	2.7	10.1	540.0	224.4
SPI, Slagging Pyrolysis	64	8.8	7.1	138.6	158.9

probably capable of being designed to process 45 kg/hr. Presented in Figure 3-1 are the installed capital cost per unit throughput capacity relative to the combustion system capacity. The cost of the Electric Controlled Air Incinerator is shown in a special note on this figure because of its high cost. Including this in the figure would have required an unwanted compression of the vertical scale. The Electric Controlled Air Incinerator at SRP was designed to process waste with a high curie content which may be part of the reason for the high cost. Only five of the systems were designed to process high levels of fissile material: Acid Digestion, Rotary Kiln, Fluidized Bed, Electric Controlled Air, and Slagging Pyrolysis. If the Acid Digestion and the Rotary Kiln systems were designed for non-glove box generated waste (low fissile content) the cost would probably be lowered because of the less stringent geometrical size limitations. The cost of the Slagging Pyrolysis and the Electric Controlled Air would not be expected to change significantly if they were designed only for low fissile content waste. Since the Fluidized bed incinerator is a totally dry system, design of a unit to process only non-glove box generated waste or LSA waste may not result in a major cost reduction. This system has processed non-glove box generated waste with significant levels of TRU contamination, but has not been operated with glove box generated waste. It would be beneficial to verify the nuclear safety of this system by conducting tests with higher levels of fissile material content waste generated in glove box operations. The other systems were designed for processing non-glove box generated waste or LSA waste only.

To provide a more direct comparison of the capital cost of the various processes, the cost of each system has been estimated for a capacity of 45 kg/hr. This information is presented in Figure 3.2. The capital cost varies from a low of \$1,100,000 for the Cyclone Drum Incineration to a high of \$10,500,000 for the Electric Air Incineration System. Because of the unwanted compression of the vertical scale, the costs for the slagging pyrolysis unit and the Electric Controlled Air incinerator are included in a special note.

**FIGURE 3-1
CAPITOL INVESTMENT PER UNIT CAPACITY
FOR INSTALLED COMBUSTION SYSTEM
IN 1979 DOLLARS**

An evaluation of the operating costs for each system is needed but is not available for this report. Two factors which would have a major impact on the operating costs are the operating labor and the maintenance requirements. If one assumes that these two factors do not vary greatly among the various systems presented (which may be overly simplistic), then the capital costs presented could be used as an economic guide for selecting a suitable system for specific applications.

**FIGURE 3-2
INSTALLED COST OF EACH
COMBUSTION SYSTEM ESTIMATED
FOR A CAPACITY OF 45Kg/hr**

4.0 INCINERATOR SELECTION

4.1 Selection Criteria

The various nuclear waste incinerators now under development have all been evaluated by various people and committees² in regard to their safety, effectiveness, flexibility, operability, cost, developmental stage, etc. However, it is difficult to evaluate and rate incinerators in these areas without consideration of potential applications. The Goldberg Committee noted that each of the developmental units had been designed for a specific use and concluded that no one system would be successful in all applications. All of the new design incinerators have been determined to be safe, effective, and operable for at least one application; this does not necessarily signify that they would perform as well in other applications. Consequently, the choice of an incinerator must be based upon the application as well as the general capabilities of the unit.

The Goldberg Committee cited the following list of selection criteria:

- Effectiveness
- Elimination of combustibles
- Volume reduction
- Weight reduction
- Secondary waste generation
- Off-gas composition
- Availability
- Maintainability
- Flexibility
- Waste compounds handled
- Throughput
- Resource use
- Compatibility with downstream processes
- Product characteristics
- Operability
- Feed preparation requirements

A study by the FMC Corporation for the "Selection of waste treatment process for retrieved TRU waste at Idaho National Engineering Laboratory"²⁰ considered many different criteria for process comparison. They stated that the process must:

- Render the waste inert
- Immobilize the residue
- Prepare waste to meet WIPP criteria
- Process at least 300,000 cubic feet of waste per year
- Input unsegregated waste
- Be operating full-scale by 1987
- Have provision for emergency power
- Be maintainable
- Be a safe operation in terms of criticality, containment, radiation, exposure, and DOE and EPA exhaust gas requirements

and that the process should:

- Maximize process simplicity
- Minimize number of process parameters requiring control
- Minimize time to maintain
- Minimize routine maintenance
- Maximize mean time between failures
- Minimize processing (operating) cost
- Minimize capital investment
- Minimize engineering development time
- Minimize engineering development cost
- Minimize engineering development risk
- Minimize radiation exposure of operating personnel
- Minimize plutonium holdup or entrapment within processing system
- Minimize particulate load on off-gas system
- Maximize capability for remote operation
- Maximize volume reduction
- Minimize generation of additional waste during process
- Minimize use of additional fuel during the process

- Minimize startup problems
- Minimize shutdown problems
- Minimize leach rate of output residue
- Minimize production of toxic gases during processing
- Minimize input waste sizing requirements

It is evident that each use will have his own set of process selection criteria. Most of these criteria will apply to selection of an incinerator for any application; but applicability to radwaste mixtures and effects of radioactivity are of special interest to radwaste applications. These factors which are of special importance to radwaste are discussed below.

In this report an attempt will be made to establish some general guidelines for incinerator selection based on application or waste types to be processed. A breakdown of physical and chemical characteristics and the type and levels of radioactivity will provide a profile of each waste that will be relevant to incinerator choice. The various incinerators can then be analyzed for compatibility with the wastes of interest. Some of the more important waste properties are listed below.

Physical Properties

Solid Waste

- Material Content
- Size
- Noncombustible Content
- Moisture Content
- Amounts to Process

Liquid Waste

- Amounts to Process

Chemical Properties

Solid Waste

- Composition
- Acid Potential
- Volatility Potential
- Explosion Potential
- Heat Value

Liquids

- Heat Value
- Water Content
- Solids Content
- Acid Potential
- Explosion Potential

Radioactivity

- Radioactive elements present
- Fissile isotopes present
- Type of radiation - alpha, beta, gamma, neutron
- Levels of radiation
- Contact or remote operation
- Actinide recovery

The properties listed intentionally disregard the source or present state (fresh generation, stored, buried, etc.) of the waste, since this information is not pertinent to the incineration process. The source and state of waste may become important in special instances if they are an indication of specific physical or chemical problems, or unusual quantities or mixtures. While an incinerator is occasionally needed to burn a large variety of wastes (such as the materials stored and buried at INEL), most

incinerators are needed for a much more specific application. In these instances, the selection of an incinerator will be based on the capability to burn one specific waste or a limited group of wastes. Although a unit may be ideal for one waste, it may possess an inherent feature that renders it completely unacceptable for other specific wastes. Consequently, consideration of the form of the wastes to be burned may quickly narrow the choice of acceptable incinerators.

