AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 2

**DECONTAMINATION OF METALS BY
MELT REFINING/SLAGGING - AN
ANNOTATED BIBLIOGRAPHY**

**S.A. Worcester
L.G. Twidwell
D.J. Paolini
T.A. Weldon
R. E. Mizia, Editor**

July 1993

**Westinghouse Idaho
Nuclear Company, Inc.**

PREPARED FOR THE
DEPARTMENT OF ENERGY
IDAHO OPERATIONS OFFICE
UNDER CONTRACT DE-AC07-84ID12435

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *rp*

DECONTAMINATION OF METALS BY MELT REFINING/SLAGGING

EXECUTIVE SUMMARY

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, Westinghouse Idaho Nuclear Company (WINCO) 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 (100-500 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. 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 WINCO.

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 350 publications. At this time approximately 280 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.

Test work (both bench scale and larger scale) results to date demonstrate that slagging decontamination of uranium and plutonium from steel and stainless steel is an effective treatment technology. 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. At this time, however, optimum decontaminating slag compositions for the steels cannot be specified based solely on the presently available literature data.

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 is the subject of a joint WINCO/Savannah River Technical Center research initiative.

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, 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 .

A suggested program follows:

- Decontaminate, melt and cast 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.

DECONTAMINATION OF METALS BY MELT REFINING/SLAGGING

TABLE OF CONTENTS

TITLE PAGE	i
EXECUTIVE SUMMARY	ii
TABLE OF CONTENTS	vi
LIST OF TABLES	vii
 SECTION ONE: INTRODUCTION	 1
1.1. Introduction	1
1.2. Extent of Search	1
1.3. Present and Future Status of Search and Review	4
 SECTION TWO: STATUS OF MELT CONSOLIDATION/REFINING	 5
2.1. Introduction	5
2.2. France	7
2.3. Germany	8
2.4. United Kingdom	9
2.5. Japan	10
2.6. Sweden	11
2.7. United States	11
2.8. Comments on Melting Technologies	13
 SECTION THREE: EXPERIMENTAL TEST RESULTS/SLAG COMPOSITIONS	 16
3.1. Experimental Test Results	16
3.2. Comments on Literature	35
3.3. Summary	40
 SECTION FOUR: CALCULATIONAL PROGRAMS	 41
 SECTION FIVE: SURROGATES	 42
 SECTION SIX: APPENDICES	 A-1
6.1. Bibliography	A-2
6.2. Tabulation of Melt/Slag Refining Test Work Results for All Metals and Alloys	B-1

DECONTAMINATION OF METALS BY MELT REFINING/SLAGGING

LIST OF TABLES

TABLE

1.1.	Databases Searched/Keyword Codes	3
1.2.	Keywords Used in Literature Searches	4
2.1.	Summary of Large-Scale Ferrous Melt Consolidation/Refining Programs	6
3.1.	Melt/Slag Refining Test Work Results for Uranium and Plutonium Decontamination of Steel and Stainless Steel	17
3.2.	Typical Results of Smelting Uranium-Contaminated Ferrous Scrap .	28
3.3.	Melt/Slag Refining Test Work Results for Radionuclide Decontamination of Metallic Scrap	29
3.4.	Best Results for Melt/Slag Refining of Uranium Bearing Ferrous Metals	37
3.5.	Summary of Allowable Nuclide Concentrations in Low-Level Waste .	39
4.1.	Elevated Temperature Thermodynamic Equilibrium Computational Programs	41
5.1.	Surrogates Used for Radioactive Nuclides in High Temperature Studies	43
6.1.	Melt/Slag Refining Test Work Results for Uranium and Plutonium Decontamination of Metals and Alloys	B-2

DECONTAMINATION OF METALS BY MELT REFINING/SLAGGING

SECTION ONE 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, WINCO 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 (100-500 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 WINCO.

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 350 publications. At this time approximately 280 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.

United States Patents (through February 1993), Japanese Patent abstracts (1980 to 1990, but not inclusive of all dates), and Derwent World Patents (1975 to 1993), 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 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 electrosag 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.

TABLE 1.1. DATABASES SEARCHED/KEYWORD CODES

Databases	Keyword Search Number(s)*
Chemical Abstracts (1967-Dec 1992)	1-4
Derwent World Patents (1975-1993)	1-6
Energy Science & Technology (1974-1993)	1-6
Federal Research in Progress (Oct 1992)	1-4
GPO Monthly Catalog (1976-Dec 1992) US Gov't Publications	1-4
INEL Metals Recycling Information (SAIC, Sept 1992)	1-4
Japan Patent Abstracts (1980-1990)	1-7
Metadex (1966-1993)	1-4
NTIS (1964-Oct 1992)	1-4
SCISEARCH (1974-Nov 1992)	1-4
United States Patents (1959-Feb 1993)	1-7
WILSONLINE Information System (Oct 1983-March 1993)	1-7
* 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 and Decontaminat()	Stainless Steel and Slag or Glass and Actinide or Uranium or Plutonium	Stainless Steel and Slag or Glass and Decontaminat()
Keyword Search 5	Keyword Search 6	Keyword Search 7	
Radioactive and Volume Reduction	Stainless Steel and Decontaminat() and Melt Refining Thermo()	Cobalt	

1.3. Present and Future Status of Search and Review

The database searches are essentially complete (June 1993). Publications are still being collected, but it is likely that the major references have been collected and reviewed. As further publications are collected they will be reviewed and updates will be supplied as a part of the Montana Tech project bimonthly progress reports.

