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Decontamination of Metals by Melt Refining/Slagging

An Annotated Bibliography: Update on Stainless Steel and Steel

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EXECUTIVE SUMMARY

The following presentation is an update to a previous annotation, i.e., WINCO-1138 (Worcester, et al, 1993). The literature search and annotated review covers all metals used in the nuclear industries but the emphasis of this update is directed toward work performed on mild steels.

As the number of nuclear installations undergoing decontamination and decommissioning (D&D) increases, current radioactive waste storage space is consumed and establishment of new waste storage areas becomes increasingly difficult, the problem of handling and storing radioactive scrap metal (RSM) gains increasing importance in the DOE Environmental Restoration and Waste Management Program. To alleviate present and future waste storage problems, Lockheed Idaho Technologies Co (LITCO) is managing a program for the recycling of RSM for beneficial use within the DOE complex. As part of that effort, Montana Tech has been awarded a contract to help optimize melting and refining technology for the recycling of stainless steel RSM. The scope of the Montana Tech program includes a literature survey, a decontaminating slag design study, small scale melting studies to determine optimum slag compositions for removal of radioactive contaminant surrogates, analysis of preferred melting techniques, and coordination of large scale melting demonstrations (100-2,000 lbs) to be conducted at selected facilities. The program will support recycling and decontaminating stainless steel RSM for use in waste canisters for Idaho Waste Immobilization Facility densified high level waste and Pit 9/RWMC boxes. This report is the result of the literature search conducted to establish a basis for experimental melt/slag program development. The program plan will be jointly developed by Montana Tech and LITCO.

There are a significant number of publications that include information on decontamination of radioactive scrap materials, e.g., a search of Chemical Abstracts alone shows over 400 publications. At this time approximately 380 publications have been identified that are related to the decontamination of metallic scrap. A large number of literature databases have been searched. Titles, abstracts, and publications have been recovered and reviewed. Information and experimental test results are summarized in Table 2-1. Summary of Large-Scale Ferrous Melt Consolidation/Refining Program, and Table 6-2. Melt/Slag Refining Test Work Results for Uranium and Plutonium Decontamination of Metals and Alloys.

A conclusion resulting from the review of published literature by Worcester, et. al, (1993) was that test work (both bench scale and larger scale) demonstrated that slagging decontamination of uranium and plutonium from steel and stainless steel is an effective treatment technology. Laboratory and large scale test work performed at Montana Tech (Worcester, et al, 1994) and laboratory test work performed at the Oregon Graduate Institute (Atteridge, et al, 1994) have further demonstrated (using surrogates for the radioactive nuclides) effective decontamination to concentrations less than one part per million) using induction melting (in air) and electroslag melting, respectively.

Based on trends found in the literature, basic calcium-aluminum-silicate slags (with additives such as calcium fluoride, nickel oxide, ferric oxide) appear to be effective steel decontaminators. However, the recent work of Worcester (1994) demonstrates that flux composition is not very important when the decontamination is conducted in air exposed induction melting furnaces.

At present it appears that removal of most radionuclides by slagging and volatilization holds good possibilities for the treatment of steel scrap. The same slagging/volatilization possibilities appear to exist for stainless steel, except for the specific elements that constitute stainless steel. Radionuclides of iron, cobalt, nickel, manganese and chromium will be retained to a large degree in the metal product. These radionuclides could be incorporated in a melt from two sources: (a) metal that was exposed to a neutron flux in a reactor, and/or (b) metal that would have incompletely removed surface contamination containing these radionuclides.

Tritium removal was not considered in the keyword search nor was analytical data provided in any of the publications reviewed. This issue was the subject of a joint LITCO/Savannah River Technical Center (SRTC)research initiative. (Imrich, 1994)

The technological community has selected two technologies for melt/consolidation of ferrous RSM, coreless induction and electric arc furnace (EAF) melting. The choice between these two technologies involves many factors. The main factors favoring coreless induction are better melt agitation, easier fume control, and rapid heat up. These factors are particularly important when considering an initial consolidation/homogenization melt of RSM, and are the primary reasons why induction melting was selected for most of the "large scale" RSM melting described above. On the other hand, the EAF provides lower cost as heat sizes increase, accommodates larger scrap section sizes, allows for easier modification of melt composition, and provides a greater margin of reliability and safety because of the absence of the water cooled induction coil. According to Reimann (1991), an induction furnace produces 20% as much effluent dust as an EAF of similar capacity.

In the authors opinion, the reduction of effluent dust should be a major factor in furnace selection. This is of significance when designing a capture system which will control the dispersal of a significant portion of the long-lived radionuclides (e.g., Cs-137).

It appears quite obvious that melt decontamination alone will not provide steel which qualifies for free release, particularly if the trend reflected in Europe in 1989 (Janberg, 1990) toward lowering free release limits from 3.7 Bq/g to 0.1 Bq/g continues. Essentially none of the products discussed in the large scale melting section could be released under the criteria established in Europe in 1989. It might be argued that free or controlled release is not necessary; however, consolidation of RSM and removal of volatile and easily oxidized radionuclides could be accomplished in DOE-controlled melting facilities. Melt consolidated and characterized RSM from these facilities could then be released, on a controlled basis, to the steel industry for efficient incorporation into large heats for manufacture of nuclear waste or fuel containers.

The availability of stainless steel RSM at INEL and other DOE sites and the need for stainless steel for waste canisters present a unique opportunity. Methods for consolidating stainless steel RSM can be developed on a commercial scale while developing protocol for disposal of carbon steel scrap at a later date. Carbon steel might also be combined with characterized nickel RSM to produce additional quantities of stainless steel for use within the DOE program (Mizia, 1993). This approach was pursued by Manufacturing Sciences Corporation. (Nichols, 1994)

Analysis of the literature suggests the following approach:

> Decontaminate and melt stainless steel RSM into heats of sufficient size to minimize radionuclide characterization and analytical costs while casting the material into suitable shapes for recycle into a limited release remelt program, use in simple shapes in the nuclear industry, or disposal into low level waste repositories.

Such an approach would provide volume reduction while establishing protocol for at least limited release into the commercial scrap market. One of the problems associated with trying to do on-site casting of stainless heats for fabrication into canisters is the small heat size inherent in such an approach. Small heat sizes significantly drive up production costs while increasing certification costs and complexity without improving quality. Even if the largest U.S. RSM furnaces were used for ingot casting, heat size would only be 20 tons. Fabrication and QC costs for such small heats would be prohibitive. On the other hand, if characterized first melt RSM ingots were released to a commercial stainless melter/fabricator for use as scrap addition to heats, quality could be improved, with minimal risk, by relying on the melting and fabrication expertise of the steel industry .

The program suggested in the original bibliography (Worcester, 1993) follows:

- "Decontaminate and melt RSM within the DOE complex into a configuration which is acceptable for use in the commercial scrap market, for use as shielding blocks, or for land disposal. Melting parameters would be optimized for transfer of radionuclides into slag and fume, homogenizing the melt, and minimizing slag inclusions.

- Release heats which meet release specifications to a commercial stainless melter/fabricator for combination with non-contaminated melt stock into large heats for fabrication into DOE program products. These products might include 55-gallon drums for low-level nuclear waste disposal, Hot Isostatic Pressed (HIP) canisters for Idaho Chemical Processing Plant (ICPP) waste immobilization, overpack canisters for ICPP-HIP canisters, and multi-purpose containers for storage of spent nuclear fuel.

- Use non-qualifying heats for internal use, land disposal, or remelting within the DOE complex. Remelting might involve further melt refining, possibly by induction ladle metallurgy as proposed by Reimann (Reimann, 1991) or electroslag melting."

A more realistic approach may well be the establishment of a regional or national RSM processing center within the DOE complex equipped to decontaminate, melt refine, cast, roll, and final fabricate the hardware required for nuclear waste disposal.

The suggested approach is supported by the following observations:

- Free release requirements will become tighter with time.

- The steel industry is unlikely to accept RSM-derived material for input to conventional facilities.

- It is unlikely available quantities of RSM will justify more than one-large-scale processing facility. Canister quality will be enhanced by utilization of larger equipment. Quality and certification costs for containers will be significantly reduced on large heats while real quality will be improved. Consolidation of stainless steel RSM will undoubtedly introduce some carbon pickup, necessitating AOD or VOD for economical processing of low carbon stainless steel. Such refining will not be necessary for carbon steel.

- Some radionuclides will not be removed by any practical melting process known today (e.g., Co, Fe, Mn).

- Stainless steel scrap can be consolidated for costs which should allow release to the commercial market, at least on a break-even basis ($400/ton), disregarding burial costs for RSM. Mizia (1994) analyzed allowable costs for stainless RSM recycle. In the most likely scenario, burial costs were pegged at $668/cubic foot. A savings of $35,000 per 20 short ton (empty weight) canister was estimated. This estimate allowed a $2.10/lb tolling charge and a 15% premium for fabrication of the canister from RSM. Projected savings are highly dependent upon burial costs.

- Experience gained from this program should pave the way for limited release programs for carbon steel which must involve melting and releasing to large-scale facilities at much lower break-even costs ($100/ton), disregarding burial costs for RSM.

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DECONTAMINATION OF METALS BY MELT REFINING/SLAGGING

1. INTRODUCTION

1.1 Introduction

As the number of nuclear installations undergoing decontamination and decommissioning (D&D) increases, current radioactive waste storage space is consumed and establishment of new waste storage areas becomes increasingly difficult, the problem of handling and storing radioactive scrap material (RSM) gains increasing importance in the DOE Environment Restoration and Waste Management Program. To alleviate present and future waste storage problems, LITCO is managing a program for the recycling of RSM for beneficial use within the DOE complex. As part of that effort, Montana Tech has been awarded a contract to help optimize melting and refining technology for the recycling of stainless steel RSM. The scope of the Montana Tech program includes a literature survey, a decontaminating slag design study, small scale melting studies to determine optimum slag compositions for removal of radioactive contaminant surrogates from carbon and stainless steels, analysis of preferred melting techniques, and coordination of large scale melting demonstrations (100–500 lbs) to be conducted at selected facilities. The program will support recycling and decontaminating stainless steel RSM for use in waste canisters for the Idaho Waste Immobilization Facility densified high level waste. This report is the result of the literature search conducted to establish a basis for experimental program development. The program plan will be jointly developed by Montana Tech and LITCO.

1.2 Extent of Search

There are a significant number of publications that include information on decontamination of radioactive scrap materials, e.g., a search of Chemical Abstracts alone shows over 400 publications. At this time approximately 330 publications have been identified that are related to the decontamination of metallic scrap. Thirteen literature databases have been searched and titles, abstracts, and publications have been recovered. In addition to searching databases, an important source of information (often missed by computer database searching) has been individual articles, i.e., reviewing individual article reference lists has allowed the authors to identify publications that were missed by computer database keyword searching.

Databases searched and the keywords used in each database search are presented in Tables 1-1 and 1-2, respectively. Tritium removal was not considered in the keyword search nor was analytical data provided in any of the publications reviewed. This issue is the subject of a joint WINCO/Savannah River Technical Center research initiative. (Imrich, 1994)

United States Patents (through February 1993), Japanese Patent abstracts (1980 to 1994, but not inclusive of all dates), and Derwent World Patents (1975 to 1994), were searched using keywords found in Table 1-2. The patent search performed in this study is not to be considered a comprehensive Office of Patents type search.

Approximately fifty english-language patents are currently referenced in the Montana Tech database, as well as numerous world patent abstracts translated into English. Technologies found

Table 1-1. Databases searched/keyword codes.

Databases	Keyword search number(s)[a]
Chemical Abstracts (1967-May 1994)	1-4
Derwent World Patents (1975-1994)	1-6
Energy Science & Technology (1974-1994)	1-6
Federal Research in Progress (Oct 1992)	1-4
GPO Monthly Catalog (1976-Dec 1992) US Gov't Publications	1-4
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Metadex (1966-1994)	1-4
NTIS (1964-May 1994)	1-4
SCISEARCH (1974-1994)	1-4
United States Patents (1959-May 1994)	1-7
WILSONLINE Information System (Oct 1983-March 1993)	1-7

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a. See Table 1-2 for Keywords.

Table 1-2. Keywords used in literature searches.

Keyword Search 1	Keyword Search 2	Keyword Search 3	Keyword Search 4
Slag or Glass and Uranium or Plutonium or Actinide or Transuranics	Stainless Steel (or Steel) and Decontaminat()	Stainless Steel (or Steel) and Slag or Glass and Actinide or Uranium or Plutonium	Stainless Steel (or Steel) and Slag or Glass and Decontaminat()
Keyword Search 5	**Keyword Search 6**	**Keyword Search 7**	
Radioactive and Volume Reduction	Stainless Steel (or Steel) and Decontaminat() and Melt Refining Thermo()	Cobalt	

in the U.S. patents are not limited by border, as a large number of foreign authors and foreign companies are assignees of U.S. patents.

Technological information in the patents is valuable, but detailed experimental data are usually not presented. Of the available patents, only two have directly focussed on decontaminating metals by melt refining. Only one patent, Snyder (1991), has defined an integrated process for decontaminating metals (through the combination of melt refining and electrorefining in aqueous solutions). The second identified patent deals with high temperature cobalt extraction from steel, Allibert (1983). Results from laboratory scale test work for cobalt extraction from stainless steel by slagging and industrial cobalt extraction by electroslag refining were not successful, Allibert (1984).

Technologies presented in the patents include: treatment of radioactive waste solutions by vitrification processes, surface decontamination processes, radioactive waste compaction, nuclear fuel alloying, and methods for reprocessing spent oxide fuels for Integral Fast Reactor fuel recovery by molten salt electrolysis. .(The above list of patent topics is of a broader general interest than the presently focused emphasis on melt/slag refining.) The publications retrieved and reviewed in this study focused only on melt/slag refining.

Results of the patent search indicate that the technology for melt refining radioactively contaminated metals by slagging has not been developed to the commercial scale in the United States, and that this may be true for the world audience. Recent advances show that radioactive waste immobilization by thermal processing has been developed within the last decade. The United States government has sponsored most of the current nuclear technology patents reviewed herein. The search of Japanese patent abstracts shows that private industry in Japan is developing thermal technologies for processing radioactively contaminated metals.

In addition to the references discovered by using the above keywords, the names of 47 authors selected from the previous bibliography were entered in the search.

1.3 Status of Search and Review

The database searches are complete (January 1995). Publications are still being collected, but it is likely that the major references have been collected and reviewed.

2. STATUS OF MELT CONSOLIDATION/REFINING

2.1 Introduction

Although the present program deals specifically with mild steel, the authors included published information on the melting of stainless steel, mild steel, nickel, aluminum, uranium, copper, lead, tin, zinc and plutonium in the survey. Experience gained with melting and slagging these materials is directly applicable to radioactively contaminated mild steel. Several excellent reviews of refining, melt refining and volume reduction have been conducted since 1975 (Mautz 1975a, Reimann 1991, Office of Technical Services 1991, Bechtold, 1993). These documents have been very helpful in the assessment of the state-of-the-art. Selected information from the surveys is included here, but no attempt is made to completely summarize the reviews.