Examples of problems, caused by specific wastes, which must be considered in incinerator selection are given below. Past incineration operations have proven that administrative control is often inadequate to prevent the addition of noncombustibles to combustible waste streams. The presence of noncombustibles is a problem that must be provided for in nearly all applications. The chemical composition of the waste materials also greatly affects incinerator operation, maintenance requirements, and equipment life. The presence of acids, acid producing plastics, explosive materials, and volatile materials are some of the more troublesome chemical problems of nuclear wastes. Explosive materials must be sorted out of general plant wastes for special processing procedures. In situ neutralization of acids is provided by the fluidized bed and the molten salt incinerators, but other units that rely on caustic off-gas scrubbing may experience corrosion to head end equipment when burning acid producing wastes. The acid digestion system, of course, is resistant to acids but its glass lined equipment is subject to damage by fluorinated wastes. Materials that volatilize and later plate out in off-gas systems produce problems in most systems. Lead, which is very prevalent in radwastes, is particularly troublesome because it forms glassy compounds that attack and severely damage refractory linings. All of the detrimental physical and chemical characteristics of each radwaste must be carefully considered before an incinerator is chosen.

The type and level of radioactivity of the waste must also be considered when selecting an incinerator, since this affects the needs for criticality control and for shielding or remoting. Alpha contaminated

wastes have been incinerated at quite high levels of activity without remote operation. With shielding designed into the containment system, operating personnel can be adequately protected while operating the equipment. When higher quantities of beta-gamma emitting isotopes are present in the waste, however, remote operation and maintenance become a necessity. If this is the case, the potential user must not only consider the types of waste an incinerator will burn but also whether or not the unit is amenable to remote operation. Incinerators have been evaluated for remote operation, and some appear more adaptable in this regard than others. The truth of the matter is, however, that no incinerator has ever been completely remotely operated and maintained, so no operating history or data is really available in this area.

Nuclear safety is directly affected by the radioactivity levels of the waste. If large quantities of fissile isotopes are present in waste, steps must be taken to guard against a criticality incident taking place as materials are concentrated during incineration. The incinerator must either be geometrically safe in dimensions or the input and output of fissile materials must be stringently controlled. Only the acid digestion system is designed in geometrically favorable dimensions; all other units must rely on some form of administrative control for criticality protection. Other considerations such as moderation, reflection, and nuclear poisoning are also important. Where the acid digestion unit is an aqueous process confined to critically safe dimensions, the other processes intentionally maintain an entirely dry combustion area to avoid the affects of liquid moderation or reflection. When liquids are burned in these units, care must be exercised to maintain a minimum operating temperature to insure gasification and/or combustion of the materials. Incinerators with aqueous off-gas scrubbing systems must be designed with critically safe dimension scrubbers or scrubbers that incorporate nuclear poisoning devices such as boron glass Raschig rings.

Absorption of radioactive materials into the system (especially refractories) is very undesirable from a nuclear safety standpoint, as well

as contributing to increased radiation exposure to operating personnel. Refractories that have absorbed radioactive materials constitute a secondary waste when they are routinely replaced.

4.2 Suggested Incinerators for Radwaste Applications

One way to determine the potential uses of specific incinerators is to categorize the applications and evaluate each combustion unit with respect to its ability to process the waste materials (which would be) typical to that application. The TRU waste and Low Level waste applications are presented in Figures 4-1 and 4-2, respectively.

Incinerators suggested for each application are listed in the figures and discussed below. The purpose of incinerating TRU waste can be divided into three general objectives: (1) Burning combustible materials to produce an ash or residue which could be subjected to chemical treatment for removal and recovery of transuranic elements; (2) Processing of combustible material to produce ash or residue which will be converted to an immobilized product form; and (3) Processing combustible waste with the primary objective of volume reduction and elimination of the potential for gas generation under storage conditions. For the low level waste the principal objective is to reduce the volume and eliminate the hazards associated with storage, transportation, and disposal of the combustible materials.

To determine the type of incineration system which is best suited to meet the specific objectives, an accurate definition of the waste material and the operation are needed. This categorization is provided under the waste and site specific factors presented in Figures 4-1 and 4-2. It is not intended that this categorization provide a complete breakdown of waste compositions; rather, only the major factors relevant to waste composition or site operation are considered. The waste and site specific factors will be discussed in the next section of this report along with the features of the various incinerator systems in an attempt to define the most suitable systems for each application.

FIGURE 4-1

TRU WASTE INCINERATION SELECTION MATRIX

AD, Acid Digestion Unit
 AH, Agitated Hearth Inc.
 CAI, Controlled Air Inc.

CYC, Cyclone Drum Inc.
 EAI, Electric Controlled Air Inc.
 FBI, Fluidized Bed Inc.

MS, Molten Salt Inc.
 RKI, Rotary Kiln Inc.
 SPI, Slagging Pyrolysis Inc.

FIGURE 4-2

LOW LEVEL WASTE INCINERATION SELECTION MATRIX

4.2.1 TRU Waste Applications

The incinerator waste applications can be broken down into the three categories discussed in the following subtopics.

4.2.1.1 Transuranic Recovery

Combustible materials which are to be processed to recover TRU elements will contain greater concentrations of fissile materials than other TRU combustible waste. The content of fissile materials will necessitate selection of an incinerator which lends itself well to nuclear criticality control. The combustibles will contain higher levels of PVC plastic (up to 50 wt percent). Since it will probably be currently generated material, a high degree of segregation of noncombustible materials should be possible. Because incineration of plutonium contaminated materials at high (800°C) temperatures produces a refractory type of plutonium oxide which is more difficult to dissolve, a site specific factor has been provided with respect to the type of dissolution system which will be available for processing the ash. If a nitric acid dissolution system is to be used, then the desired incinerator would be a low temperature unit. If the dissolution system to be used can handle high fired oxide, then the major factor affecting the incinerator selection will be nuclear criticality control.

If dissolution enhancement is not available, the acid digestion (AD) unit and the fluidized bed incinerator (FBI) are the leading candidates for this application. The acid digestion unit is a low temperature process which produces a soluble sulfate for recovery operations. Because it is a highly moderated and reflected aqueous system, nuclear criticality control has dictated the use of size limitations and geometrical configuration restraints. The unit at HEDL has undergone a complete nuclear safety evaluation and is suitable for handling the high concentration of fissile material encountered in recovery operations. Because it is an aqueous system there is very little carryover of fissile material into the off-gas

system, minimizing geometrical and size restrictions of that equipment. Because of the equipment size limitations for the head end process, it is best suited for small throughput. The unit is constructed of acid resistant materials and is suitable for the high PVC feed material. The HCl, generated from the decomposition of (the high percentage of) PVC plastic in the feed, would be vented to the atmosphere in the HEDL facility. In addition to the acid fractionating equipment used at HEDL, an HCl scrubbing system may have to be added to the system to make it acceptable at many other locations. The unit is considered a high capital cost unit per kg of waste handled, and this cost would be increased with the addition of a HCl scrubbing system.

The FBI operates at moderate temperatures (550-600°C) to produce a non-refractory type of plutonium oxide in the ash when processing plutonium contaminated materials. The in situ neutralization of acid gases with the bed material makes the FBI an ideal candidate for processing a high concentration of PVC plastic in the feed stream, thereby minimizing halide corrosion throughout the system. The ash produced is continuously elutriated from the bed by the gas stream. This results in very low inventory of fissile material holdup in the unit. The low inventory of fissile material combined with the totally dry process, minimizing moderation and reflection of neutrons, renders the unit suitable for processing high levels of fissile material. The capital cost per kg of waste capacity is lower for the FBI than that of the AD unit primarily because of higher throughput capabilities. The plutonium oxide produced by the FBI would be slightly less soluble than the sulfate produced by the AD unit. While both the AD and the FBI are good processes for TRU recovery operations, the AD is better suited for lower capacities, and the FBI may cost less and be better suited for higher throughputs.

The molten salt process would appear to be a possible candidate for this application because of the in situ neutralization of acid gases and the production of soluble forms of TRU elements in the salt cake. However, the large amount of salt compared to the ash (maximum of about 20% ash) and

the fact that the unit will maintain a high inventory of fissile material in the salt bath, renders it somewhat less attractive than the AD and FBI processes. With proper administrative control for nuclear safety, it can be considered a marginal candidate.

The Rotary Kiln (RKI), Controlled Air (CAI), Electric Controlled Air (EAI), Slagging Pyrolysis (SPI), Agitated Hearth (AH), and Cyclone Drum (CYC) incinerators are undesirable candidates for this application because of elevated operating temperatures ($>800^{\circ}\text{C}$) producing refractory oxides of TRU elements. Some of these candidates are also inadequate because of the potential for accumulation of fissile material in the process equipment under normal operating conditions.

If dissolution enhancement is available, other incinerators are also good choices. For the reasons stated in the previous section, the FBI and AD units are also good candidates for use in TRU recovery operations where dissolution enhancement is available. If enhanced dissolution is available, the recovery efficiency can be improved for the product from either the FBI or AD as compared to a straight nitric acid system.

The availability of an enhanced dissolution makes possible the use of some of the incinerators which operate at high temperatures. One of the primary criteria for an acceptable system in this application is the nuclear criticality control features of the process. The RKI and EAI are good candidate processes for this application.

The RKI has been designed to burn both liquid and solid TRU contaminated materials for recovery at the Rocky Flats Plant. The primary chamber normally operates at 800°C with 1000°C temperature maintained in the after-burner. The rotation of the kiln provides for continuous automatic removal of ash to minimize the inventory of fissile material in the unit. The ash will be in a well defined small stream the full length of a kiln. At least two failsafe conditions must be met to introduce liquid in the incinerator; i.e., minimum temperature and flame required to feed liquids and a double

gravity overflow to prevent scrub liquid backup into the kiln. These features allow the fissile material inventory to exist with minimal moderation and reflection. Of greater concern is the possibility of accumulating fissile material in off-gas cleaning equipment. A combination of geometrical size limitations, boron glass Raschig rings, and gravity overflow are used for criticality control. The system has undergone a complete nuclear safety evaluation and is suitable for handling a high concentration of fissile material on a continual basis. It was also designed to process a feed containing up to 50% PVC plastic and will accommodate a high level of noncombustibles. The unit at Rocky Flats is designed to process 45 kg/hr of high PVC content solid waste and chlorinated solvents, and could be adopted to greater throughputs.

The EAI at SRL was designed for a capacity of about 5 kg/hr of solid waste. Because of the low throughput, the unit could be satisfactorily operated with high concentrations of fissile material through administrative control on the feed to the unit. Because no liquid fuel is used in the primary chamber moderating conditions are minimized. Gravity removal of the ash is provided before the gas passes into the afterburner and the off-gas scrubbing system. The unit is well suited for a high concentration of PVC in the feed because the metal equipment exposed to combustion conditions is minimized. However, because of the small throughput, the capital cost per kg of waste capacity is high.

The EAI and the AD units are best suited to small capacity applications and are both higher cost units. The FBI and the RKI are more suitable to high throughput applications.

The AH, CAI, and SPI are not desirable candidates for combustion of high levels of fissile materials because of high inventory of ash in the equipment under normal operating conditions. The AH is operated batchwise, where the ash is accumulated from 5 hours of operation before discharge and the ash removal system does not permit for complete removal of the ash from the hearth plate. The CAI does not provide a method for

complete removal of ash from the hearth plate during normal operations and the total amount of waste inventory in the SPI incinerator would make it somewhat undesirable for high levels of fissile material. The SPI unit also produces a product form that would be unsuitable for processing for TRU element recovery. The high temperatures of operation of the CYC would limit its use for TRU recovery applications. The off-gas scrubbing equipment of each of these systems is not acceptable for treating off-gas from combustion of high levels of fissile material.

4.2.1.2 Transuranic Immobilization

Generally, the TRU combustibles, which are to be processed to produce an immobilized product for transportation and storage, will contain less fissile material than those processed for TRU recovery. This lower fissile material content will reduce the level of restrictions placed on the process for nuclear safety control. Since much of this waste material will be generated outside of glove boxes, it will contain less PVC plastic, which is primarily generated from glove box bagout operations. Since the objective is to convert the TRU combustible material to an immobilized product, either the incinerator should produce an immobilized product or should produce an intermediate product which would be compatible with subsequent processing to produce the immobilized product. The secondary waste produced by the incineration process will also have to be considered as a feed to an immobilization process. The secondary waste will include the salts produced from conversion of aqueous scrub solutions to a dry product.

If the waste is coming from a retrieval operation, it may not be well characterized. However, if the waste is being processed from a current operation, the waste may be well characterized and most of the noncombustibles could be segregated from the combustible materials. Each of these waste and site specific factors are considered separately in selection of suggested incineration processes.

The wastes are split into two categories for this discussion, those which are well characterized and those which are not well characterized. Newly generated wastes can usually be segregated and are thus well characterized. The major factor affecting the selection of a suitable incineration system will be the fissile material concentration level in the waste. For the waste generated in glove box operations, nuclear safety considerations discussed in Section 4.2.1.1 would apply to the selection of an incinerator. Therefore, the AD unit, the FBI, the RKI, and the EAI are acceptable for this application. Some of the immobilization processes being developed for subsequent treatment of ash or residue from the combustion unit may not be able to tolerate the high sulfate concentration of the AD residue. This could eliminate the use of AD for specific site applications.

The waste generated outside of the glove box line in the TRU processing areas will contain very low levels of fissile material. Less stringent restrictions can be used to maintain nuclear criticality control in the incineration operations. The four combustion processes identified as acceptable for the glove box generated waste could equally well be utilized for the non-glove box generated waste. In addition, the AH, CAI, and CYC are also considered technically acceptable for this application. However, because of the high capital cost per kg of waste processing capability in the case of the acid digestion and the EAI processes, they are undesirable candidates for this application. This is particularly true when several less costly processes are available covering a wide capacity range. For the SPI process to be suitable for this category of waste, it will have to be demonstrated at a much lower capacity than the present commercial systems. The cost of this unit is also very high per kg of processing capacity.

A slightly different set of conditions apply when the wastes are not well characterized and segregated. Major exhumation operations will produce a feed stream which is not well characterized and may contain a

significant quantity of soil as well partially decomposed packaging material and a composite of combustibles and noncombustibles. If the waste comes from an exhumation operation, it may contain a wide variety of TRU elements which may restrict the amount of sorting or treatment performed prior to processing. Because some of the waste may be from early operations of government laboratory and production facilities, each package may contain a wide variety of scrap metal, combustibles sludges, etc. Retrieval of more recently produced waste may result in a better segregation of combustibles from scrap metal and solid residues or sludges.