Several laboratory scale and large scale melt consolidation programs have been conducted during the past thirty years. Although the major tonnage has been produced by the treatment of mild steel, relatively large scale treatment efforts have also been conducted on stainless steel, nickel, and aluminum. Although the degree of cleanup varied from one program to the other, a large degree of success has been achieved by melt refining for reducing the concentrations of lanthanides, actinides, and most other fission products that are easily oxidized. On the other hand, melt refining to remove troublesome transition elements from stainless steels, such as cobalt and technetium, has met with little success. Efforts to decontaminate aluminum have also been much less successful, as might be expected from the consideration of the thermodynamic properties of the radionuclide-aluminum systems.

Efforts are continuing to calculate the amount of RSM. The available RSM for recycle will come from the decommissioning of commercial nuclear generating plants and various DOE facilities. The most current estimate of the amount of stainless steel RSM that could be made available from the commercial facilities is 90,000 tons (Mizia, 1994). This study showed that there would be gaps in the availability of this material. The end use product of this material is postulated to be dry fuel storage canisters for the spent fuel that will be removed from these reactors. This could dovetail into the needs of DOE as it must take ownership of the commercial spent fuel in 1998. The DOE must also store large quantities of government owned nuclear fuel. As has already been mentioned, DOE has need for various types of metal waste storage containers. Table 2-1 summarizes the available RSM stockpiled at selected DOE sites and Table 2-2 summarizes the RSM burial rates at these sites (Bechtold,1994;Funk,1994). Preliminary information on the total amount of RSM at nine sites gives a value of 100,000 tons (S. Warren, 1994). If a recycle program is to be successful, DOE must make a decision to stockpile this material for reuse rather than bury it to augment the amount of commercial RSM available.

The DOE/Oak Ridge Scrap Metal Program (SMP) suggested a mix of metals in RSM as follows: "ferrous metal/steel 45 to 88 percent, nickel 0 to 32 percent, aluminum 10 to 12 percent, copper 0 to 45 percent, and lead/mixed metal turnings about 5 percent" (Office of Technical Services, 1991). The relative amounts of each type of RSM varies at each facility; however, its is probably safe to say that in excess of 50 percent of the RSM in the DOE inventory is ferrous metal and stainless steel.

Table 2-1. RSM stockpiled at select DOE sites (Funk, 1994).

DOE sites	Tons
Idaho National Engineering Laboratory	907
Nevada Test Site	70
Sandia National Laboratory	31
Hanford	56
Savannah River	4,812
Los Alamos National Laboratory	Unavailable
TOTAL	5,876

Considerable large scale melt refining treatment experience exists for melt consolidation/

Table 2-2. Annual burial of RSM at select DOE sites (Funk 1994).

DOE site	Buried 10/92 to 9/93 (tons)	Buried 10/93 to 7/94 (tons)
Idaho National Engineering Laboratory		
Aluminum	39.3	32.7
Carbon Steel	4.0	3.4
Stainless Steel	52.4	43.6
Miscellaneous Steel	26.3	22.0
Nevada Test Site		
Shipments received[a]	411.9	193.5
Sandia National Laboratory	Recycles uncontaminated metal. Does not generate RSM.	Recycles uncontaminated metal. Does not generate RSM.
Hanford[a]		
Aluminum	8.8	1.8
Copper	23.0	12.6
Wire	37.4	10.3
Lead	702.3	100.3
Metal/Iron/Sheet/Gal	7,828.9	1,426.0
Savannah River[a]	Does not track metal sent for burial.	Does not track metal sent for burial.
Los Alamos National Laboratory	1,020.9	850.8
TOTAL	10,155.2	2,697.0

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a. Buries RSM and uncontaminated scrap

refining of ferrous RSM. This experience is revealed in the following paragraphs on a country by country basis. The following discussion should not be considered to be an exhaustive survey of the technologies practiced in the countries, but represents the state-of-art as revealed by published literature. A summary of large scale world wide ferrous melt consolidation/refining programs is presented in Table 2-3. Previously reported (Worcester, 1993) quantities were not updated for this bibliography.

2.2. France

In one program, the French have selected arc-furnace melt consolidation as their technology for the treatment of ferrous materials that are recovered from the dismantling of the CO_2 systems from the G2-G3 graphite moderated, CO_2 cooled plutonium production and power generation reactors at Marcoule. In addition, they have installed a gas-fired metal separation/homogenization/casting facility of a nominal 1 to 1.5 tonne/hr capacity for consolidation of aluminum scrap recovered from the dismantling of the gaseous diffusion plants at Pierrelatte. (Peulve, 1992)

The ferrous melting facility consists of a three phase arc furnace of nominal 15 tonne capacity (8,000 kva) with a 2.5 m opening diameter, allowing a nominal maximum charge piece size of 1.7 m × 1.7 m × 1.3 m. The installation is sized for two 12.5 tonne taps per shift with the nominal product being 25 kg (300 mm × 150 mm × 30 mm) cast iron ingots produced on a continuous casting line. Alternate products may be cast. For this application arc melting was selected over induction melting for ease of operation, greater safety, acceptance of large feed piece sizes, and ease of modifying the charge composition. Production of cast iron was chosen as the product over steel because of its lower melting temperature and casting ease. Costs at an annual production rate of 15,000 tonne are projected at less than 6 (1992) francs per kg including investment cost.

The furnace has been installed within the primary containment of the G3 reactor with continuous radiological monitoring of flue gas emissions. The furnace has dust extraction at the source with a capacity of 7500 m^3/hr (4400 cfm) with an additional 40,000 m^3/hr (24,000 cfm) in the foundry area. The ventilation system incorporates three stages of filtration before discharge to the flue. Peulve (Peulve, 1993) projected costs at less than 14 francs per kg for 10,000 tonne annual quantities.

Peulve (1993) reports the furnace has been operating since the end of April, 1992, averaging one casting/day, four days per week. In April, 1993, an estimated 2,580 tonne of cast iron had been produced. Product, cast into shapes for re-use in the nuclear industry, has been sorted into two categories: (1) "low contaminated (up to several dozens Bq/g)—" which might be used for structural components in power plants, transport casks with lead walls, transport boxes, etc. and (2) "contaminated (up to two to three thousand Bq/g): which might be used for substitution of lead as biological protection (with less chemical harmful effect) in waste disposal packages, waste containers, storage accessories (ballasts, caps) etc." Dusts from this melting operation constitute approximately 2.25% and slag constitutes approximately 2.8% of the weight introduced to the melting operation.

Table 2-3. Summary of large-scale ferrous melt consolidation/refining programs.

Reference/country/ (location)	Type/size of furnace	Total weight melted	Material melted	Ingot contaminant level
Peulve (1992)/France/ (Marcoule)	Arc/15 tonne	2,580 tonne	Cast iron	"low-<several dozen Bq/g; contaminated<3,000 Bq/g"
Sappok (1992)/Germany/ (Siempel-kamp)	Induction/ 20 tonne 3.2 tonne	2,000 tonne 7,000 tonne	Carbon steel	Partition distribution table in Sappok, 1994
Mies (1991)/Germany	Same as above	500 tonne	Carbon steel	<0.3 Bq/g
Thoma (1990)/ Germany/(EIRAM)	Induction/2 tonne	150 tonne	Carbon steel	<1 Bq/g
Gomer (1985)/UK/ (Swinden, Grangetown, Sheffield)	Induction/0.5 tonne Arc/5 tonne and 150 tonne 3 tonne basic O_2	2 tonne diluted to approx. 22 then re-diluted	Carbon steel	$2x10^{-6}$ uCi/g with dilution-then diluted to deminimus
Nakamara (1992)/Japan/ (JPDR)Nakamara (1992)/Japan/	Induction/0.5 tonneI	Approx. 5 tonne (11 heats)A	Carbon and stainless steelC	Approx. 15 Bq/g in spiked ingotsA
Menon (1990)/Sweden/ (Studsvik)	Induction/1.5 tonne	190 tonne (93 heats)	90 % Carbon, 10 % stainless steel	<3.5 Bq/g for stainless
Mautz (1975a)/USA	Arc/10 ton	27,000 ton (2037 heats)	Carbon steel	0.4 ppm U Avg. 3.5 ppm max.
Mautz (1975a)/USA	Arc/10 ton	2,200 ton (218 heats)	Stainless steel	0.6 ppm U Avg. 3.2 ppm max.
Large, SEG (1993)/USA	Induction/20 ton	2,200 ton	Carbon steel (to be rolled into plate)	<10 mR/hr
Echols, SEG (1993)/USA	Induction/20 ton	2,735 ton	Carbon steel (cast to shield blocks)	<10 mR/hr
Larsen (1985a)/ USA/(INEL)	Induction/ 1500 lb	78 ton (123 heats)	Carbon and stainless steel	21 pCi/g Avg.- 27 pCi/g max. Co-60
Nichols, MSC (1994)/USA	Vacuum Induction/3000 lb	2 ton stainless steel/3,000 ton uranium	Stainless steel,nickel, uranium	not reported

Jacquet-Francillon and others (Jacquet, 1991a, b) reported the operation of a cold-crucible induction melting prototype (non-radioactive) capable of melting zircaloy and stainless steel ingots of up to 200 mm diameter and up to 1m long weighing 200 to 250 kg. The authors reported the construction of an industrial-scale melting facility designed to process stainless steel or zircaloy hulls from the pilot nuclear fuel reprocessing facility at Marcoule. This facility is scheduled for operation in 1993. Ingot size will be the same as described in the prototype above. Anticipated melting capacity will be 40 kg/hr for stainless steel hulls and one ingot will be produced at "one or two day intervals during operation." Anticipated production is 15 ingots per year.

2.3 Germany

Sappok and Rettigelt (Sappok, 1992) describe melt consolidation of ferrous scrap (from dismantling nuclear power plants) which began at the Siempelkamp foundry, Krefeld Germany, in 1984. Products of this melting, totalling approximately 4500 tonne have been radioactive waste casks, shielding doors, and plates. Early melts were performed using a commercial 20 tonne coreless induction furnace modified to provide additional fume collection capabilities. In 1990 a single purpose plant designed for melting contaminated material began commercial production at Siempelkamp. By 1992, 2500 tonne of material, which included ferrous metals, copper, and brass, had been melted in that facility.

The facility consists of a 3.2 tonne, 300 to 500 Hz coreless induction furnace with a melting capacity of 2 tonne/hr. The primary filter plant, which provides fume control to specific areas of the melting facility has a capacity of 15,000 m^3/hr (9,000 cfm) while the backup fume system (which provides negative pressure to the housing which encloses the furnace facility) provides an additional 12,000 m^3/hr (7,000 cfm). Future plans include remote loading of charge to the furnace.

Sappok (Sappok, 1990a) described the decontamination effect, averaged over 400 tonne of melting as being 43.8%, i.e. entry activity of 7.8 Bq/g was reduced to an average of 4.4 Bq/g. Average activities in the dust and slag were 401 and 205 Bq/g respectively.

Mies (Mies, 1991) reports results of melting 500 tonne of steel scrap from decommissioning the nuclear power plant Gundremmingen Unit A (KRB A) at the Siempelkamp foundry described above. He reports no impermissible levels of activity have been determined for samples resulting from melting of KRB-A scrap. The slag could be disposed of at normal industrial waste repositories, while filter dust could be stored as low level waste. Activities resulting from this melting test program were reported as follows (reference nuclide, Co-60):

Melt samples:	max. 0.4 Bq/g
Cast samples:	max. 0.3 Bq/g
Slag:	max. 1.0 Bq/g
Dust:	max. 30.0 Bq/g

Thoma (1990) described melting 150 tonne of RSM from the Niederaichbach nuclear power plant during 1989. The core of the EIRAM melting facility is a 600 kva line frequency induction melting furnace of 2 tonne capacity, located in a decommissioned research reactor building. According to the operating license, material of radioactivity up to 200 Bq/g can be melted, however, the maximum contamination level melted during the campaign was 1.88 Bq/g. Activity in the product castings was <1 Bq/g while the maximum activity measured in the slag was 1.1 Bq/g. At these low measured activity levels encountered it was difficult to discern significant partition of specific radionuclides into the slag.

2.4 United Kingdom

Gomer (1985) reported results of a 16-heat program at British Steel Corporation wherein approximately 2 tonne of contaminated scrap steel components from three different reactor systems were melted (at various ratios) along with uncontaminated scrap. Heats up to 0.5 tonne were melted in 50 kg and 0.5 tonne induction furnaces while 10 heats totalling 22 tonne were melted in a 5 tonne electric arc furnace. Detailed information is provided regarding the partitioning of Co-60 and Cs-134,137 into ingot, slag, and fume products. Co-60 consistently reported to the castings while Cs transferred to the slag and fume. Amounts of Cs lost to the fume were highly dependent on melt type, slag composition, melt technique, and Cs source material. All of the ingots from this work were subsequently diluted to de minimis (<10-5 µCi/g) in 300 tonne basic oxygen steel furnaces. The results of this work were used to support release of properly characterized and monitored RSM to commercial electric furnace operations. Harvey (1990) concluded from further work by British Steel, which continued through 1988, "Considerations of costs and benefits suggest that some steelwork of low radioactivity could be incorporated in industrial steelmaking and its use would comply with published safety criteria. There is, however, no intention by British Steel to undertake such a program."

2.5 Japan

Fujiki, et al. and Nakamura, et al.(Fujiki, 1991a, and Nakumura, 1994) have described the melting facility and program schedule for the Japan Power Demonstration Reactor (JPDR) decommissioning program. The melting component of this program was conducted in a 360 kVA, 500 kg capacity 1,000 Hz coreless induction furnace installed in a former dump condenser building in the JPDR. The furnace is enclosed in a steel enclosure to allow maintenance of a negative pressure in the melting and casting area. In addition, a ring hood is used to pick up local fume emissions at the top of the crucible. Size of the exhaust system was not specified, but it consists of cyclones, bag filters, and HEPA filters in series. Coreless induction was selected for this program for the following reasons: (1) allows melting of stainless and carbon steel, (2) "Less secondary wastes (aerosol, dust, etc.)," and (3) easier fume hooding. Test variables to be addressed in the program include material type (carbon or stainless steel), degree of radioactive contamination, nature of radioactivity (activated vs contaminated), flux types and melting temperatures. Items to be assessed included a material balance and partitioning of radioactive elements to the slag, off gas, and casting; distribution of radioactive elements within the ingot; radiation dose rate in the workplace; and present of radioactive dust and aerosol in the workplace.

Nakamura and Fujiki (Nakamura, 1992) described preliminary results of the JPDR decommissioning melting program. A total of 11 heats were cast into a 450 kg tapered square ingot mold. Two heats of Type 304 stainless steel and four carbon steel heats were from JPDR contaminated scrap, while two heats of stainless steel and three heats of carbon steel were cast from uncontaminated steel to which radioactive tracers(Co-60, Cs-137, Mn-54, Sr-85, Zn-65) were added. For the eleven ingots, material accountability was greater than 99%. Ingot yield was 95%, slag weight 2 to 3%, <1% dust, and 1 to 2% splatter and residuals. The radioactive tracer (RI) ingots were sectioned at top, middle and bottom and sampled across each section to represent the cross section from edge to center. Each radioisotope which remained in the ingot (Co-60, Mn-54, Zn-65) was uniformly distributed throughout the ingot, the largest standard deviation being 9% (of 2.2 Bq/g) for Co-60. Measurements were made on the ingot with the following results: 99.5% of the Co-60, 91% of the Mn-54, and 75% of the Zn-65 were accounted for in the ingot; none of the Sr-85 and Cs-137 were present in the ingot. Measurement on the slag showed the following results: none of the Co-60 was present while 1% of the Zn-65, 7% of the Mn-54, 39% of the Cs-137, and 73% of the Sr-85 were accounted for in the slag. Measurement for the exhaust gas showed: none of the Co-60 and Mn-54 were present, but 13% of the Zn-65, and 38% of the Cs-137 were accounted for in the fume. The authors questioned the offgas sampling accuracy, since only 1/2500 of the gas stream was sampled. Also, since much of the fume may have condensed before the gas stream reached the sample position, a considerable amount of the lack of closure reported (7% for Zn-65, 27% for Sr-85, and 23% for Cs-137) might be attributable to condensed fume. According to the experience of Gomer (Gomer, 1985) soaking times exceeding 20 minutes after the RI addition would have resulted in significantly lower Cs values in the slag, larger amounts being lost to fume. Nakamura concluded that 90 to 100% of Mn, Co, and Zn were transferred to the ingot while Sr and Cs were transferred to the slag or offgas. He also concluded the activity concentrations in the produced ingot were essentially homogeneous.

2.6 Sweden

Ninety-three melts were performed at Studsvik AB (Menon, 1990), consuming 190 tonne of RSM of Swedish origin between October 1987 and May 1988. By the end of 1988, more than 400 tonne of low activity metallic scrap had been melted. (Menon, 1990). Approximately 90% of the material was carbon steel; the remainder was stainless steel. The facility consists of a preparation area where scrap is sized, an induction furnace of nominal 1.5 tonne/hr melting capacity, and a cool down area. The preparation and furnace areas have separate ventilation systems each of which has 99% effective filters which discharge to a release point 20 to 25 m above the ground. A total airborne release of 640 kBq of beta-gamma and 200 Bq of alpha activity occurred from this source in 1988. The results on 5.4 tonne of stainless steel (discussed in more detail elsewhere in this report) were consistent with other work, showing Co, Mn, Zn, Ag, and Sb reporting to the ingot while Cs reported to the slag and dust.

2.7 United States

Several large-scale melt consolidation/refining programs conducted in the U. S. since the 1950's are summarized in Table 2-3. The table is not intended to represent all of the large scale melting performed during this period, but serves to emphasize the magnitude of the experience base established over this period. The melting experience described by Mautz, (Mautz, 1975a) represented 27,000 tons of Uranium contaminated "common steel" scrap accumulated at the Y-12 Plant from the early 1940's to the early 1960's. Melting, supervised by Y-12 personnel, was accomplished in a 20 ton electric arc furnace. Mautz reports extensive data for slag and ingot chemistry indicating the propensity for the uranium to report to the slag. One set of typical data showed ingot uranium values ranging from 0.10 to 2.1 ppm with slag values ranging from 707 to 8,406 ppm U. Analytical data for 2,037 steel melts showed that 46% of the ingots contained <0.2 ppm U, 94% contained <1.0 ppm U, and 1% contained >2.0 ppm U. Experience from melting 2200 tons of stainless steel in the 20 ton arc furnace yielded similar results (Mautz, 1975b—personal communication with Sanders, 1962). Sanders data showed an average uranium content of 0.6 ppm with a single high value of 3.2 ppm. From that population of ingots, 32.1 % of the ingots contained <0.2 ppm U, while 79.8 % contained <1.0 ppm U.

Larsen (1985a) reported on the melting of 78 ton of RSM from a decommissioned test reactor (SPERT III). The Waste Experimental Reduction Facility (WERF), which includes a melting facility, along with a material sizing and incineration facility, is located within the decommissioned SPERT III reactor building at the Idaho National Engineering Laboratory (INEL). The melting furnace is a Pillar 1500 lb, tilt pour, coreless induction furnace, equipped with local hooding as well as filtered building ventilation. Larsen used an in-situ sintered high alumina refractory. Five refractory linings were used for 123 heats, the maximum refractory life reported was 44 heats. Prior to casting a "slag coagulant" was added to the top of the molten metal to aid in removing slag. Metal was cast into a prismatic mold with sufficient capacity to hold the entire furnace charge. Grouping four castings together into a square cross section gave maximum packing density. Molten metal samples yielded Co-60 activity ranging from 11 to 27 pCi/g. On occasion, Cs-137 was also found in the metal at levels of 1 or 2 pCi/g. Cs-137, Eu-152, 154, and 155, and U-235, although not detected in the RSM, were detected in the slag, presumably as a result of concentration during melting. These same constituents were analyzed in the baghouse dust.

Scientific Ecology Group, Inc (SEG, 1993) operates a 20 ton 7200 kw induction melting furnace as a part of its 50,000 square foot metal processing facility. This furnace is equipped with local hooding as well as being located in a building with HEPA filtered ventilation. Details of the operation are not reported, but the facility does include a HEPA-ventilated charge preheating furnace capable of 1000°F to eliminate volatiles from the charge prior to introduction to the melting furnace. One campaign at this facility produced 2,735 tons of carbon steel shielding blocks (Echols, 1993) while another produced 2,200 tons of carbon steel intended for rolling to plate in the future (Large, 1993). Details of product composition are unknown at this writing. The shielding blocks were produced to a density specification of 440 lb/ft^2 with a maximum surface dose rate of 10 mR/hr.

Manufacturing Sciences Corporation (MSC, 1994) installed two 3,000 lb (steel) vacuum induction melting units in 1990. MSC has cast over 2 tons of stainless steel RSM, some of which was cast into 4-in thick slabs for subsequent rolling into sheet 12 and 16 gage sheet. MSC experience includes conversion of over 6 million pounds of depleted uranium into various products. Plans for expansion of the RSM recycle capability at MSC include installation of two 6 ton tilt-pour vacuum furnaces with associated feed storage, surface decontamination, feed preparation, and product fabrication facilities.

The participants in the DOE program for recycle of RSM are listed and their roles defined in Appendix A of the "WINCO Metal Recycle Annual Report for FY 1993." (Bechtold, 1993)

2.8 Comments on Melting Technologies

The technological community has selected two technologies for melt/consolidation of ferrous RSM, coreless induction and electric arc furnace (EAF) melting. The choice between these two technologies involves many factors. The main factors favoring coreless induction are better melt agitation, easier fume control, and rapid heatup. These factors are particularly important when considering an initial consolidation/homogenization melt of RSM, and are the primary reasons why induction melting was selected for most of the "large scale" RSM melting described above. On the other hand, the EAF provides lower cost as heat sizes increase, accommodates larger scrap section sizes, allows for easier modification of melt composition, and provides a greater margin of reliability and safety because of the absence of the water cooled induction coil. According to Reimann (1991), an induction furnace produces 20% as much effluent dust as an EAF of similar capacity.

In the authors opinion, the reduction of effluent dust should be a major factor in furnace selection. This is of significance when designing a capture system which will control the dispersal of a significant portion of the long-lived radionuclides (e.g., Cs-137).

It appears quite obvious that melt decontamination alone will not provide steel which qualifies for free release, particularly if the trend reflected in Europe in 1989 (Janberg, 1990) toward lowering free release limits from 3.7 Bq/g to 0.1 Bq/g continues. Essentially none of the products discussed in the large scale melting section could be released under the criteria established in Europe in 1989. It might be argued that free or controlled release is not necessary; however, consolidation of RSM and removal of volatile and easily oxidized radionuclides could be accomplished in DOE-controlled melting facilities. Melt consolidated and characterized RSM from these facilities could then be released, on a controlled basis, to the steel industry for efficient incorporation into large heats for manufacture of nuclear waste or fuel containers.

The availability of stainless steel RSM at INEL and other DOE sites and the need for stainless steel for waste canisters present a unique opportunity. Methods for consolidating stainless steel RSM can be developed on a commercial scale while developing protocol for disposal of carbon steel scrap at a later date. Carbon steel might also be combined with characterized nickel RSM to produce additional quantities of stainless steel for use within the DOE program (Mizia, 1993).

Analysis of the literature suggests the following approach:

> Decontaminate and melt SS RSM into heats of sufficient size to minimize radionuclide characterization and analytical costs while casting the material into suitable shapes for recycle into a limited release remelt program, or use in simple shapes in the nuclear industry.

Such an approach would provide volume reduction while establishing protocol for at least limited release into the commercial scrap market. One of the problems associated with trying to do on-site casting of stainless heats for fabrication into canisters is the small heat size inherent in such an approach. Small heat sizes significantly drive up production costs while increasing certification costs and complexity without improving quality. Even if the largest U.S. RSM furnaces were used for ingot casting, heat size would only be 20 tons. Fabrication and QC costs for such small heats would be prohibitive. On the other hand, if characterized first melt RSM ingots were released to a commercial stainless melter/fabricator for use as scrap addition to heats, quality could be improved, with minimal risk, by relying on the melting and fabrication expertise of the steel industry.

The program suggested in the original bibliography (Worcester, 1993) follows:

- "Decontaminate and melt RSM within the DOE complex into a configuration which is acceptable for use in the commercial scrap market, for use as shielding blocks, or for land disposal. Melting parameters would be optimized for transfer of radionuclides into slag and fume, homogenizing the melt, and minimizing slag inclusions.

- Release heats which meet release specifications to a commercial stainless melter/fabricator for combination with non-contaminated melt stock into large heats for fabrication into DOE program products. These products might include 55-gallon drums for low-level nuclear waste disposal, Hot Isostatic Pressed (HIP) canisters for Idaho Chemical Processing Plant (ICPP) waste immobilization, overpack canisters for ICPP-HIP canisters, and multi-purpose containers for storage of spent nuclear fuel.

- Use non-qualifying heats for internal use, land disposal, or remelting within the DOE complex. Remelting might involve further melt refining, possibly by induction ladle metallurgy as proposed by Reimann (Reimann, 1991) or electroslag melting."

A more realistic approach may well be the establishment of a regional or national RSM processing center within the DOE complex equipped to decontaminate, melt refine, cast, roll, and finally fabricate the hardware required for nuclear waste disposal.

The suggested approach is supported by the following observations:

- Free release requirements will become tighter with time.

- The steel industry is unlikely to accept RSM-derived material for input to conventional facilities.

- It is unlikely available quantities of RSM will justify more than one-large-scale processing facility. Canister quality will be enhanced by utilization of larger equipment. Quality and certification costs for containers will be significantly reduced on large heats while real quality will be improved. Consolidation of stainless steel RSM will undoubtedly introduce some carbon pickup, necessitating AOD or VOD for economical processing of low carbon stainless steel. Such refining will not be necessary for carbon steel.

- Some radionuclides will not be removed by any practical melting process known today (e.g., Co, Fe, Mn).

- Stainless steel scrap can be consolidated for costs which should allow release to the commercial market, at least on a break-even basis ($400/ton), disregarding burial costs for RSM. Mizia (1994) analyzed allowable costs for stainless RSM recycle. In the most likely scenario, burial costs were pegged at $668/cubic foot. A savings of $35,000 per 20 short ton (empty weight) canister was estimated. This estimate allowed a $2.10/lb tolling charge and a 15% premium for fabrication of the canister from RSM. Projected savings are highly dependent upon burial costs.

- Experience gained from this program should pave the way for limited release programs for carbon steel which must involve melting and releasing to large-scale facilities at much lower break-even costs ($100/ton), disregarding burial costs for RSM.

3. EXPERIMENTAL TEST RESULTS/SLAG COMPOSITIONS

3.1 Experimental Test Results Summary

Reimann (1991) has presented the most recently published technical assessment and compilation of data for metal decontamination by slag/metal melt processing. His compilation of test results for type of metal, slag composition, type of contaminant has been expanded and the results are presented in Table 3-1 (for steel and stainless steel) and in Table 6-1 in Appendix Section 6.2 (for all metals including aluminum, copper, lead and lead-tin alloys, nickel, steel, stainless steel, tin, and zinc).

Mautz, et al (1975a) reviewed and summarized large scale test work conducted on uranium decontamination by melt refining. A summary of the experimental results is presented in Table 3-2. Information on slag compositions used in these large scale tests is not provided. The only statement is that standard smelting practice was used to produce the ingots.

The additional studies located during the literature review do not change the conclusions that Reimann has presented, i.e., "contaminants that readily form oxides may be reduced to below *de minimis* levels and combined with a slag. Radionuclides that chemically resemble the elements that comprise stainless steel can not be removed effectively."

Most of the reported test work summarized by Reimann has dealt with slagging of uranium or plutonium. Scattered information for other radionuclides is available (without much detail however) for other nuclides. Available data for melt refining of actinides, activated and fission nuclide products are summarized in Table 3-3.

Most of the available published data relates to large scale test work, e.g., Jacquet-Francillon and others (1991) reported on the work being conducted by the Commissariat d l'Energie Atomique at Marcoule. This work has progressed to a full-scale qualified industrial facility, i.e., the Rhone Valley Nuclear Research Center in Marcoule, France. Stainless steel and zircaloy hulls have been melted. Eight three kg stainless steel ingots have been produced under argon using 3–6 % slag containing alkaline fluorides, e.g., 75% CaF_2-25% MgF_2. The resulting metal ingots contained a total of 3321 uCi/g of fission and activated products (beta and gamma) and 23 uCi/g of actinides (alpha). The distribution results showed 84.9% total beta remained in the metal, 9.6% in the slag and 5.5% in the off-gas. Total alpha distribution was 0.1% in the metal, 99.5% in the slag, and 0.4% in the off-gas.

Ren (Ren, 1994) reported that laboratory melt refining of uranium in the Taiynan Steel Plant with a blast furnace slag (basicity of 1.1) will result in uranium concentrations of <1.0 ppm in steels.

Two 2-kg ingots of zircaloy (with 10% stainless steel added) have also been produced at the Marcoule facility using a charge containing 9.5% and 10.5% fluoride slag, i.e., 50% CaF_2-50% BaF_2. The results showed similar volatility behavior to the stainless steel test work but analytical data was not yet available at the time of these publications. Industrial operation was quoted as

Table 3-1. Melt/slag refining test work results for uranium and plutonium decontamination of steel and stainless steel.