For the waste containing a low percentage of noncombustible material, the SPI, RKI, CAI, and AH are suitable candidates. However, if higher concentrations of fissile material are present in the waste, only the RKI process contains adequate nuclear criticality control features. The SPI is a highly desirable candidate if the concentration of the fissile material can be accommodated by the unit. This unit can accept a wide variation of feed composition and produces an immobilized product directly. A very low level of fissile material will be needed before the CAI or AH can be utilized. Because of the need for pretreatment or shredding of feed materials, the AD unit, the FBI process, and the EAI system seem to be less desirable candidates for this application. In addition, the EAI and the AD unit have high capital cost per kg of throughput capacity.

For the case where the waste would contain high percentages of noncombustible materials, the SPI unit and the RKI would be the only acceptable candidates. The RKI would be the preferred process for higher concentrations of fissile material. For lower concentrations of fissile material, the SPI may be the preferred process because of the direct conversion to an immobilized product form. The CAI and the AH are not well suited for processing waste containing large percentages of scrap metal or other noncombustible materials. Because of waste shredding requirements, the AD unit, FBI, and the EAI are not well suited for this waste application.

4.2.1.3 Reduced Volume and Gas Generation

The type of TRU combustible wastes which would be processed for volume reduction or elimination of gas generation characteristics can be considered comparable with those wastes processed for TRU immobilization. The waste and site specifications, presented in Figure 4-1, for this incineration objective are the same factors used for the TRU immobilization case. The logic used for selecting incinerator candidates is similar, except that because of the volume reduction objective, the SPI process would not appear to be a logical candidate. The product volume from this unit is larger than from other systems because of materials added to produce a slag. The candidate combustion processes suggested for this application are presented in Figure 4-1.

4.2.2 LLW Applications

In addition to reducing the volume of the low level waste, which could reduce transportation costs and conserve space at disposal sites, incineration of combustibles can improve the safety of transportation and disposal operations. Incineration will reduce the fire hazards of the waste and will produce an ash which is chemically inert. However, regulations may require some form of immobilization before shipment or storage. Three major waste and site specific factors, which will help in defining the type of combustion process that would be best suited for processing the low level waste, are presented in Figure 4-2.

4.2.2.1 LLW from Power Plant Operations

The major portion of the combustible LLW generated at power plants also has only low levels of β - γ activity. This waste generally will contain a high percentage of plastic and paper and lower percentages of cloth, rubber, glass, and wood. It can contain up to about 20% PVC plastic. The plants will also generate some waste oils, ion exchange resin, and sludges collected on filter elements. The ion exchange resin and sludge filters will tend to be of higher β - γ activity.

Most of the combustion processes considered in this report have been developed for use with TRU waste. They have not been tested with β - γ waste, and some development or testing will have to be done before they could be applied to β - γ waste. Most off-gas systems would have to be modified to remove volatile isotopes. Testing with spiked waste would then be required to evaluate the off-gas cleaning systems. Some development would be needed to evaluate the combustion processes for burning the types of ion exchange resin and oils in power plant waste. An experimental program is now under way to evaluate the controlled air incinerator for these types of materials, as well as removal of fission products from the off-gas.

Two processes, the FBI and the AD unit, have processed the types of ion exchange resins used in TRU operations. When resin is transported as a slurry and the water drained off, the resin beads will contain about 50 wt percent water. Experience has shown that resin beads containing 50 wt percent water will fracture when atomized in a high temperature process, resulting in premature carryover of unburned resin into the off-gas system. Also, resin burned in bulk on a hearth plate or pan tend to carbonize, preventing complete combustion unless continual mixing is provided. The addition of the resin beads under the aqueous surface in AD or under the surface of the bed in the FBI has resulted in good combustion of the resin. These two units are the best candidates for the high β - γ activity waste (resin and sludge filters) at the present time. Both systems would need testing for removal of the volatile isotopes. In the FBI process, iodine could be removed by reaction with the sodium carbonate bed material in the primary vessel. However, this would also have to be demonstrated. Both of these units could be designed and operated to minimize operator radiation exposure.

For the low β - γ activity waste (combustible trash and oils) the CYC, RKI, AH, and FBI are the preferred candidates. The AD unit has exhibited some problems in combusting normal paraffin hydrocarbons and may have problems with the waste oils. The capacity of slagging pyrolysis exceeds

that which would normally be required for power plant waste generation. The EAI and the SPI would be quite high in capital cost for this application.

4.2.2.2 Burial Site LLW

If the waste being received at a LLW disposal site is to be incinerated, one can expect a wide variety in feed composition and β - γ activity levels. The capacity requirements of an incinerator would be considerably higher than that for a power plant or single industrial application. The high β - γ activity waste may be segregated from the other waste because of shielding requirements during transportation. As discussed previously, the resin and high β - γ activity filters could be handled by a FBI or the AD process. However, if pathological waste such as animal carcasses are to be processed, a second incineration system may be necessary, such as the CAI, RKI, or AH incinerator. Because of the high cost and low capacity of the AD process and the EAI, these processes are not well suited for this application. The CYC process does not seem well suited for processing ion exchange resins or animal carcasses. It would appear suitable for processing only the drums of combustible trash, and because of its limited applicability to other waste, is not considered an acceptable candidate for burial site operations. Both the Molten Salt and the SPI units appear to add considerably to the quantity of waste product and are not well suited for processing at a burial site.

4.2.2.3 Institutional and Medical Wastes

Because combustible trash from institutional and medical facilities would be similar to the combustible trash from power plant operations, the same logic can be used to select suitable combustion processes. However, the volume of waste to be processed should be quite low and the incinerator for this application should either be a low capacity unit or a batch operation which could be started up and shut down easily. The CYC incinerator is the preferred candidate with the AH and the CAI being acceptable units. For the pathological wastes, the CAI would be the best process, utilizing supplemental firing and a long residence time to complete combustion.

5.0 CONCLUSIONS

1. Incineration of combustible radwaste can significantly reduce the volume of waste requiring immobilization and/or disposal. Incineration will eliminate the fire hazard and reduce the chemical reactivity of the waste subjected to subsequent processing, transportation, and disposal operations.
2. All of the incineration systems developed recently in the U.S. have been thoroughly tested and demonstrated suitable for processing the general trash, such as plastic, paper cloth, etc., which is common to TRU waste. However, many of these systems have not been demonstrated suitable for processing some specific waste components such as TBP-solvent mixture, ion exchange resin, or lead loaded gloves.
3. Each of the recently developed TRU waste incineration systems have been identified as a preferred candidate for one or more specific applications, as shown in Figure 4-1 and 4-2. The available systems represent capacities ranging 5 to 850 kg/hr.
4. The Fluidized Bed Incinerator, Rotary Kiln Incinerator, Electric Controlled Air Incinerator, and the Acid Digestion Unit were designed to accommodate high levels, as well as low levels, of fissile material. The Agitated Hearth, Controlled Air, and Cyclone Drum incinerators were designed for processing combustible waste with low concentrations of fissile material and extensive equipment modification would be required to implement the needed nuclear criticality control for these units to be suitable for processing high levels of fissile material.
5. A considerable benefit could be realized in terms of waste volume reduction and improved safety of low level waste operations if incineration is utilized. Many of the combustion systems developed

for processing TRU waste appear to be applicable to treatment of low level waste, however, they have not been tested with LLW, and the off-gas systems would have to be modified to accommodate removal of volatile fission products.

6. None of the recently developed TRU waste incineration have been demonstrated for total remote operation and maintenance.
7. The present burial ground capacities for low level commercial waste are adequate for present generation rate. However, reduction in amounts being accepted at specific sites and political disruptions of receiving waste at other sites has created a present need for incineration of commercial low level combustibles for volume reduction. The projected commercial LLW generation will exceed the burial capacities in 20 years unless additional capacity is developed. The present storage capacities for LLW and TRU waste at DOE facilities exceed the present waste volume and projected generation of DOE waste for the next 20 years. However, the projected volumes will exceed the storage capabilities at ORNL and LANL necessitating either shipment of waste to alternate sites or the use of incineration for volume reduction.

6.0 RECOMMENDATIONS

1. Research and development of TRU incineration should be pursued only in support of well defined specific applications. Generic background data is available on the incineration systems for present contact handled TRU waste.
2. The TRU waste incineration technology should be transferred to the commercial nuclear industry for processing low level waste. This will require experimental testing to demonstrate combustion of component waste materials, and removal of fission products from the incinerator off-gas. A technology transfer program for the Controlled Air Incinerator is providing technical advise and experimental information for commercialization of that system. If other systems are selected for low level waste application, they should be subjected to the same type of testing and evaluations.
3. Nuclear safety documentation should be provided for all incineration systems specifically designed for processing waste with high levels of fissile processing material. The Acid Digestion Unit, Slagging Pyrolysis, Electric Controlled Air, and Rotary Kiln Incinerator sytems will be, or are being, implemented in production operations and the nuclear safety data should become available as a part of the implemen-tation activities. The Fluidized Bed Incinerator was designed to process waste containing up to 0.8 percent ^{239}Pu . Since the unit has not processed glove box generated waste, nuclear safety experiments should be conducted and the process demonstrated with actual glove box generated waste as a part of the nuclear safety documentation. For incinerators which were not constructed with TRU waste management funds, such as the Rotary Kiln, the documentation of nuclear safety and operating information is more important because the present published information is somewhat limited.

4. Remote operation and maintenance of an incineration system will be needed if low level waste with high levels of β - γ activity are to be processed. The used ion exchange resin and cartridge filter from nuclear power plant operations represent the types of high β - γ waste materials. The Acid Digestion Unit and the Fluidized Bed Incinerator are the preferred candidates for this type of waste because of their demonstrated ability to process ion exchange resin, and they do not utilize refractories which can become impregnated with β - γ type materials. If the presently planned combustion tests of resin and oil in the CAI (as a part of the commercialization of that system) are successful, this unit will also become a logical candidate for remote process development work. Design and experimental work will be required to demonstrate remote operation and maintenance of any of the TRU combustion systems if the TRU waste technology is to be applied to high β - γ waste.

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8.0 APPENDICES

APPENDIX AAppendix A
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EARLY UNITED STATES RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFF GAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
I. Mound Laboratory Miamisburg, OH	1948-1950	Pilot Unit - Other unknown	Steam injector, water cooled expansion chamber, spray/packed tower	Unknown	Unknown	Limited use, retained 98.8% radioactivity
	19507	Pilot Unit - Electrically heated; tangential air nozzels into stainless steel vertical tube with bottom grate	Coarse filter, water spray, heat exchanger, scrubber, heat exchanger, steam nozzle, expansion chamber, heat exchanger, scrubber, filter	6.8	Unknown	Appears only 5 cold & 7 hot runs made, burning 9.1 kg waste generated 1260 gal. of contaminated water
II. Knolls Atomic Power Laboratory, Schenectady, NY	1949-1950	Pilot Unit; unknown other than pure oxygen used and bottom grate for ash dropout	Condensation column, sulfur burner to remove oxygen, agglomeration section, CO ₂ packed absorption tower, centrifugal waster, reheater, CWS filter	9.1	Unknown	Tried to "dead end" offgas, performed very poorly, system redesigned in 1950
	1950-1951	Retained from 49-50 pilot unit; added firebrick wall and propane gas burner	Settling chamber, scrubber, condensor, reheater, coarse filter, CWS filter	18.2	Unknown	Problems with filters and scrubber lines plugging, some corrosion
III. Argonne National Laboratory Argonne, ILL	1951-1955	All welded stainless steel vertical cylinder with movable grates; primary air nozzles below grates; secondary air and gas burners above grate	Ten plate centrifugal gas washer, venturi scrubber, Peabody scrubber, reheater, AEC filters	68(max)	>50mR/hr	Some corrosion and plugging problems, cost-benefit analysis showed unit economic only with 24 hr operation so shut down
IV. Los Alamos Scientific Laboratory Los Alamos, NM	1951-1953	Production unit with batch charging; cylindrical combustion chamber with tangential underfire air below grate and overfire air above grate; auxillary gas burners	Dry cyclone, spray cooler, venturi scrubber, two-stage fiberglass filter	45-91	Essentially None	Waste not presorted, burned in cardboard shipping box, poor combustion and overpressure large problems, noncombustibles clogged grate

EARLY UNITED STATES RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFF GAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
V. Bettis Atomic Power Laboratory West Mifflin, PA	1953-1969	Cylindrical firebrick lined combustion chamber of steel, tangential air nozzles; bottom grate	Fog spray nozzle, rotocloner, damper	Unknown	>40mR/hr	Consisted of two nearly identical units, 1 started 1953, other in 59, shut down due to high maintenance costs
VI. Shippingport Atomic Power Station, PA	Unknown	Unknown	Unknown	Unknown	Unknown	Problems with incomplete combustion due to low temperatures
VII. United Nuclear Industries Richland, WA	1949-1960's	Open pit or trench	None	Unknown	Unknown	Discontinued after empty oil drum explosions
	1967-1971	Natural draft incinerator over an ash pit	None	Unknown	Unknown	Were two units, one started in 1967, other in 1968, wastes now buried directly
VIII. Bureau of Mines, Combustion Research Pittsburgh, PA	1954-1955	Pilot Unit - Cylindrical steel combustion chamber feed tangential overfire air; cyclone type; called BOMAEC-30	Heat exchanger, glass-fiber bag filters, AEC type filter	Unknown	Contaminated wastes, cold tested only	Tried only on sawdust, tested by Harvard Air Cleaning Lab., ACL, and judged unsatisfactory
	1955	First modification of BOMAEC-30 with deeper combustion chamber	Spray cooler added to above	Unknown	Contaminated wastes, cold tested only	Tried on sawdust mixed with rubbish, ACL tests showed still unsatisfactory