	Slag									Final metal contamination			
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
S.S.	Calcium-Aluminum-Silicate	40	40	20						10	U	<1	Abe (1985a)
S.S.	High Silica	60	30	10						5	Pu	0.21	Hobbick (1981)
S.S.	Calcium-Aluminum-Silicate	40	40	20						10	U	<1	Abe (1985a)
S.S.	Nickel Containing	10	40	40				10 NiO		10	U	0.005	Abe (1985a)
S.S.	Fluoride Containing	40	30	20				10 CaF_2		10	U	0.10	Abe (1985a)
S.S.	Calcium-Aluminum-Silicate	40	40	20						10	U	<1	Abe (1985a)
S.S.	Fluoride Containing	40	30	20				10 CaF_2		10	U	0.083	Abe (1985a)
S.S.	Fluoride Containing	30	40	10	15			5 CaF_2		5	Pu	0.50	Hobbick (1981)
S.S.	Fluoride Containing	40	30	20				10 CaF_2		10	U	0.10	Nafziger (1988)
S.S.	Fluoride Containing	30	40	10	15			5 CaF_2		10	Pu	0.30	Hobbick (1981)
S.S.	High Silica	75	25								U	λ^c=226	Snyder (1991)
S.S.	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.003	Seitz (1979)
S.S.	High Silica	60		40						10	UO_2	2.53	Heshmatpour (1981a)
S.S.	Borosilicate	80		2		4	1	13 B_2O_3		5	Pu	0.75	Hobbick (1981)

Table 3-1. (continued).

	Slag										Final metal contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contaminant	Conc., ppm	Reference
S.S.	High Silica	75	25							10	UO_2	<0.01	Heshmatpour (1981a)
S.S.	Fluoride Containing	10	60	25				5 CaF_2		10	UO_2	2.39	Heshmatpour (1981a)
S.S.	Fluoride Containing	30	50	10	5			5 CaF_2		5	UO_2	0.05	Heshmatpour (1981a)
S.S.	High Lime	35	65							10	UO_2	0.28	Heshmatpour (1981a)
S.S.	Borosilicate	80		2		4	1	13 B_2O_3		10	Pu	0.60	Hobbick (1981)
S.S.	High Silica	60	30	10						10	Pu	0.42	Hobbick (1981)
S.S.	High Silica	60	30	10						5	Pu	0.4	Copeland (1981)
S.S.	No Flux									0	UO_2	0.65	Heshmatpour (1981a)
S.S.	Borosilicate	80		2		4		13 B_2O_3		10	Pu	1.9	Copeland (1981)
S.S.	Industrial	30	40	10	15			5 CaF_2		10	Pu	0.8	Copeland (1981)
S.S.	Borosilicate	80		2		4	1	13 B_2O_3		5	Pu	1.5	Copeland (1981)
S.S.	High Silica	60	30	10						10	Pu	0.5	Copeland (1981)
Steel	High Lime	35	65							9	UO_2	2.72	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	40	50	10						9	UO_2	0.014	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	X[d]	X	X					1.6	10	U	<0.02	Abe (1985a)
Steel	High Silicate	70	10	20					0.13	10	U	0.11	Uda (1985)

Table 3-1. (continued).

	Slag										Final metal contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	Bl[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Steel	Calcium-Aluminum-Silicate	40	40	20						10	U	<0.1	Abe (1985a)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		NA[e]	Pu	0.0012	Seitz (1979)
Steel	Calcium-Aluminum-Silicate	X	X	X				X NaF_2	1.5	10	U	0.01	Abe (1985a)
Steel	Calcium-Aluminum-Silicate	X	X	X				X NiO	1.5	10	U	0.01	Abe (1985a)
Steel	Calcium-Magnesium-Silicate							$CaMgSi_2O_6$		0.97	Pu	NA	Seitz (1979)
Steel	Calcium-Aluminum-Silicate	X	X	X					0.1	10	U	<0.1	Abe (1985a)
Steel	High Silica	75	25							9	UO_2	0.21	Heshmatpour (1981a)
Steel	High Silica	60		40						9	UO_2	4.60	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	X	X	X					2.35	10	U	<0.1	Abe (1985a)
Steel	Calcium-Aluminum-Silicate	50	30	20					0.52	10	U	0.10	Uda (1985)
Steel	Calcium-Aluminate		50	50						9	UO_2	0.45	Heshmatpour (1981a)

Table 3-1. (continued).

	Slag										Final metal contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Steel	Calcium-Aluminate		40	60						9	UO_2	0.42	Heshmatpour (1981a)
Steel	Fluoride Containing	10	60	25				5 CaF_2		9	UO_2	0.44	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	30	50	20					1.28	10	U	0.059	Uda (1985)
Steel	Calcium-Silicate		20	80						9	UO_2	0.36	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	X	X	X					0.5	10	U	<0.1	Abe (1985a)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		12	Pu	0.0063	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.0007-0.00009	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.0003	Seitz (1979)
Steel	No Flux									9	UO_2	0.52	Heshmatpour (1981a)
Steel	Calcium-Aluminate		20	80						9	UO_2	0.20	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	40	40		20						UO_2	0.70	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	10	70		20						UO_2	0.84	Heshmatpour (1981a)

Table 3-1. (continued).

	Slag										Final metal contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Steel	Calcium-Ferric-Silicate	25	50		25						UO_2	0.05	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	40	30		30						UO_2	5.23	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	20	70		10						UO_2	1.08	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	40	50		10						UO2	0.14	Heshmatpour (1981a)
Steel								No Flux			UO_2	0.52	Heshmatpour (1981a)
Steel	Borosilicate	80		2		4	1	13 B_2O_3			UO_2	<0.01	Heshmatpour (1981a)
Steel	High Lime, Fluoride Containing	25	60	10				5 CaF_2			UO_2	0.03	Heshmatpour (1981a)
Steel	High Lime, Fluoride Containing	10	60	25				5 CaF_2			UO_2	0.44	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	30	40		30						UO_2	3.90	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	15	55		30						UO_2	2.04	Heshmatpour (1981a)

Table 3-1. (continued).

	Slag										Final metal contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Steel	Calcium-Aluminum-Silicate	10	50	40					1.60	10	U	0.027	Uda (1985)
Steel	High Lime	10	60	30					2.32	10	U	0.13	Uda (1985)
Steel	Calcium-Aluminum-Silicate	40	40	20						10	U	<0.1	Abe (1985a)
Steel	Calcium-Aluminum-Silicate	X	X	X					0.12	10	U	<0.1	Abe (1985a)
Steel	High Silica	80	10	10					0.12	10	U	0.16	Uda (1985)
Steel	Calcium Ferrite		50		50						UO_2	0.45	Heshmatpour (1981a)
Steel	Calcium Ferrite		10		90						UO_2	0.51	Heshmatpour (1981a)
Steel	Calcium Ferrite		20		80						UO_2	0.36	Heshmatpour (1981a)
Steel	Calcium Ferrite		30		70						UO_2	0.47	Heshmatpour (1981a)
Steel	Calcium Ferrite		40		60						UO_2	0.42	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	X	X	X					0.26	10	U	<0.1	Abe (1985a)
Steel	Calcium Silicate							$CaSiO_3$		5	Pu	0.27-6.4	Seitz (1979)

Table 3-1. (continued).

	Slag									Final metal contamination			
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Steel	Fluoride Containing, High Lime	25	60	10				5 CaF_2		9	UO_2	0.03	Heshmatpour (1981a)
Steel	High Silica	60	30	10						5	Pu	0.4	Copeland (1981)
Steel	Fluoride Containing, High Lime	35	60					5 CaF_2		9	UO_2	0.016	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	40	40	20						10	U	<0.1	Abe (1985a)
Steel	Borosilicate	80		2			1	13 B_2O_3		9	UO_2	<0.10	Heshmatpour (1981a)
Steel	Industrial	30	40	10	15			5 CaF_2		5	Pu	8.6	Copeland (1981)
Steel	Basalt	42	12	8	26	4	2	6 MgO		10	Pu	8.3	Copeland (1981)
Steel	Calcium-Silicate							$CaSiO_3$		20	Pu	0.065-7.56	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.001-0.003	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		19	Pu	0.041-0.32	Seitz (1979)
Steel	High Lime	20	70	10						9	UO_2	1.08	Heshmatpour (1981a)
Steel	Fluoride Containing	25	50	10	5			10 CaF_2		9	UO_2	0.91	Heshmatpour (1981a)
Steel	None									None	Pu	0.77-Very High	Seitz (1979)
Steel	Calcium-Aluminum-Silicate	25	50	25						9	UO_2	0.05	Heshmatpour (1981a)

Table 3-1. (continued).

	Slag									Final metal contamination			
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contaminant	Conc., ppm	Reference
Steel	High Lime	10	70	20						9	UO_2	0.84	Heshmatpour (1981a)
Steel	Fluoride Containing	10	50	25	5			10 CaF_2		9	UO_2	<0.01	Heshmatpour (1981a)
Steel	Borosilicate	80		2		4	1	13 B_2O_3		10	Pu	1	Copeland (1981)
Steel	Calcium-Aluminum-Silicate	40	40	20						9	UO_2	0.70	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	30	40	30						9	UO_2	3.90	Heshmatpour (1981a)
Steel	Borosilicate	80		2		4	1	B_2O_3		5	Pu	0.6	Copeland (1981)
Steel	High Silica	60	30	10						10	Pu	2.5	Copeland (1981)
Steel	Industrial	30	40	10	15			5 CaF_2		10	Pu	1	Copeland (1981)
Steel	Calcium-Aluminum-Silicate	40	30	30						9	UO_2	5.23	Heshmatpour (1981a)
Steel	Calcium-Silicate							$CaSiO_3$		11	Pu	0.09-22.0	Seitz (1979)
Steel	Hearth Slag							$CaFeSiO_4$, Minor SiO_2		10	Pu	NA	Seitz (1979)
Steel	High Lime	10	60		30						U	$\lambda=583$	Snyder (1991)
Steel	Calcium-Aluminum-Silicate	40	40	20					0.83	10	U	0.19	Uda (1985)

Table 3-1. (continued).

	Slag										Final metal contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Steel	Calcium-Aluminum-Silicate	15	55	30						9	UO_2	2.04	Heshmatpour (1981a)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.006	Seitz (1979)
Steel	High Silica	60	20	20					0.30	10	U	0.26	Uda (1985)
Steel	Calcium-Aluminate		30	70						9	UO_2	0.31	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	X	X	X					1.25	10	U	<0.08	Abe (1985a)
Steel	Calcium-Aluminum-Silicate	X	X	X					0.73	10	U	<0.1	Abe (1985a)
Steel	Calcium Aluminate		30	70						9	UO_2	0.47	Heshmatpour (1981a)
Steel	Calcium Aluminate		10	90						9	UO_2	0.51	Heshmatpour (1981a)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		11	Pu	0.00186	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		20	Pu	0.005-0.20	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.017-0.22	Seitz (1979)
Steel	Calcium-Aluminum-Silicate									10	Pu	0.09-1.6	Seitz (1979)
Steel	Calcium-Aluminum-Silicate									10	Pu	NA	Seitz (1979)

Table 3-1. (continued).

	Slag									Final metal contamination			
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Steel	Calcium-Magnesium-Silicate							$CaMgSi_2O_6$		10	Pu	0.18-21.0	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.001-0.002	Seitz (1979)
Steel	High Lime	10	60	30						9	UO_2	0.04	Heshmatpour (1981a)
Steel	Calcium-Magnesium-Silicate							$CaMgSi_2O_6$		19	Pu	0.0037	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		11	Pu	0.001	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		7	Pu	0.002-0.03	Seitz (1979)
Steel	Calcium-Aluminum-Silicate							$CaMgSi_2O_6$		15	Pu	0.0162	Seitz (1979)
Steel	Calcium-Aluminum-Silicate	10	40	40				10 NiO		10	U	0.005	Nafziger (1988)

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a. BI = Basicity Index = (wt.% basic oxides)(wt.% acidic oxides)
b. % Slag in charge.
c. Partition Ratio, λ, is defined as the ratio of concentration of constituent in the slag phase/concentration of constituent in the metal phase.
d. X = Constituent is present in the slag, but concentration is unknown.
e. NA = Not Available

Table 3-2. Typical results of smelting uranium-contaminated ferrous scrap (From Mautz, 1975a).

Material	Product Ingot U Content, ppm[a]		
	Average	Low	High
Common Steel	0.4	0.00	3.50
Stainless Steel	0.6	0.01	3.20
Ni-Bearing Steel	0.5	0.02	2.38
Nickel	1.25	0.9	1.6
Monel (Ni Alloy)	0.5	0.01	4.00
Copper	0.4	0.01	2.5
Brass	0.4	0.01	2.5
Yellow Brass	2.1	0.3	3.2
Bronze	0.3	0.04	1.2
Aluminum	200	3	1400

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[a] Data primarily from Oak Ridge Y-12 plant except for aluminum data from Goodyear Atomic Corp; ppm = parts per million by weight = micrograms per gram (µg/g)

Table 3-3. Melt/slag refining test work results for radionuclide decontamination of metallic scrap.

	Slag												
		Composition, Nominal %					Final Radionuclide Contamination in Metal Product						
Metal	Type	SiO_2	CaO	Al_2O_3	Other	Amount, %[a]	Co-60	Cs-137	Sr-85	Other	Other	Other	Reference
Steel Scrap	Reducing	3% Coal, 2.5% SiC, 1% Slag Formers				6	15 pCi/g	0.25 pCi/g		Alpha <0.8 Bq/g			Schuster (1990)
Steel Scrap	Reducing	3% Coal, 2.5% SiC, 1% Slag Formers				6				Am-241, 1%: 0.1 Bq/g	U: added as U, 93-161 ug/g (avg. 130); added as UO_2 2-52 ug/g (avg. 27)		Schuster (1990)
Steel Scrap	Reducing	3% Coal, 2.5% SiC, 1% Slag Formers				6	108 %			Fe-55, 70%	C-14, 91% (Various Locations:106-110-89-24)	Ni-63, 82% (Various Locations: 86-90-96-90)	Schuster (1990)
S.S.	Calcium Silicate	$CaSiO_3$, BI[b] = 3					2.21 Bq/g	To slag & vapor	To slag	Mn-54, 4.06 Bq/g	Zn-65, 6.67 Bq/g		Nakamura (1992)
S.S.	Slag Gel 160	72	0.7	13	4.5% Na_2O, 5.0% K_2O	0.09-0.44	91-100%	0-15%	0-4%				Reimann (1991) quoting Larsen (1985a)
S.S. and Steel (123 melts)	Unknown, probably as above						0-27 uCi/g	1-2 uCi/g		Eu-152, O uCi/g	Eu-150, O uCi/g	U-235, O uCi/g	Larsen (1985a)
S.S.	Fluoride				75% CaF_2-25% MgF_2	3-6				Beta, Gamma: 3321 uCi/g	Alpha: 23 uCi/g		Jacquet-Francillon (1991)

Table 3-3. (continued).

	Slag												
		Composition, Nominal %					Final Radionuclide Contamination in Metal Product						
Metal	Type	SiO_2	CaO	Al_2O_3	Other	Amount, %[a]	Co-60	Cs-137	Sr-85	Other	Other	Other	Reference
Zircaloy/ 10% S.S.	Fluoride				50% CaF_2- 50% BaF_2	9.5-10.5				NA[c]	NA		Jacquet-Francillon (1991)
Zircaloy, Inconel, Stainless Steel	Cold Crucible IF, Fluoride				50% CaF_2, 50% BaF_2	2%				Alpha Distribution 5% gas, 80% slag, 15% ingot; sp. act. 0.8 Ci/tonne; decontam. 85%			Berthier, et al (1993)
Ziraloy, Inconel, Stainless Steel	Cold Crucible IF, Fluoride				45% CaF_2, 45% BaF_2, 10% CaO					Alpha Distribution 1% gas, 5% slag, 94% ingot;decontam. 85%			Berthier, et al (1993)
S.S.	Unknown						76 mCi, 99.7%				Mn-54, 0.2%	Zn-65, 0.1%	Lacroix (1986)
S.S. and Steel	Unknown						Completely in ingot	0 in ingot: half to slag/half to dust	0 in ingot: all to slag				Nakamura (1992)
S.S.	Silicate	<20	Unknown				Essentially in ingot	Cs-137, Cs-134 to slag and dust					Gomer (1985)

Table 3-3. (continued).

	Slag												
		Composition, Nominal %					Final Radionuclide Contamination in Metal Product						
Metal	Type	SiO_2	CaO	Al_2O_3	Other	Amount, %^{a}	Co-60	Cs-137	Sr-85	Other	Other	Other	Reference
S.S. and Steel	Unknown									Alpha: U-235, U-238, Pu-241, all <D.L.^{d}	Beta: Fe-55, 100%; Ni-63, 90%; Sr-90, 3%	Gamma: Co-60, 90%; Cs-134,137, <D.L.; Ag-110, 95%, Ce-144, 50%; Mn-54, 95%; Zn-65, <D.L.	Sappok (1992)
S.S. and Steel	Unknown						Remained in Melt	Completely Eliminated		Ce-144, Mn, Zn, Eu Removed From Melt			Eickelpasch (1992)
Steel Scrap	Unknown									Activity ranged from 0.1-0.67 Bq/g			Thoma (1990)
Steel Scrap	Unknown						1330 Bq/g			Activity, Bq/g: Mn-54, 8.4; Co-58, 20; Zn-65, 30; Ag-110, 54; Sb-125, 29			Menon (1990)
Steel Scrap	BOF^{e}, IF^{f}						BOF: 0.16 Bq/g, no activity in slag or dust. IF: to metal						Harvey (1990a)

Table 3-3. (continued).

	Slag												
		Composition, Nominal %					Final Radionuclide Contamination in Metal Product						
Metal	Type	SiO_2	CaO	Al_2O_3	Other	Amount, %[a]	Co-60	Cs-137	Sr-85	Other	Other	Other	Reference
Steel Scrap	IF									Eu-152/154, 0 in ingot, 0.00 Bq/g, all in slag			Harvey (1990a)
Steel Scrap	Arc Furnace									Eu-152/154, 0 in ingot, <0.02 Bq/g, stable in slag under oxidizing and reducing conditions			Harvey (1990a)

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a. % Slag in charge
b. BI = Basicity Index = wt.% basic oxides/wt.% acidic oxides
c. NA = Not Available
d. D.L. = Detection Limit
e. BOF = Basic Oxygen Furnace
f. IF = Induction Furnace

being scheduled to begin operation in 1993. The unit is quoted to produce 15 ingots/yr of about 240 kg. The melting capacity is to be 40 kg/hr for stainless steel waste. A later paper published by this research organization (Berthier, et al, 1993) shows 85% alpha removal by the calcium-barium-fluoride slag to near the France decategorization value (0.1 regulatory level, 0.8 Ci/tonne achieved). However, the presence of 10% CaO in the flux results in essentially no removal, i.e., 6% alpha decontamination resulted. Berthier states that a production facility has been qualified. The production facility is expected (no date given) to have a capacity of 60 kg/hr.

Another large scale French study (four castings totaling about 3660 kg) has been described by Lacroix and Tailliez (1986). The slag used was not specified. The activity after melting was distributed as follows: 76 mCi was in the ingots (99.7% as Co-60, 0.2% as Mn-54, 0.1% as Zn-65); 217 uCi was in the slag; and 148 uCi was in the filter dust.

Melt/slag test work is also being conducted in Japan (by the Japan Atomic Energy Research Institute) under the sponsorship of the Science and Technology Agency (Nakamura 1992). The major objectives of this work was to investigate the transfer behavior of radionuclides during melting operations and to provide data for development of regulation standards. Scrap melt studies (six decommissioning melt studies were conducted during the period 1988—1991) and tracer studies using Mn-54, Co-60, Zn-65, Sr-85, and Cs-137 beta/gamma emitters were performed to determine radionuclide distribution factors. Variables studied have included melt temperature (1873°-1913° K), slag composition (basicities of 1 and 3 were tested), and type of steel (ASTM-A335 and SUS 304). Insufficient data are presented in the publications to state the influence of the selected variables but the results of one tracer test (ASTM-A335, 1903° K, basicity of 1) showed the distribution to be as follows: Mn-54 was retained primarily in the ingot (a small fraction distributed to the slag, <10%); Co-60 remained completely in the ingot; Zn-65 was retained mostly in the ingot (~10% to the exhaust gas); Sr-85 transferred completely to the slag; and Cs-137 transferred equally to the slag and exhaust gas. (These results are in general agreement with results obtained by Larsen and Reimann, (1985, Personal communication between Larsen and Reimann as referenced in Reimann (1991)) on spiked samples using conditions: 230–320 kg metal, slag of composition 72% SiO_2, 13% Al_2O_3, 4.5% Na_2O, 5.0% K_2O, 0.7 % CaO. The results showed 91–100% of the Co-60, 0–15% of the Cs-137 and 0–4% of the Sr-85 remained in the ingot; most of the Sr-85 collected in the slag and most of the Cs-137 distributed to the baghouse.)

Recent European large scale test work results have been summarized by Gomer (British Steel Corporation), Sappok (Siempelkamp), M. Allibert (Inst. Nat. Polytechnique de Grenoble) and Delabbaye (Seri) (1984).

> The BSC test work was conducted on 1.65 tonne of iron and iron alloy scrap with the goal to demonstrate that reclamation can be achieved by dilution. Gomer demonstrated that Co-60 was uniformly distributed and essentially completely retained in the metal while Cs-137, Cs-134 distributed mainly to the slag and flue dust. The relative distribution depended on the melt holding time. The slag used was ~20% silica and lime (amount unknown). The author states that the cesium can be made to stay substantially in the slag but data was not presented to confirm this nor was the slag composition quoted.

The work at Seri (Allibert, 1984, 1991) was directed toward determining the feasibility of extracting cobalt from contaminated stainless steel. Two approaches were taken (neither of which was successful), i.e., selective extraction of the cobalt into a slag phase or selective oxidation of the iron and chromium leaving a concentrated cobalt metal phase. The selective extraction into a slag phase was based on the potential preferential formation of cobalt phosphide. The results were unfavorable. The selective oxidation process resulted in appreciable cobalt distribution to the oxidized slag phase rather than remaining in a concentration metal phase.

The work at Siempelkamp (Gomer, 1984) was directed at volume reduction. Test work results were not presented in this publication but Sappok did update this report in SPECTRUM 92 (see following paragraph).

Sappok (1992) described successful decontamination of large quantities of metallic scrap for iron and iron alloys, copper, brass, and aluminum. The data are summarized in Table 3-3, e.g., for the iron melts alpha emitters (U-235, U-238, Pu-241) were all below detection limit in the ingot. Ninety-eight percent of the alpha emitters reported to the slag phase. Beta emitters were distributed as follows: Fe-55, 100% to melt; Ni-63, 90% to melt, 10% to slag; Sr-90, 3% to melt, 95% to slag, 2% to dust. Gamma emitters were distributed as follows: Co-60, 90% to melt, 10% to slag; Cs-134, Cs-137, 45% to slag, 55% to dust; Ag-110, 95% to melt, 5% to slag; Ce-144, 50% to melt, 50% to slag; Mn-54, 95% to melt, 5% to slag; Zn-65, 10% to slag, 90% to dust. The slag composition used was not reported.

Mies (1991) reported that over 500 tons of steel scrap has been treated at Gesellschaft fur Nuklear Service (GNS) by melt refining. Although experimental data are not reported the final product activities were <0.4 Bq/g in the melt, <0.3 Bq/g in the cast product, <1.0 Bq/g in the slag, and <30 Bq/g in the dust. The slag composition used was not reported.

Eickelpasch (1992) reported that over 1500 tonne of steel scrap has been handed over for treatment in melt refining. Although experimental data are not reported the following summary was presented to illustrate elemental distribution during the melting treatment: Cesium was completely eliminated from the melt and distributed to the slag (composition unknown) and to the dust. Cobalt remained in the metal. Ce-144 distributed completely to the slag. Manganese, zinc, europium left the melt (their relative distribution to slag and dust was not stated).

Thoma (1990), Federal Republic of Germany, reported that over 150 tonne of steel scrap from the Niederaichbach Nuclear power plant were treated in 1989 at the EIRAM melting plant. The total activity of the products were measured; the activities in the slag and ingot product were approximately the same; the activities in the furnace dust and in the melt crucible were below the analytical detection limit. Activity in the ingot products ranged from 0.01 to 0.67 Bq/g. The slag composition used was not reported.

Menon, et al. (1990) reported that approximately 190 tonne of steel and stainless steel scrap from three Swedish and one West Germany reactor sites were melted in 1987-1988 at the Studsvik Melting Facility. Very little information is presented for the melt tests and the 548 ingots produced. Example activities measured for the ingot product are (in Bq/g): Co-60, 1330; Mn-54, 8.2; Co-58, 20; Zn-65, 34; Ag-110m, 54; Sb-125, 29. Janberg and Rittscher (1990) state that for the free use of beta, gamma scrap the activity must be less than 0.1 Bq/g. As with the other publications dealing with large scale test work discussed above, the slag composition used was not reported.

Harvey (1990a), reported on the results of the British Steel Corporation test work program to investigate the feasibility of melting contaminated waste. Cobalt distribution was investigated during induction melting and basic oxygen furnace (BOF) melting and cesium and europium distribution was investigated during induction melting and arc melting. Co-60 remained essentially in the metal even under the highly oxidizing conditions of BOF steelmaking, i.e., cobalt was not oxidized and distributed to the slag. Co-60 distributed mainly to the metal phase in induction furnace treatment but some metallic globules were temporarily entrapped in the slag phase. Cesium distributed to the slag phase and dust during induction melting. The amount depended on the basicity of the slag, time of sampling and to a lesser extent on temperature. The higher the slag basicity the less cesium was retained in the slag phase. In arc melting, Gomer (1985) reported that 96% of the cesium distributed to the dust when a basic slag was used. British Steel investigated acidic slag conditions and found that 56% of the radioactivity remained in the slag phase. In induction melting and in large scale arc melting experiments, europium was wholly retained in the slag phase under both oxidizing and reducing conditions.

3.2 Comments on Literature

Variables that are expected to influence the decontamination efficiency of slagging include: temperature, time, initial contaminant concentration, slag composition, metal composition, and gas environment (oxygen potential). Equilibrium may or may not have been established in the individual slagging studies. In actuality equilibrium probably was not established in most of the studies and the results were most likely influenced by variables such as time of exposure, method of addition of radioactive constituents (metals, oxides, hydroxides, halides), initial concentration of radioactive constituents, slag/metal contact (static, dynamic), reaction with crucible materials, slag/metal disengagement technique (slag inclusions formed in the metal phase), and method of sampling final products (surface samples, core samples). None of the published studies reported the product slag composition, i.e., in general, only the composition of the initial slag has been reported not the final slag composition. Therefore, because of the many differences in experimental techniques and the lack of complete characterization, the published test work results must be reviewed from a phenomenological viewpoint.

As Reimann has stated, there does not appear to be a clearly discernable trend with respect to the influence of slag composition on uranium and plutonium removal from steel scrap. There are, however, some generalities that can be made from the published results, e.g., Abe (1985a) showed calcium-aluminum-silicates to be effective for uranium removal to below one ppm for stainless steel scrap and to a fraction of a ppm for calcium-aluminum-silicate slags containing calcium fluoride and nickel oxide. The calcium-aluminum-silicate/calcium fluoride and nickel oxide tests resulted in uranium removal to below the initial uranium content, e.g., 0.005 ppm uranium concentration was achieved in the treated melt product compared to 0.01 ppm in the starting steel (natural background); 0.10 ppm uranium concentration was achieved in the treated melt product compared to 0.11 ppm in the starting stainless steel (natural background). Nafziger (1988) showed the same result for stainless steel using calcium-aluminum-silicates with calcium fluoride, i.e., 0.1 ppm. Abe's conclusions were that slag composition (basicity should be >1.5 and the presence of calcium fluoride or nickel oxide is beneficial), and temperature (1550° C for stainless steel, 1700°C for mild steel) are important, but time (half an hour is sufficient) is not.

Heshmatpour and Copeland (1981a, 1981b) concluded that the extent of decontamination was not very sensitive to slag type and composition but did conclude borosilicate and oxidizing slags were more effective for decontaminating mild steels and stainless steels. Inference from the Heshmatpour, Copeland work is that the most effective slag combinations were calcium-aluminum-silicate bearing slags containing a high lime content and containing some calcium fluoride and/or ferric oxide.

In general, comparison of resultant uranium ingot concentration levels to the "natural background uranium concentration" [0.06 ppm uranium measured in carbon steel produced prior to 1942, Blatz (1951); 0.23 ppm measured in stainless steel produced prior to 1942, Klevin (1956)] shows that decontamination by slagging is effective for steels and stainless steels using several different slag compositions.

Test results that show uranium lowering to below the natural concentration levels established by Blatz and Klevin are presented in Table 3-5. In general the slags containing a high basicity index, and especially a high basicity index (high lime, lower silica) while containing ferric oxide or calcium fluoride, appear to be especially appropriate for treating steels. However, Table 3-5 is a bit misleading, because slag compositions quite similar to the successful slags showed much poorer results.

With respect to stainless steels the slags that achieved less than natural levels of uranium (Table 3-5) were the calcium-aluminum-silicates containing additives of calcium fluoride, nickel oxide, or ferric oxide and calcium fluoride. A trend is not evident at this time.