EARLY UNITED STATES RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFF GAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
IX. Harvard Air Cleaning Laboratory Boston, MASS	1955 (approx)	Second modification of BOMAEC-30 with auxillary air nozzle at top and gas burner	Spray cooler added to above	Unknown	Contaminated wastes, low temps and cold tested only	ACL tests showed rapid bag filter plugging
	1955 (approx)	Final design of BOMAEC-30 with top waste feed, otherwise similar	Same as above	Unknown	Unknown, never operated	ACL analysis indicated unit was not workable
	1955 (approx)	Called BOMAEC-100, a larger version of BOMAEC-30	Same as above	Unknown	Unknown	ACL tests gave similar results to BOMAEC-30
	late 1950's	Pilot Unit - 55 gal. drum lined with firebrick; tangential over-fire air; had grate; ash clean-out port; upper drying chamber	Unknown	Unknown	Contaminated wastes cold tests only	Burned sawdust only, sometimes charges extinguished flames or started burning in drying chamber
	late 1950's	Modification of above pilot unit; with side charging door; brick lined afterburner with auxillary air inlet; sliding fork above grate for drying charges	Air dilution, crushed stone and slag-wool filter	Unknown	See above	Fiber filters and electrostatic precipitators were both tried and worked poorly, specifications were published

EARLY UNITED STATES RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFF GAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
X. U.S. Army Nuclear Defense Laboratory Edgewood Arsenal, MD	1963-?	Production Unit - Primary combustion chamber with tangential overfire air; secondary chamber with tangential auxiliary air; both refractory lined	Air dilution, cyclone, electrostatic precipitator, high efficiency filter bank	22.7	High level wastes	Strontium became fixed in refractory, much warpage, funding problems & licensing requirements shut unit down
XI. Uranium Waste Incinerators:						
A. United Nuclear Corp. Montville, CT	Early 1960's	Production, otherwise unknown	Auxiliary fly-ash settling, stack	95.3	High level wastes	-----
B. Metals & Controls Attleboro, MA	Early 1960's	Production, otherwise unknown	Cyclone, low stack	90	Unknown	All contaminated combustibles burned
C. Pratt & Whitney Middletown, CT	Early 1960's	Production, otherwise unknown	Exhaust stack	272	High level wastes	HLW burned in 55 gal. drum which vented to same stack
XII. G.E. Atomic Power Dept. San Jose, CA	1960-1962	Production Unit - Three chambers, firebrick lined with gas burners to maintain 800°C temperature; removable ash tray	Baffled water-spray cooler to 315°C, prefilter, absolute filter	45.5	Plastics, rubber, tape	Used to burn uranium contaminated paper and polyethylene, unit couldn't meet load so shut-down, filter problems from condensation
XIII. Nuclear Materials and Equipment Corporation Apollo, PA.	1969-1971	Full scale prototype; single refractory lined chamber with baffles & three gas burners to effect three chamber combustion	Hot unit to have: cyclone, absolute filters, wet scrubber, heater, final absolute filters; prototype had stack only	9.1	Contaminated waste, cold waste only	Hot unit never built due to economics, burning of polyethylene produced heavy black smoke

APPENDIX B

RECENT UNITED STATES RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFF GAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
I. National Lead Company of Ohio Fernald, OH	1954-?	Production - Refractory lined; 3 chamber unit; first chamber is primary burn for oil and secondary for trash, afterburner has gas burners	None, direct exhaust from afterburner to stack	998	Plastics	Low enrichment uranium contaminated trash and oil sludge are burned, no major problems
	1962-?	Production Unit - of tall, refractory lined cylinder with bottom air lance and ash rakeout ports	None, stack integral with incinerator, uranium release of .23kg/24 hr estimated	~72	Any waste other than graphite	Graphite is sized to ~12 cm dia. pieces, operation is only 4 wks/yr, ash is ~60% uranium
	1957-?	Production Unit - of burner pot in bottom of tall stack; compressed and blower air fed at bottom; six tank system for removing sludge-water-volatiles and heating makes up pretreatment system	None, stack integral with incinerator	45	Any waste other than oil	Operation of 4-6 wk/yr, burning of TBP-kerosene causes nasal irritations downwind of stack
II. United Nuclear Corp. Wood River Junction, RI	1967-1974	Production - Single chamber unit with gas burner	Cyclone, scrubber system	45.5	Unknown	Evidence of incomplete combustion, NRC closed down unit due to "problems in effluent control"
III. Goodyear Atomic Corp. Piketon, OH	1971-?	Production Unit - Commercial (Mark VI radiator); refractory lined, dual chamber with gas burner in secondary chamber	None, direct exhaust to stack from secondary chamber	2270kg/mo	Unknown	Batch basis operation on uranium contaminated waste
IV. Union Carbide Corp. K-25 Plant Oak Ridge, TN	1972-?	Production - Dual chamber unit; primary chamber has underfire air and gas burner	None, direct exhaust to stack from secondary chamber	Unknown	Rubber, PVC	Unit is cycled daily from hot to cold, burns uranium containing floor sweepings

RECENT UNITED STATES RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFF GAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
V. Union Carbide Corp. Paducah, KY	Unknown, re-started in 1976-7	Unknown	Scrubber	Unknown	Unknown	Had corrosion problems and poor scrubber efficiency
VI. Union Carbide Corp. Y-12 Plant Oak Ridge, TN	~1955-?	Production - Single vertical cylinder; refractory lined with rabble arm and two gas fired burners	Heat exchanger, cyclone, multi-tube dust collector, air dilution, baghouse	20	PVC and rubber content are controlled	Used for highly enriched uranium waste, some containment problems, only one baghouse fire, refractory replaced every 2-3 years
VII. Gulf General Atomics San Diego, CA	1963-1965, 1973-?	Production - Multi-chamber, fire brick lined unit; primary chamber with propane burner; secondary also with propane burner; and mixing chamber with additional air	Long duct with four wire mesh screens, baghouse, filter unit	8-10 barrels per 8 hr day	Plastics, rubber	Used for enriched uranium waste, charging limit for U-235 controls operation, long duct with screens was added in 1973 to prevent filter failures in baghouse
VIII. General Electric Nuclear Fuel Plant Wilmington, NC	1970-?	Production - Commercial (Vortex Incinerator) unit; blown waste is fed tangentially into fire-brick cylindrical chamber; natural gas burner used to maintain temperature	Wet spray scrubber, mist eliminator, reheater, pre-filter, HEPA filters	227	Liquids	Problems have been - shredder damage from metal, contamination from pneumatically conveying waste, corrosion problems in scrubber & mist eliminator, plugged filters, large natural gas usage