A variety of slags have been successfully used to lower the plutonium content in both mild steels and stainless steels to plutonium concentrations less than one ppm. Borosilicate slags appear to be effective for steels, e.g., Seitz (1979) presents data showing plutonium removals over the range 0.001-0.32 ppm. Hobbick (1981) has demonstrated effective plutonium removal using borosilicate slags, high silica calcium-aluminum-silicate slags and fluoride containing basic calcium-aluminum-silicate-ferrite slags. Copeland (1981) has demonstrated similar results except for borosilicate slags, e.g., effective plutonium removal was achieved using high silica calcium-aluminum-silicate slags, and fluoride containing basic calcium-aluminum-silicate-ferrite slags, but higher residual plutonium concentrations remained when borosilicate slags were used. Optimum slag compositions for the removal of plutonium are presently unknown.

The authors of this literature survey did not attempt to delineate regulatory concentrations that decontamination must achieve for individual radionuclides in the product metals. However, as a convenience to the reader (for comparative purposes referring to the results presented in Tables 3-1–3-5) a table prepared by Reimann (1991, p. 18) has been included below as Table 3-5. Reimann has stated that EG&G's assumption is that metal wastes "will conform generally to the requirements that define low-level waste".

Table 3-4. Best results for melt/slag refining of uranium bearing ferrous metals (data source Table 3-1).

Slag								
Composition, Nominal %						Contamination		
SiO_2	CaO	Al_2O_3	Fe_2O_3	CaF_2	Other	Natural, ppm	Achieved, ppm	Reference
						S.S.		
40	30	20		10		0.23	0.083	Abe (1985a)
40	30	20		10		0.23	0.10	Abe (1985a)
40	30	20		10		0.23	0.10	Nafziger (1988)
75	25					0.23	<0.01	Heshmatpour (1981a)
30	50	10	5	5		0.23	0.05	Heshmatpour (1981a)
35	65					0.23	0.28	Heshmatpour (1981a)
						Steel		
30	50	20				0.06	0.059	Uda (1985)
10	50	40				0.06	0.027	Uda (1985)
10	40	40			10 NiO	0.06	0.005	Nafziger (1988)
10	40	40			10 NiO	0.06	0.005	Abe (1985a)
40	40	20				0.06	<0.08	Abe (1985a)
Calcium-Aluminum-Silicate With Varying Basicity Index: 0.5-3.5						0.06	0.01 to <0.1, Lowest value for BI = 1.5	Abe (1985a)
40	50	10				0.06	0.014	Heshmatpour (1981a)
25	50	25				0.06	0.05	Heshmatpour (1981a)
10	40	40			10 NiO	0.06	0.005	Nafziger (1988)
10	50	25	10			0.06	<0.01	Heshmatpour (1981a)
35	60		5			0.06	0.016	Heshmatpour (1981a)

Table 3-4. (continued).

Slag								
Composition, Nominal %						Contamination		
SiO_2	CaO	Al_2O_3	Fe_2O_3	CaF_2	Other	Natural, ppm	Achieved, ppm	Reference
80		2			13 B_2O_3	0.06	<0.01	Heshmatpour (1981a)
25	60	10	5			0.06	0.03	Heshmatpour (1981a)
10	60	30				0.06	0.04	Heshmatpour (1981a)
10	60		30			0.06	0.04	Heshmatpour (1981a)
25	50		25			0.06	0.05	Heshmatpour (1981a)
25	60	10		5		0.06	0.03	Heshmatpour (1981a)
10	50	25	5	10		0.06	<0.01	Heshmatpour (1981a)

Table 3-5. Summary of allowable nuclide concentrations in low-level waste (from Reimann, 1991).

Radionuclide	Concentration Ci/m^3	ppm[b]	g/m^3
C-14	8	1.8	2.2
C-14 in activated metal	80	18	22
Ni-59 in activated metal	220	2750	3300
Co-60	[c]	[c]	[c]
Ni-63	700	11.3	13.6
Ni-63 in activated metal	7000	113	136
Sr-90	7000	142	170
Nb-94 in activated metal	0.2	1.1	1.3
Tc-99	2	150	180
I-129	3	150	600
Cs-137	4600	53	64
Pu-241	3500[d]	0.03	0.037
Cm-242	20000[d]	0.006	0.007
alpha emitting TRU nuclides with half life >5 yr	100[d]		
Total, all nuclides with half life >5 yr	[c]	[c]	[c]

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a. Data extracted from 10CF61, 1-1-88 ed., 61.55, Tables 1 and 2.

b. ppm calculated from specific activity and estimated weight of stainless steel in 1 m^3 of scrap, using equation from ref. 10 (Blatz, 1951) and half life data from ref. 11 (Klevin, 1956).
1 ppm = 1 g/metric ton.

c. No limits established for these radionuclides in Class C waste. Practical considerations such as the effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentration of these wastes.

d. Units are nanocuries per gram.

3.3 Recent Experimental Test Results

3.3.1 Montana Tech Study Results: Stainless Steel

Montana Tech has conducted a program wherein the surrogates La, Ce, Nd, Sr, and Cs were added to a 6-in. diameter 304 stainless steel master melt weighing 300 lb. The ingot was prepared by encapsulating metallic (fluorides in the case of Cs and Sr) surrogates under argon in stainless steel tubing. These capsules were welded to scrap 304L feed stock which was plasma cold-hearth melted under helium at Retech, Inc. (Worcester, 1994). Surrogates, introduced into the feed stock at 0.1%, were analyzed in the master melt at 0.04% La, 0.06% Ce, 0.05% Nd, <1 ppm Cs, and <1 ppm Sr. Loss of Cs and Sr was attributed to elemental and fluoride vapor transport, and losses of Ce, La, and Nd were attributed to surrogate reaction with oxygen in the gas phase and with oxide scale on the feed metal to form surrogate oxides with subsequent collection in a slag phase. Sections from the master melt were used as feed stock for a series of 2-lb air induction melts performed under a series of time, temperature, and flux conditions. Results of some of those experiments are summarized in Table 3-6. (Worcester, 1994a).

Results of this work can be summarized as follows:

1. Surrogates can be reduced to <1 ppm after induction melting for 30 minutes.

2. Surrogate removal was relatively insensitive to flux used.

3. Air oxidation of the melt is probably sufficient for surrogate removal. (This has been subsequently confirmed on a 2,000-lb air induction melt which has not yet been reported)

3.3.2 Montana Tech Study Results: Mild Steel

A similar program to that described above was conducted by Montana Tech on mild steel. A 250-lb 6-in. diameter surrogate ingot was cold-hearth plasma melted and forged into 1.75-in. round bar to form starting material for subsequent 2-lb. induction melting experiments. Slag compositions, melting temperatures, and times were varied to assess surrogate removal by air induction melting. Typical data are summarized in Table 3-7. (Paolini, 1995)

Results of this work are summarized below:

1. Decontamination of steel is achieved at faster rates and lower temperatures than for the stainless steel.

2. The flux is only required for the handling and fluidity of the slag.

3. Decontamination is achieved within 5 minutes at 1600°C.

Table 3-6. Stainless steel induction test results at Montana Tech.

Time (min)	Flux used[a]	Surrogate in metal phase, $PPM_{initial}$			Cr & Mn in metal phase, wt. $\%_{initial}$	
		La_{350}	Ce_{600}	Nd_{530}	$Cr_{18.7}$	$Mn_{1.42}$
Temperature = 1600±50° C						
0.5	Borate (5%)	15.0	49.0	37.0	18.7	1.29
0.5	Fluoride (5%)	11	24	21	18.5	1.22
5	None (Argon)	1.8	14	6.2	NA	NA
4	None	0.55	2.4	2.2	NA	NA
5	Borate (5%)	1.6	6.6	5.1	18.2	1.02
5	Borate w/o Fe Oxide (5%)	1.6	6.3	<1.0	NA	NA
5	Fluoride (5%)	2.1	4.6	5.2	18.7	1.04
Temperature 1645±45°C						
30	Borate (5%)	<1.0	<1.0	<1.0	16.6	
30	Borate w/o Fe Oxide (5%)	5.0 <1.0	8.0 <1.0	7.0 <1.0	17.1	0.55

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a. Borate: 30%SiO_2, 40%CaO, 10%Al_2O_3, 15%Fe_2O_3, 5%$Ca_2B_6O_{11}$
Borate w/o Fe Oxide: 13%CaO, 12%Al_2O_3, 68%$CaSiO_3$, 7%$Ca_2B_6O_{11}$
Fluoride: 30%SiO_2, 40%CaO, 10%Al_2O_3, 15%Fe_2O_3, 5%CaF_2

b. Results of new sample not reported in referenced document.

NA Not Analyzed.

Table 3-7. Steel induction test results at Montana Tech.

Time (min.)	Flux used	Surrogate in metal phase, $PPM_{initial}$			Mn in metal phase, wt.$\%_{initial}$
		La_{113}	Ce_{200}	Nd_{205}	$Mn_{0.75}$
		Temperature = 1600 ± 50°C			
5	(5%)	<1.0	<1.0	<1.0	0.23
15	(5%)	<1.0	<1.0	<1.0	0.077
30	(5%)	<1.0	<1.0	<1.0	0.021
		Temperature = 1675 ± 50°C			
5	(5%)	3.5	<1.0	5.5	0.094
15	(5%)	<1.0	<1.0	<1.0	0.044
15	NO FLUX	<0.5	<1.0	<2.0	0.26

Flux: 32% SiO_2, 42% CaO, 16% Fe_2O_3, 10% Al_2O_3

3.3.3 Oregon Graduate Institute Study Results: Stainless Steel

Atteridge and others (Atteridge, 1994) have described work completed in preparation for evaluation of electroslag melting (ESR) and vacuum arc remelting (VAR) as surrogate removal techniques. Starting material for that program was clean, uncontaminated stainless steel scrap supplied by INEL. The scrap was melted in three heats in a 2,000-lb. air induction furnace at ESCO in Portland, Oregon. The heats were cast into 120 2.5-in. diameter by 1 to 2-ft. long bars which make ideal starting electrodes for further ESR and arc melting experiments. Surrogates selected for study were La_2O_3 and CeO_2. Surrogate additions were made by plasma spraying a mixture of surrogate oxides and stainless steel on the surface of the cast bars. Using sprayed bars as starting material, remelts were performed by ESR, VAR, air induction, and cold hearth inert-gas plasma melting. Preliminary results for this study follows:

1. ESR reduced La concentrations to <1 ppm. Ce concentrations were below detection limits using Instrumental Neutron Activation Analysis (INAA).

2. VAR reduced surrogate concentration levels slightly, but La and Ce levels remained at 230 and 159 ppm respectively. The surrogate oxides tended to segregate on the surface of the ingot.

3. Air induction melting reduced La levels to <1 ppm and Ce to levels below the detection limit of INAA.

4. Cold hearth plasma melting reduced Ce and La to <1 ppm each. It should be noted from the Montana tech experience that this is not the case for La, Ce, and Nd if the surrogates are not in oxide form prior to plasma melting.

Atteridge also includes an excellent assessment of analytical techniques applicable to surrogate analysis.

3.4 Summary

Test work (both bench scale and larger scale) results to date do demonstrate that slagging decontamination of uranium and plutonium from steel and stainless steel is an effective treatment technology.

A conclusion resulting from the review of published literature by Worcester, el al (1993) was that test work (both bench scale and larger scale) demonstrated that slagging decontamination of uranium and plutonium from steel and stainless steel is an effective treatment technology. Laboratory and large scale test work performed at Montana Tech (Worcester, et al, 1994) and laboratory test work performed at the Oregon Graduate Institute (Atteridge, et al, 1994) have further demonstrated (using surrogates for the radioactive nuclides) effective decontamination of stainless steel to concentrations less than one part per million) using induction melting (in air) and electroslag melting, respectively. Furthermore, Paolini (1995) has demonstrated that mild steel can be decontaminated (using surrogates) to less than one part per million with or without flux by induction melting in air.

Based on trends found in the literature, basic calcium-aluminum-silicate slags (with additives such as calcium fluoride, nickel oxide, ferric oxide) appear to be effective steel decontaminators. However, the recent work of Worcester (1994) demonstrates that flux composition is not very important when the decontamination is conducted in air exposed induction melting furnaces.

At present it appears that removal of most radionuclides by slagging and volatilization holds good possibilities for the treatment of steel scrap. Very little information on slagging removal of non-uranium/plutonium is available. The same slagging/volatilization possibilities appear to exist for stainless steel, except for the active specific elements that constitute stainless steel. Radionuclides of iron, cobalt, nickel, manganese and chromium will be retained to a large degree in the metal product.

Nafziger and Elger (1988) and Reimann (1991) have suggested that a fluorite bearing mineral-like (Colemanite) slag flux be utilized for stainless steel decontamination of uranium and plutonium. It appears likely (from Heshmatpour and Abe's work) that this slag composition would also be appropriate for decontaminating steel. The proposed slag composition is nominally: 30% SiO_2, 40% CaO, 10% Al_2O_3, 15% Fe_2O_3, 5% $Ca_2B_6O_{11}$. This is a basic slag and will, therefore, function as an oxidizing slag. Because it is an oxidizing slag it probably will also be effective in removing other contaminating radioactive nuclides, like strontium, europium, etc.

4. CALCULATIONAL PROGRAMS

There are a number of computer software programs available for multi-component high temperature thermodynamic equilibrium calculations. The identified programs are presented in Table 4-1. Bale (1990) has conducted a review of several of the calculational programs (CSIRO/MONASH, FACT, MTDATA, THERMO-CALC, HSC, THERMODATA, THERDAS) and has provided contact names, phone numbers and addresses for information on each program.

The CSIRO/MONASH thermodynamic equilibrium program will be utilized as a calculational tool to assist in the slag/melt and slag/refractory design portion of the present project.

Table 4-1. Elevated temperature thermodynamic equilibrium calculational programs.

Program	Reference
CSIRO/MONASH Thermochemical System (Australia)	Wadsley (1993), Bale (1990)
Facility for Analysis of Chemical Thermodynamics: FACT (Canada)	Thompson (1985, 1988), Bale (1990)
Metallurgical and Thermochemical Data Service: MTDATA (U.K.)	Davies (1990, 1991), Bale (1990), Barry (1993)
THERMO-CALC (Sweden)	Sundman (1988), Bale (1990)
OUTOKUMPU HSC (Finland)	Roine (1988), Bale (1990)
THEMODATA (France)	Cheynet (1988), Bale (1990)
THERDAS (Germany)	Barin (1980), Bale (1990)
UM/ROLLA-PYROMETALLURGY: STEPSOL, STGSOL (U.S.)	Morris (1993)

5. SURROGATES AND RADIONUCLIDES

There have only been a limited number of test programs that have used surrogates to simulate the distribution of radioactive nuclides during melt refining. However, a few studies have been identified that relate directly to the present project. The literature that has been identified is presented in Table 5-1.