RECENT UNITED STATES RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFF GAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
IX. Westinghouse Nuclear Fuel Division Columbia, SC	1974-?	Production - Dual chamber, refractory lined unit; primary and secondary chambers both have burners and air inlets	Wet spray scrubber, demister, prefilters, HEPA filters	Unknown	Unknown	Used for slightly enriched uranium waste, problems with scrubber liquid filters plugging and high HEPA use rate, operation controlled by U-235 limits
X. Nuclear Fuel Services, Incorporated Erwin, TN	Unknown	Production - Commercial (Combustion by Air Preheater) unit of air preheater; primary refractory lined chamber with gas burner; afterburner with additional air input	Spray prescrubber, venturi scrubber, disengaging tank, stack	272	Unknown	Operation controlled by U-235 limits
XI. Kerr-McGee Nuclear Corporation Crescent, OK	1972-?	Production - Refractory lined, dual chamber unit with two gas fired burners; batch ash removal	Dilution air, baghouse, filters	~72	PVC	Operation controlled by U-235 limits, low combustion temperature requires ash treatment to remove residual carbon
XII. Los Alamos Scientific Laboratory Los Alamos, NM	1952-1959 -rebuilt- 1959-?	Production - Stainless steel burn basket in electrically heated 316SS tube; pure oxygen used as oxidizer; batch feed and ash removal; rebuild included parts replacement; excessive pressure relief vent; and addition of another glove box	Water-filled bubbler, heat exchanger, slight warming, Nash vacuum pump, plant-process air-exhaust system	to .5	Plastics & rubber whenever possible	Have had one baghouse fire, designed for plutonium recovery from wastes, some pressure excursions from HNO_3 fumes forming nitrocellulose, otherwise very few problems, duplicate unit is being installed in new Pu processing facility

RECENT UNITED STATES RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFFGAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
XIII. Yankee Atomic	Late 1960-?	Production - Single chamber with vortex air flow	Rotoclone, deep-bed glass wool filter, stack	18.2	Plastics	Reportedly has worked well
XIV. Mound Laboratory Miamisburg, OH	Unknown	Essentially identical to LASL unit above, XII, also for Pu recovery	Heat exchanger, bubbler vessel, caustic scrubber tower, mist eliminator, casson filter, HEPA filter	~20gal/day	PVC, glove box gloves	Very few operational problems
XV. Rockwell International Rocky Flats, CO.	1959-?	Production - For Pu recovery; dual chamber, firebrick lined unit, supplementary oxygen is used to maintain temperature	Heat exchanger, second heat exchanger, caustic spray cooler, wet venturi scrubber, wet cyclone, mist eliminator, filters	16	Potentially explosive materials	Original offgas system was dry and had filter fires, have salt build-up problems in caustic spray cooler, ash contains ~30% carbon
	Projected for 1982	Production - For waste containing $<3 \times 10^{-3}$ mg of Pu/gm of waste; refractory lined, vertical cylinder with air cooled rabble arms primary; refractory lined afterburner; both chambers have diesel fuel fired burners	Wet venturi scrubber, gas liquid separator, wet venturi scrubber, gas-liquid separator, four stage HEPA filters	68	Liquids	System is set up for glove/remote operation, ash discharge is essentially batchwise
	Projected for 1982	Production - For waste containing $<3 \times 10^{-3}$ mg of Pu/gm. of waste; refractory lined, rotary kiln, diesel fired burner primary chamber, refractory lined afterburner with diesel-fired burner	Essentially same as above with exception of borosilicate Raschig rings in first separator and geometry changes for criticality safety	41	Essentially none	HEPA filters, rubber gloves, graphite and used resins will be compaigned thru, have extensive safety and backup systems

RECENT UNITED STATES RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFFGAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
XVI. Atlantic Richfield Hanford Company Richland, WA	1961-?	Production - For Pu recovery; high alloy semicylinder tube for primary chamber connected to high alloy tubular secondary with four flue risers, electrically heated, conveyer system moves waste thru primary chamber	Two cyclones in series, quench-spray scrubber with baffles, reheater, prefilter, two stage HEPA filtration	~1.9	Leaded gloves	Had been shut down but possible restart in 1976, incinerator chambers have been replaced three times due to thermal and corrosion cracking, conveyor belt last ~6 mo., combustion is incomplete, flashback has occurred, still have plugging problems
XVII. Idaho National Engineering Lab	1978-? Built but in storage	Production - Combustion occurs in molten salt bed of 90% Na ₂ CO ₃ and 10% Na ₂ SO ₄ ; alumina brick lined cylinder, waste feed by screw feed and pneumatics, propane burner for startup, coke added for temperature control	Mist eliminator, waster cooler, baghouse, reheater, HEPA filters	50	Alpha waste	In-situ acid gas neutralization reduces corrosion, NaCl volatility causes some particulates in offgas, system in storage due to hands on/internal maintenance requirements
XVIII. Babcock & Wilcox Lynchburg, VA	1972-?	Production - Refractory lined unit with gas fired primary chamber and gas-fired afterburner in the exhaust duct	Venturi wet scrubber, stack	79.4	Unknown	No data available on problems, operation controlled by U-235 limits

APPENDIX C FOREIGN RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFF GAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
I. UNITED KINGDOM						
A. Harwell, Berkshire	1950-1953	Pilot - Vertical tube with one stage combustion	Gas cooler, scrubbing tower, glass felt filter	Unknown	Unknown	
	1954-50's	Pilot - Grate type with air cooled walls and one stage combustion	Fly ash settler, water spray cooler, venturi scrubber, cyclone, heater, three stage filtration	Unknown	Unknown	Corrosion problem with stainless steel incin., lowered operating temp but often incomplete combustion and three filter fires, so replaced dry system with 1954's wet system both 1959 and 1962 units were operating in 1970
	1959-7	Production - Annular, refractory lined, with grates, natural gas auxillary burners	Heat exchanger, roughing glass bag filters, three absolute filters	180(design) 100(oper)	Unknown	
	1962-7	Experimental - Two chamber; fire brick lined; oil burners in both chambers	Heat exchanger, cyclone, electrostatic precipitator, absolute filter	To 27	High Level Wastes	
B. Windscale, Cumberland	1973 to present	Pilot - Electrically heated, Inconel 600, tubular primary chamber with 3 separate vertical afterburner chambers in series also electrically heated	Spray column, coolers, roughing filter, demister, heater, absolute filter	5	Unknown	Corrosion of primary furnace tube and off-gas lines have been problems, ash sometimes up to 22% carbon similar to electric air at SRP
C. Bradwell	Operated in 1967	Production - Uses afterburner	Cyclone, absolute filters	18,000 kg/yr	>9.5mR/hr levels	
D. Berleley, BNL	Operated in 1967	Production - Uses afterburner	Water scrubbing, absolute filters	37,000 kg/yr	>15mR/hr levels	
E. Hunterston "A"	Operated in 1967	Production - Unknown	Unknown	74m ³ /yr	>3mCi of ³⁵ S	