Plutonium oxide has been investigated by several investigators using surrogates, e.g.,

- Ochiai, et el (1982) investigated the distribution of HfO_2 (as a surrogate for PuO_2) in an electro-slag melting study. They determined that the best initial slag was composed of 47% CaO, 48% Al_2O_3, 5% B_2O_3 (the silica content of the slag rose to approximately 20 % after repeated exposure). The hafnium distribution was 96% to the slag phase. The final ingot contained 2.53 ppb hafnium.

- McAtee (1991) has reviewed the high temperature chemistry of plutonium and the rare earths. He quotes the work of Shaw (1988a, 1988b), Hooker (1981), Weidner (1991), and Bergsman (1991) who have used rare earth oxides as surrogates for plutonium oxide. Shaw (1988a) and Hooker have reported the use of dysprosium oxide in incineration tests. Shaw also reported the use of dysprosium oxide in a glove box scale study of excavated buried transuranic wastes. Bergsman (1991) and Weidner (1991) used rare earth oxides to simulate plutonium in in-situ vitrification studies. Weidner used dysprosium oxide in test work on in-situ vitrification of basaltic melts and Weidner found that the simulates dysprosium, neodymium, ytterbium and cerium oxides were uniformly distributed in the silicate melt product at approximately uniform concentrations.

- Stoots (1990) recommended the use of rare earth oxides of dysprosium, terbium and ytterbium as simulates for plutonium oxide in soils. This was a work plan for in-situ vitrification studies. Experimental data were not yet collected at the time of this report.

- Whitworth (1993) is presently conducting a study at MSE in Butte, MT to investigate the distribution of plutonium oxide during the plasma melting of contaminated wastes and soils. Cerium oxide is being used as the surrogate for plutonium oxide. Results of this work are not presently published.

Schuster (1990) investigated the distribution of Co-60 in melt experiments performed on beta and gamma contaminated steel scrap. The distribution of cobalt was taken to be an effective indicator for the distribution of iron (Fe-55) and nickel (Ni-59, Ni-63).

In a current RSM decontamination program, Atteridge and others (Atteridge, 1994) state "The surrogate choices for cesium and strontium were merely the naturally-occurring isotopic mixtures of these elements. The naturally-occurring isotopic mixtures of the rare earth elements cerium and neodymium were used because rare earth elements are the most abundant fission products and because these two elements could be used as surrogates for uranium and plutonium,

Table 5-1. Surrogates used for radioactive nuclides in high temperature studies.

Radionuclide/Oxide	Surrogate	Comment	Reference
PuO_2	HfO_2	Simulate plutonium oxide in electro-slag melting	Ochiai (1982)
Fe-55, Ni-59, Ni-63	Co-60	Melt experiments with β,γ-contaminated material	Schuster (1990)
PuO_2	UO_2	Resistance heating & arc melting techniques	Levitz (1975)
PuO_2	Rare Earth Oxides of Dysprosium, Terbium, Ytterbium	Simulate plutonium in soils in vitrification study	Stoots (1990)
PuO_2 and Transuranic Oxides	Dysprosium Oxide	Incinerator tests and Glove box tests	Shaw (1988) as referenced by McAtee (1991); Hooker (1981); Shaw (1988)
PuO_2	Rare Earth Oxides of Dysprosium, Neodymium, Ytterbium, Cerium	Vitrification and slagging in silicate melts	Bergsman (1991) as referenced by McAtee (1991)
PuO_2	Dysprosium Oxide	Vitrification and slagging in silicate melts	Weidner (1991) as referenced by McAtee (1991)
PuO_2	All Rare Earth Oxides (Especially Cerium)	Based on high temperature chemistry considerations	McAtee (1991)
PuO_2	Cerium Oxide	Simulate plutonium oxide distribution during plasma melting of contaminated soils	Whitworth (1993)

respectively. The choices of Ce and Nd as substitutes for all rare earths were reasonable because, in general the reactivities and thermochemical properties of the rare earths are quite similar to one another; lanthanum was chosen as a general surrogate for these same reasons." Atteridge lists the free energies of stable oxides of radionuclides of interest and possible surrogate elements and states "The choice of Ce as a surrogate for actinide elements is a common one; the suitability for Ce as a Pu surrogate has recently been discussed by Raraz, Mishra, and Averil." (Raraz) Worcester and others (Worcester, 1994) present similar arguments for selection of the same surrogates and present the argument for tracking cobalt in the experimentation. Herbst and others (Herbst) selected Hf as a surrogate for U based on thermodynamic and density considerations in their work on "Quantum-Catalytic" extraction at Molten Metal Technology Corporation.

In a DOE report, Stockdale and others (Stockdale) state "The chief radioactive nuclides of concern in the treatment of mixed wastes are ^{239}Pu, ^{238}U, ^{235}U, ^{137}Cs, ^{103}Ru, ^{99}Tc, and ^{90}Sr. These nuclides are largely by-products of uranium enrichment, reactor fuel processing, and weapons program activities. ... The seven radionuclides listed can therefore be simulated by a surrogate package containing stable isotopes of ruthenium, strontium, cesium, and cerium.

Elert and others (Elert, 1992) have summarized the ten radiologically most important radionuclides present (as a function of time) in decommissioning waste materials, their results are presented in Table 5-2.

Dyer and Bechtold (1994) surveyed the types of nuclide contamination present in eleven pressurized boiling reactors (PWRs) and eight boiling water reactors (BWRs). They found that "For the PWR reactor coolant, about 90% of the radionuclide activities are the radiocesium fission products with the other 10% being iron and cobalt activation products, Fe-55 and Co-60. For the BWR reactor coolant, about 91% of the activities are from Sb-125 which is an activation product of tin from the condenser tubing. The other 9% of the BWR reactor coolant activities is mainly from the activation products, Fe-55 and Co-60. For the samples of reactor component parts, between 86% to as much as 99% of the radionuclide activities are the activation products, Fe-55, Co-60, and Ni-63. This distribution of radionuclides for the reactor components appears to be the same whether the activities are contamination on the part surfaces or are contamination distributed within the part materials. In summary, for all the samples reviewed, the radionuclides that provided 1% or more of the total activities were: Mn-54, Fe-55, Co-60, Ni-63, Zn-65, Sb-125, Cs-134, and Cs-137. It appears that these would be the main radionuclides of concern for the recycling of material and stainless steel components from commercial nuclear power reactors in the United States".

Table 5-2. The ten radiologically most important radionuclides at different times for surface contamination for decommissioning waste (Elert, et al, 1992).

+0 Years	+10 Years	+100 Years
Co-60	Co-60	Cs-137
Mn-54	Cs-137	Sr-90
Co-58	Sr-90	Ni-63
Cs-137	Fe-55	Co-60
Sr-90	Ni-63	Ni-59
Fe-55	Mn-54	Am-241
Zn-65	Cs-134	Pu-238
Ni-63	Ni-59	Pu-240
Cs-134	Am-241	Pu-239
Ce-144	Pu-238	Cs-135

6. APPENDICES

6.1 Bibliography

A complete listing of the collected literature related to melt/refining and associated supporting reference publications is presented in the following bibliography.

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6.2 Tabulation of Melt/Slag Refining Test Work Results for All Metals and Alloys

The following summary, Table 6-1, is a compilation of test results for type of metal, slag composition, and type of contaminant for all metals (including the data presented previously in the text as Table 3-1 for stainless steel and mild steel) including aluminum, copper, lead, lead-tin alloys, nickel, steel, stainless steel, tin and zinc.

Table 6-1. Melt/slag refining test work results for uranium and plutonium decontamination of metals and alloys.

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Aluminum	Caustic				5			50 NaOH, 45 NaCl		9	UO_2	70.5	Heshmatpour (1981a)
Aluminum	No Flux									9	UO_2	447.0	Heshmatpour (1981a)
Aluminum								Sb		1	UO_2	91.3	Heshmatpour (1981a)
Aluminum	Fluoride Slag							100 CaF_2		9	UO_2	1.2	Heshmatpour (1981a)
Aluminum	Hexachloroethane degasser							Cl_3CCCl_3		1	UO_2	88.7	Heshmatpour (1981a)
Aluminum	Fluoride Slag							20 CaF_2, 80 NaF		9	UO_2	315.0	Heshmatpour (1981a)
Aluminum	Fluoride, Containing High Lime	30	55	10	5			5 CaF_2		9	UO_2	308.0	Heshmatpour (1981a)
Aluminum	Borosilicate	80		2			1	13 B_2O_3		9	UO_2	50.6	Heshmatpour (1981a)
Aluminum								S		1	UO_2	66.4	Heshmatpour (1981a)
Aluminum								NaF		9	UO_2	111.0	Heshmatpour (1981a)
Aluminum								C		1	UO_2	87.9	Heshmatpour (1981a)
Aluminum	Fluoride Slag			10				55 NaF, 35 AlF_3		4.5	UO_2	81.1	Heshmatpour (1981a)
Aluminum	Fluoride Slag			10				55 NaF, 35 AlF_3		4.5	UO_2	31.4	Heshmatpour (1981a)
Aluminum	No Flux										UO_2	469.0	Heshmatpour (1981a)
Aluminum	Fluoride Slag							60 CaF_2, 40 NaF		9	UO_2	0.9	Heshmatpour (1981a)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Aluminum	No Flux										UO_2	430.0	Heshmatpour (1981a)
Aluminum	Fluoride Slag							40 CaF_2, 60 NaF		9	UO_2	2.4	Heshmatpour (1981a)
Aluminum								Si		1	UO_2	82.3	Heshmatpour (1981a)
Aluminum								CaF_2			U	λ^c=810	Snyder (1991)
Aluminum								B		1	UO_2	95.3	Heshmatpour (1981a)
Copper	Calcium-Aluminum-Silicate	40	40	20						10	U	<0.1	Abe (1985a)
Copper	High Silica	65	35					5 CuO		9	UO_2	0.14	Heshmatpour (1981a)
Copper	Calcium-Aluminum-Silicate	40	40	20						10	U	<1	Abe (1985a)
Copper	High Silica	75	10	10	5					9	UO_2	0.83	Heshmatpour (1981a)
Copper	High Silica	65	20	10				5 CuO		9	UO_2	0.54	Heshmatpour (1981a)
Copper	High Silica	70	15	15						9	UO_2	0.11	Heshmatpour (1981a)
Copper	High Silica	50	25	25							U	λ=718	Snyder (1991)
Copper	Calcium-Aluminum-Silicate	40	40	20						10	U	<0.1	Abe (1985a)
Copper	High Silica	60	20	20						9	UO_2	0.37	Heshmatpour (1981a)
Copper	High Silica	55	30	10	5			5 CuO		9	UO_2	0.45	Heshmatpour (1981a)
Copper	No Flux										UO_2	1.96	Heshmatpour (1981a)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Copper	High Silica	65	10	10	5					9	UO_2	0.04	Heshmatpour (1981a)
Copper	High Silica	50	25	25						9	UO_2	0.13	Heshmatpour (1981a)
Copper	High Lime	30	50	10	5			5 CaF_2		9	UO_2	0.14	Heshmatpour (1981a)
Copper	Borosilicate	80		2			1	13 B_2O_3		9	UO_2	1.36	Heshmatpour (1981a)
Copper	High Silica	55	30	10						9	UO_2	0.25	Heshmatpour (1981a)
Lead 50-Tin 50	No Flux										UO_2	1.66	Heshmatpour (1981a)
Lead 50-Tin 50	Calcium-Aluminum-Silicate	45	30	20	5					9	UO_2	1.04	Heshmatpour (1981a)
Lead 50-Tin 50	Borosilicate, High Silica	80		2			1	13 B_2O_3		9	UO_2	3.02	Heshmatpour (1981a)
Lead 50-Tin 50	No Flux										UO_2	2.56	Heshmatpour (1981a)
Lead 50-Tin 50	Sodium Slag							40 $NaNO_3$, 30 NaCl, 30 NaOH		9	UO_2	1.44	Heshmatpour (1981a)
Lead 80-Tin 20	Calcium-Aluminum-Silicate	45	30	20	5					9	UO_2	0.06	Heshmatpour (1981a)
Lead 80-Tin 20	No Flux										UO_2	<0.01	Heshmatpour (1981a)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Lead	Sodium Slag							50 $NaNO_3$, 20 NaCl 20 NaOH, 10 PbO		9	UO_2	0.31	Heshmatpour (1981a)
Lead	Calcium-Aluminum-Silicate	40	20	25	15					9	UO_2	0.048	Heshmatpour (1981a)
Lead 80-Tin 20	Sodium Slag							40 $NaNO_3$, 40 NaOH, 20 NaCl		9	UO_2	1.35	Heshmatpour (1981a)
Lead	Sodium Slag							35 NaCl, 25 NaOH, 30 $NaNO_3$, 10 PbO		9	UO_2	0.35	Heshmatpour (1981a)
Lead	Sodium Slag							80 Na_2CO_3, 10 $NaNO_3$, 10 PbO		9	UO_2	1.03	Heshmatpour (1981a)
Lead	Sodium Slag							45 NaCl, 35 NaOH, 10 $NaNO_3$, 10 PbO		9	UO_2	0.24	Heshmatpour (1981a)
Lead	Sodium Slag							40 Na_2CO_3, 50 $NaNO_3$, 10 PbO		9	UO_2	0.26	Heshmatpour (1981a)
Lead	Sodium Slag							60 Na_2CO_3, 30 $NaNO_3$, 10 PbO		9	UO_2	0.49	Heshmatpour (1981a)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Lead	Sodium Slag							70 $NaNO_3$, 10 NaCl, 10 NaOH, 10 PbO		9	UO_2	0.06	Heshmatpour (1981a)
Lead	No Flux										UO_2	0.11	Heshmatpour (1981a)
Lead	Sodium Slag							80 Na_2CO_3- 10 $NaNO_3$- 10 PbO			U	λ=433	Snyder (1991)
Lead	Sodium Slag							40 $NaNO_3$, 30 NaCl 30 NaOH		9	UO_2	0.99	Heshmatpour (1981a)
Lead	Borosilicate	80		2			1	13 B_2O_3		9	UO_2	3.16	Heshmatpour (1981a)
Lead	No Flux										UO_2	0.23	Heshmatpour (1981a)
Lead	Fluoride Containing	30	50	10	5			CaF_2		9	UO_2	0.72	Heshmatpour (1981a)
Nickel	Fluoride Containing	30	50	10	5			5 CaF_2		9	UO_2	0.61	Heshmatpour (1981a)
Nickel	Borosilicate										U	λ=77	Snyder (1991)
Nickel	Borosilicate	80		2		4	0.5	13 B_2O_3		9	Pu	0.0366	Seitz (1979)
Nickel	High Lime	10	70		10					9	UO_2	0.33	Heshmatpour (1981a)
Nickel	Calcium-Aluminum-Silicate	40	50		10					9	UO_2	0.12	Heshmatpour (1981a)
Nickel	High Lime	35	60							9	UO_2	1.94	Heshmatpour (1981a)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Nickel	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.068	Seitz (1979)
Nickel	Borosilicate	80		2			1	13 B_2O_3		9	UO_2	0.78	Heshmatpour (1981a)
Nickel	Calcium-Aluminum-Silicate	40	40		20					9	UO_2	0.16	Heshmatpour (1981a)
Nickel	No Flux									9	UO_2	2.17	Heshmatpour (1981a)
Nickel	High Silica	75	20		5					9	UO_2	<0.01	Heshmatpour (1981a)
S.S.	Calcium-Aluminum-Silicate	40	40	20						10	U	<1	Abe (1985a)
S.S.	High Silica	60	30	10						5	Pu	0.21	Hobbick (1981)
S.S.	Calcium-Aluminum-Silicate	40	40	20						10	U	<1	Abe (1985a)
S.S.	Nickel Containing	10	40	40				10 NiO		10	U	0.005	Abe (1985a)
S.S.	Fluoride Containing	40	30	20				10 CaF_2		10	U	0.10	Abe (1985a)
S.S.	Calcium-Aluminum-Silicate	40	40	20						10	U	<1	Abe (1985a)
S.S.	Fluoride Containing	40	30	20				10 CaF_2		10	U	0.083	Abe (1985a)
S.S.	Fluoride Containing	30	40	10	15			5 CaF_2		5	Pu	0.50	Hobbick (1981)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
S.S.	Fluoride Containing	40	30	20				10 CaF_2		10	U	0.10	Nafziger (1988)
S.S.	Fluoride Containing	30	40	10	15			5 CaF_2		10	Pu	0.30	Hobbick (1981)
S.S.	High Silica	75	25								U	λ=226	Snyder (1991)
S.S.	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.003	Seitz (1979)
S.S.	High Silica	60		40						10	UO_2	2.53	Heshmatpour (1981a)
S.S.	Borosilicate	80		2		4	1	13 B_2O_3		5	Pu	0.75	Hobbick (1981)
S.S.	High Silica	75	25							10	UO_2	<0.01	Heshmatpour (1981a)
S.S.	Fluoride Containing	10	60	25				5 CaF_2		10	UO_2	2.39	Heshmatpour (1981a)
S.S.	Fluoride Containing	30	50	10	5			5 CaF_2		5	UO_2	0.05	Heshmatpour (1981a)
S.S.	High Lime	35	65							10	UO_2	0.28	Heshmatpour (1981a)
S.S.	Borosilicate	80		2		4	1	13 B_2O_3		10	Pu	0.60	Hobbick (1981)
S.S.	High Silica	60	30	10						10	Pu	0.42	Hobbick (1981)
S.S.	High Silica	60	30	10						5	Pu	0.4	Copeland (1981)
S.S.	No Flux									0	UO_2	0.65	Heshmatpour (1981a)
S.S.	Borosilicate	80		2		4		13 B_2O_3		10	Pu	1.9	Copeland (1981)
S.S.	Industrial	30	40	10	15			5 CaF_2		10	Pu	0.8	Copeland (1981)
S.S.	Borosilicate	80		2		4	1	13 B_2O_3		5	Pu	1.5	Copeland (1981)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
S.S.	High Silica	60	30	10						10	Pu	0.5	Copeland (1981)
Steel	High Lime	35	65							9	UO_2	2.72	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	40	50	10						9	UO_2	0.014	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	X[d]	X	X					1.6	10	U	<0.02	Abe (1985a)
Steel	High Silicate	70	10	20					0.13	10	U	0.11	Uda (1985)
Steel	Calcium-Aluminum-Silicate	40	40	20						10	U	<0.1	Abe (1985a)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		NA[e]	Pu	0.0012	Seitz (1979)
Steel	Calcium-Aluminum-Silicate	X	X	X				X NaF_2	1.5	10	U	0.01	Abe (1985a)
Steel	Calcium-Aluminum-Silicate	X	X	X				X NiO	1.5	10	U	0.01	Abe (1985a)
Steel	Calcium-Magnesium-Silicate							$CaMgSi_2O_6$		0.97	Pu	NA	Seitz (1979)
Steel	Calcium-Aluminum-Silicate	X	X	X					0.1	10	U	<0.1	Abe (1985a)
Steel	High Silica	75	25							9	UO_2	0.21	Heshmatpour (1981a)