FOREIGN RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFF GAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
II. FRANCE						
A. Cadarache Nuclear Study Center	Unknown	Production - Primary chamber for pyrolysis & combustion; secondary combustion chamber; fly ash settler with soot burning	Cooling chamber, air dilution to $<200^{\circ}\text{C}$, packed tower scrub, heater, pre-filter, absolute filter	30 for Solids - 10 for Liquids	Non-TRU Waste, PVC whenever possible	Study being made to permit burning TRU waste
B. Fontenay-aux-Roses Center (CEN-FAR)	1967-?	Production - Very similar to Cadarache	Cooled by air dilution to $\sim 350^{\circ}\text{C}$, further cooled to $\sim 130^{\circ}\text{C}$, glass-wool bag filter, asbestos absolute filters	50 for Solids - 15 for liquids	Unknown	Have offgas corrosion problems from PVC combustion
C. Strasbourg - Cronenbourg, CNRS	1970-?	Production - Vertical primary chamber with oil burner and stairstep grate for combustion of plastics; secondary chamber with separate oil burner; all refractory lined steel	High temp. filter of asbestos filled micro-expanded refractory metal which allows soot burnoff, air dilution to $\sim 150^{\circ}\text{C}$, two stage absolute filters	15	Unknown	Primarily for contaminated animal remains, can handle small quantities of solvents
D. Marcoule	1964- To Present	Production - Three firebrick chambers; primary separated by bridge-wall from secondary; expansion chamber; propane burners in first two chambers	Two heat exchangers to lower gas to 150°C , cyclone, anti-spark mat, glass-fiber bag filters, prefilter, absolute filter, acid scrub column, demister	60-70 (solids) 50%/hr (oil)	PVC whenever possible	Feed is usually blended stream of oil and shredded waste
	1970 - To Present	Pilot - One piece cast refractory in metal shell with main combustion and afterburner chambers; both electrically heated	Air dilution to cool to 300°C , heat exchanger cools to 60°C , double absolute filters, HCl is not treated	1	Non-Pu Contaminated waste	Incinerator was built as part of plutonium recycle system, screw conveyor system for feed hasn't worked satisfactorily

FOREIGN RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFF GAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
D. Marcoule (Continued)	To Be Built	Production - Very similar to above pilot unit	Will use high temp. filter like Strasbourg-Cronenbourg unit	10	Unknown	
E. Grenoble, CEN-G	1961-1964	Pilot - Unknown	Cyclone, Water scrubber	~8	See Comments	Unit was built specifically to handle biological & organic waste, unit will handle solvents
	7-Present	Production - Primary combustion chamber with after burner	High temp. filter like H.B., air dilution to cool to ~140°C, absolute filter	Unknown	Alpha Waste	Unit was built specifically to handle biological & organic wastes unit will handle solvents
III. BELGIUM						
A. Belgium Nuclear Center, Mol	1960's	Production - Three chambers; lined with refractory brick; first chamber for combustible wastes; second for other wastes (animal remains); third as afterburner for first two; propane burners for temperature control	Several systems tried, end system had cooler, expansion chamber, packed tower, electrostatic precipitator, absolute filter	200(max)	>200 mR/hr level	Many corrosion problems, most in offgas system
	1970-?	Pilot - Tangential; propane burner to maintain temperature	Cyclone, heat exchanger, sand filter, wet cleanup system	10	Unknown	Are investigating a slagging unit for ash treatment
	1977-?	Production - Slagging type, conical primary chamber of tamped refractory; afterburner with secondary air, ash melts at bottom of primary and drips into quench tank, fuel oil-fired burner in primary	Input air preheater, heat exchanger, sand panel bed, heat exchanger, caustic wet scrubber, preheater, HEPA filters, preheater, stack	100	PVC when possible	Sand may be added to increase slagging and Na ₂ CO ₃ to neutralize acid gases, waste must be sized to less than 5 cm. dimension to fit waste feed system, hot operation planned for 1979
IV. PORTUGAL						
Sacavem Center	Planned	Pilot - Barred grate and rocking plate	Cyclone, dry filters	25	High level waste	Primarily for small animal bodies

FOREIGN RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFF GAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
V. REPUBLIC OF GERMANY						
A. Nuclear Research Center, Karlsruhe	1963-1970	Pilot - Vertical tube; refractory lined; two bottom air feeds, gravity ash drop	Course, SiC filter which is also afterburner at 900°C, fine SiC filter at 600°C, tar separator at 80°C	Unknown	High level wastes	Original offgas system had bag filters also several fires, had some problems with pressure surges
	1971 To Present	Production - Similar to; but larger than pilot	Similar to pilot plant, except no tar separator and air dilution used after fine filter	50-70	Alpha wastes	Have parallel filter systems, wet scrubber system for high levels of activity in offgas
B. Other	Unknown	Pilot - Electrically heated vertical tube with precombustion chamber; grate; and afterburner chamber	Cyclone, air dilution, coarse filter, fine filter	~10	>100mCi/kg	Specifically for animal waste disposal
VI. INDIA						
A. Bhahha Atomic Research Center Trombay	1963-1966	Pilot - High alumina refractory vertical tube cast in one piece with bottom air feed and kerosene burners	Cooled in long, bare ducts to ~200°C, single bag fabric filter, asbestos glass absolute filter	11.3 (design) up to 22	All other than wood	For thorium contaminated wood waste, little corrosion even with C. steel and 310SS materials
	1966-?	Production - Two separate chambers of refractory lined steel; primary with underfire air and gravity ash drop; oil burners	Cyclone, then same as above pilot unit	45	>200mR/hr, alpha waste	

FOREIGN RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFF GAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
VII. JAPAN						
A. JAERI, Tokai	1966-?	Production - Upper primary combustion chamber; grate; lower secondary chamber; refractory lined; both chambers oil fired	Spray-scrubber, cyclone, electrostatic precipitator, cooler-heater unit, cloth filter, HEPA filter	50	>50mR/hr, alpha waste, plastics, rubber	Corrosion problems in offgas system, similar 30kg/hr unit is also operated
	1973-?	Pilot - Unknown	High temperature alumina filter (800°C), secondary alumina filter	12	Alpha wastes	Built to test alumina filters
B. Oavai Research Establishment at JAERI	1973-?	Production - Primary, secondary, tertiary, & final combustion chambers; cooling air introduced in final chamber; kerosene burner in primary; propane in secondary	Last 2 chambers act as settling basins, 2 heat exchangers in series, electrostatic precipitator, heat exchanger, dry filters, caustic wet scrubber	~30	Alpha wastes, >50mR/hr	Plastics & rubber are limited to <30% by weight, some corrosion problems in offgas equipment
VIII. CANADA						
A. Chalk River Nuclear Laboratory, Ontario	1960-1961	Pilot - Refractory-insulation-steel construction; primary chamber with propane burner to maintain 815°C; mixing chamber where overflow air introduced & 2nd propane burner to maintain temperature; secondary combustion chamber last	Spark hold-up tank, air dilution to cool, glass-cloth bag filters, absolute filters	to 250	>200mR/hr	Serious cracking of refractory curtain wall occurred, operation found to be uneconomical
B. Douglas Point Station, Ontario	Unknown	Unclassified - Open pit	None	Unknown	> 26mR/hr	Used on nuclear power plant waste

FOREIGN RADIOACTIVE WASTE INCINERATORS

LOCATION	PERIOD OF OPERATION	INCINERATOR TYPE	OFF GAS SYSTEM	CAPACITY (kg/hr)	COMBUSTIBLE WASTES NOT ACCEPTABLE	COMMENTS
C. Bruce Nuclear Complex, Ontario	Scheduled 1976 start	Production - Controlled air; batch loads; primary chamber with gas heated afterburner	Cooled to 204°C, bag filters	Unknown	Unknown	For disposal of nuclear generating station waste
D. Chalk River Laboratory Ontario	Planned	Pilot - Similar to Bruce Nuclear Complex	Similar to Bruce Nuclear Complex	Unknown	Unknown	For filter testing, will be smaller than Bruce Nuclear