Table 6-1. (continued).

	Slag									Final Metal Contamination		
		Composition, Nominal %										
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Steel	High Silica	60		40						9	UO_2	4.60	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	X	X	X					2.35	10	U	<0.1	Abe (1985a)
Steel	Calcium-Aluminum-Silicate	50	30	20					0.52	10	U	0.10	Uda (1985)
Steel	Calcium-Aluminate		50	50						9	UO_2	0.45	Heshmatpour (1981a)
Steel	Calcium-Aluminate		40	60						9	UO_2	0.42	Heshmatpour (1981a)
Steel	Fluoride Containing	10	60	25				5 CaF_2		9	UO_2	0.44	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	30	50	20					1.28	10	U	0.059	Uda (1985)
Steel	Calcium-Silicate		20	80						9	UO_2	0.36	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	X	X	X					0.5	10	U	<0.1	Abe (1985a)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		12	Pu	0.0063	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.0007-0.00009	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.0003	Seitz (1979)
Steel	No Flux									9	UO_2	0.52	Heshmatpour (1981a)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Steel	Calcium-Aluminate		20	80						9	UO_2	0.20	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	40	40		20						UO_2	0.70	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	10	70		20						UO_2	0.84	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	25	50		25						UO_2	0.05	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	40	30		30						UO_2	5.23	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	20	70		10						UO_2	1.08	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	40	50		10						UO_2	0.14	Heshmatpour (1981a)
Steel								No Flux			UO_2	0.52	Heshmatpour (1981a)
Steel	Borosilicate	80		2		4	1	13 B_2O_3			UO_2	<0.01	Heshmatpour (1981a)
Steel	Fluoride Containing, High Lime	25	60	10				5 CaF_2			UO_2	0.03	Heshmatpour (1981a)
Steel	Fluoride Containing, High Lime	10	60	25				5 CaF_2			UO_2	0.44	Heshmatpour (1981a)
Steel	Calcium-Ferric-Silicate	30	40		30						UO_2	3.90	Heshmatpour (1981a)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Steel	Calcium-Ferric-Silicate	15	55		30						UO_2	2.04	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	10	50	40					1.60	10	U	0.027	Uda (1985)
Steel	High Lime	10	60	30					2.32	10	U	0.13	Uda (1985)
Steel	Calcium-Aluminum-Silicate	40	40	20						10	U	<0.1	Abe (1985a)
Steel	Calcium-Aluminum-Silicate	X	X	X					0.12	10	U	<0.1	Abe (1985a)
Steel	High Silica	80	10	10					0.12	10	U	0.16	Uda (1985)
Steel	Calcium-Ferrite		50		50						UO_2	0.45	Heshmatpour (1981a)
Steel	Calcium-Ferrite		10		90						UO_2	0.51	Heshmatpour (1981a)
Steel	Calcium-Ferrite		20		80						UO_2	0.36	Heshmatpour (1981a)
Steel	Calcium-Ferrite		30		70						UO_2	0.47	Heshmatpour (1981a)
Steel	Calcium-Ferrite		40		60						UO_2	0.42	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	X	X	X					0.26	10	U	<0.1	Abe (1985a)
Steel	Calcium Silicate							$CaSiO_3$		5	Pu	0.27-6.4	Seitz (1979)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Steel	Fluoride Containing, High Lime	25	60	10				5 CaF_2		9	UO_2	0.03	Heshmatpour (1981a)
Steel	High Silica	60	30	10						5	Pu	0.4	Copeland (1981)
Steel	Fluoride Containing, High Lime	35	60					5 CaF_2		9	UO_2	0.016	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	40	40	20						10	U	<0.1	Abe (1985a)
Steel	Borosilicate	80		2			1	13 B_2O_3		9	UO_2	<0.10	Heshmatpour (1981a)
Steel	Industrial	30	40	10	15			5 CaF_2		5	Pu	8.6	Copeland (1981)
Steel	Basalt	42	12	8	26	4	2	6 MgO		10	Pu	8.3	Copeland (1981)
Steel	Calcium-Silicate							$CaSiO_3$		20	Pu	0.065-7.56	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.001-0.003	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		19	Pu	0.041-0.32	Seitz (1979)
Steel	High Lime	20	70	10						9	UO_2	1.08	Heshmatpour (1981a)
Steel	Fluoride Containing	25	50	10	5			10 CaF_2		9	UO_2	0.91	Heshmatpour (1981a)
Steel	None									None	Pu	0.77-Very High	Seitz (1979)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Steel	Calcium-Aluminum-Silicate	25	50	25						9	UO_2	0.05	Heshmatpour (1981a)
Steel	High Lime	10	70	20						9	UO_2	0.84	Heshmatpour (1981a)
Steel	Fluoride Containing	10	50	25	5			10 CaF_2		9	UO_2	<0.01	Heshmatpour (1981a)
Steel	Borosilicate	80		2		4	1	13 B_2O_3		10	Pu	1	Copeland (1981)
Steel	Calcium-Aluminum-Silicate	40	40	20						9	UO_2	0.70	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	30	40	30						9	UO_2	3.90	Heshmatpour (1981a)
Steel	Borosilicate	80		2		4	1	B_2O_3		5	Pu	0.6	Copeland (1981)
Steel	High Silica	60	30	10						10	Pu	2.5	Copeland (1981)
Steel	Industrial	30	40	10	15			5 CaF_2		10	Pu	1	Copeland (1981)
Steel	Calcium-Aluminum-Silicate	40	30	30						9	UO_2	5.23	Heshmatpour (1981a)
Steel	Calcium-Silicate							$CaSiO_3$		11	Pu	0.09-22.0	Seitz (1979)
Steel	Hearth Slag							$CaFeSiO_4$, Minor SiO_2		10	Pu	NA	Seitz (1979)
Steel	High Lime	10	60		30						U	λ=583	Snyder (1991)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Steel	Calcium-Aluminum-Silicate	40	40	20					0.83	10	U	0.19	Uda (1985)
Steel	Calcium-Aluminum-Silicate	15	55	30						9	UO_2	2.04	Heshmatpour (1981a)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.006	Seitz (1979)
Steel	High Silica	60	20	20					0.30	10	U	0.26	Uda (1985)
Steel	Calcium-Aluminate		30	70						9	UO_2	0.31	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	X	X	X					1.25	10	U	<0.08	Abe (1985a)
Steel	Calcium-Aluminum-Silicate	X	X	X					0.73	10	U	<0.1	Abe (1985a)
Steel	Calcium Aluminate		30	70						9	UO_2	0.47	Heshmatpour (1981a)
Steel	Calcium Aluminate		10	90						9	UO_2	0.51	Heshmatpour (1981a)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		11	Pu	0.0019	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		20	Pu	0.005-0.20	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.017-0.22	Seitz (1979)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contaminant	Conc., ppm	Reference
Steel	Calcium-Aluminum-Silicate									10	Pu	0.09-1.6	Seitz (1979)
Steel	Calcium-Aluminum-Silicate									10	Pu		Seitz (1979)
Steel	Calcium-Magnesium-Silicate							$CaMgSi_2O_6$		10	Pu	0.18-21.0	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		8	Pu	0.001-0.002	Seitz (1979)
Steel	High Lime	10	60	30						9	UO_2	0.04	Heshmatpour (1981a)
Steel	Calcium-Magnesium-Silicate							$CaMgSi_2O_6$		19	Pu	0.0037	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		11	Pu	0.001	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.002-0.03	Seitz (1979)
Steel	Calcium-Magnesium-Silicate							$CaMgSi_2O_6$		15	Pu	0.016	Seitz (1979)
Steel	Calcium-Aluminum-Silicate	10	40	40				10 NiO		10	U	0.005	Nafziger (1988)
Steel-45% S.S.	Borosilicate	80		2		4	0.5	13 B_2O_3		10.7	Pu	0.0015-0.0012	Seitz (1979)
Steel-4% Copper	Borosilicate	80		2		4	0.5	13 B_2O_3		9.3	Pu	0.0004-0.0002	Seitz (1979)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contaminant	Conc., ppm	Reference
Steel- 4% Copper	Borosilicate	80		2		4	0.5	13 B_2O_3		10	Pu	0.0637	Seitz (1979)
Steel- 45% S.S.- 9% Brass	Borosilicate	80		2		4	0.5	13 B_2O_3		10.9	Pu	0.0005- 0.0004	Seitz (1979)
Steel- 45% S.S.	Borosilicate	80		2		4	0.5	13 B_2O_3		10.4	Pu	0.0014- 0.0011	Seitz (1979)
Tin	Sodium Slag							25 $NaNO_3$, 25 NaOH, 25 NaCl, 25 Na_2CO_3		9	UO_2	0.06	Heshmatpour (1981b)
Tin	Sodium Slag				5			50 $NaNO_3$, 45 Na_2CO_3		9	UO_2	0.51	Heshmatpour (1981b)
Tin	No Flux										UO_2	19	Heshmatpour (1981b)
Tin	Calcium-Aluminum-Silicate	45	30	20	5						U	λ=392	Snyder (1991)
Tin	Calcium-Aluminum-Silicate	45	30	20	5					9	UO_2	0.09	Heshmatpour (1981b)
Tin	Sodium Slag				5			50 NaOH, 45 NaCl		9	UO_2	0.10	Heshmatpour (1981b)
Tin	Fluoride Containing	30	50	10	5			5 CaF_2		9	UO_2	0.48	Heshmatpour (1981b)

Table 6-1. (continued).

	Slag										Final Metal Contamination		
		Composition, Nominal %											
Metal	Type	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Other	BI[a]	Amount, %[b]	Contam-inant	Conc., ppm	Reference
Tin	Sodium Slag							40 $NaNO_3$, 30 NaCl, 30 NaOH		9	UO_2	3.16	Heshmatpour (1981b)
Tin	No Flux										UO_2	0.08	Heshmatpour (1981b)
Zinc	No Flux										UO_2	0.07	Heshmatpour (1981a)
Zinc	Sodium Slag				5			50 $NaNO_3$- 45 NaCl			U	λ=8	Snyder (1991)
Zinc	Sodium Slag				5			50 $NaNO_3$, 45 Na_2CO_3		9	UO_2	2.10	Heshmatpour (1981a)
Zinc	Sodium Slag				5			50 $NaNO_3$, 25 NaOH, 25 NaCl, 25 Na_2CO_3		9	UO_2	0.54	Heshmatpour (1981a)
Zinc	Sodium Slag				5			50 $NaNO_3$, 45 NaCl		9	UO_2	0.14	Heshmatpour (1981a)

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a. BI = Basicity Index = wt.% basic oxides/wt.% acidic oxides

b. % Slag in charge

c. Partition Ratio, λ, is defined as the ratio of concentration of constituent in the slag phase/concentration of constituent in the metal phase

d. X = Constituent is present in the slag, but concentration is unknown

e. N.A. = Not Available