DECONTAMINATION OF METALS BY MELT REFINING/SLAGGING

SECTION TWO STATUS OF MELT CONSOLIDATION/REFINING

2.1. Introduction

Although the present program deals specifically with stainless steel RSM, 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 stainless steel. Several excellent reviews of melt refining and volume reduction have been conducted since 1975 (Mautz 1975a, Reimann 1991, Office of Technical Services 1991). 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.

Preliminary DOE assessments estimate approximately 1.5 million tons of RSM may be stored at various DOE sites in the United States with a current generation rate of 15,000 ton/year, increasing to 90,000 ton/year as major D&D programs are phased in. Complete estimates of the types and quantities of these wastes were not available in 1991 and have not been revealed nor sought in this survey. WINCO is currently conducting a program to reassess RSM inventories at seven DOE sites. 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, it is probably safe to say that in excess of 50 percent of the RSM in the DOE inventory is ferrous

metal and stainless steel. Although there is a tendency to become overwhelmed by a figure like 1.5 million tons of RSM, the steel industry in the United States alone consumed 70 million tons of ferrous scrap in 1992 (Mineral Commodity Summaries, USBM 1993).

Considerable large scale melt refining treatment experience exists for melt consolidation/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 2.1.

TABLE 2.1. 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 2,500 tonne	Carbon and stainless steel	Not Reported
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)	Induction/0.5 tonne	Approx. 5 tonne (11 heats)	Carbon and stainless steel	Approx. 15 Bq/g in spiked ingots

Reference/Country/ (Location)	Type/Size of Furnace	Total Weight Melted	Material Melted	Ingot Contaminant Level
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

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 CO₂ systems from the G2-G3 graphite moderated, CO₂ 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 x 1.7 m x 1.3 m. The installation is sized for two 12.5 tonne taps per shift with the nominal product being 25 kg (300 mm x 150 mm x 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 m³/hr (4400 cfm) with an additional 40,000 m³/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.

Jacquet-Francillon and others (Jacquet, 1991) 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 m³/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 m³/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:	0.4 Bq/g max.;
Cast samples:	0.3 Bq/g max.;
Slag:	1.0 Bq/g max.; and,
Dust:	30.0 Bq/g max..

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 ($< 10^{-5} \mu\text{Ci/g}$) 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. (Fujiki, 1991a) 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 2.1. 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/ft² with a maximum surface dose rate of 10 mR/hr.

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, use in simple shapes in the nuclear industry, or dispose of in 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 .

A suggested program 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 electrosag melting.

The suggested approach is supported by the following observations:

- Free release requirements will become tighter with time.
- Some radionuclides will not be removed by any practical melting process known today (e.g., Co).
- Major long life radionuclides which might be released during commercial melting can be removed from the metal during the consolidation/decontamination melt performed within the DOE complex.
- Canister quality will be enhanced by utilization of the larger equipment and established expertise of commercial sources operating under DOE specifications. Quality and certification costs for containers will be significantly reduced on large heats while real quality will be improved.
- 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.
- Experience gained from this program should pave the way for limited release programs for carbon steel which must involve melting and releasing to commercial producers at much lower break-even costs (\$100/ton), disregarding burial costs for RSM.

DECONTAMINATION OF METALS BY MELT REFINING/SLAGGING

SECTION THREE EXPERIMENTAL TEST RESULTS/SLAG COMPOSITIONS

3.1. Experimental Test Results

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.

TABLE 3.1. MELT/SLAG REFINING TEST WORK RESULTS FOR URANIUM AND PLUTONIUM DECONTAMINATION OF STEEL AND STAINLESS STEEL

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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 ³ = 226	Snyder (1991)

Metal	Slag										Final Metal Contamination		Reference
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant	Conc., ppm	
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
S.S.	Borosilicate	80		2		4	0.5	13 B ₂ O 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 ₂ O 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 ₂ O 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 ₂ O ₃ ,		10	Pu	1.9	Copeland (1981)
S.S.	Industrial	30	40	10	15			5 CaF ₂		10	Pu	0.8	Copeland (1981)

Metal	Slag										Final Metal Contamination		Reference
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant	Conc., ppm	
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
S.S.	Borosilicate	80		.2		4	1	13 B ₂ O 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 ⁴	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 ₂ O ₃		NA	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 ₂ O ₆		0.97	Pu	NA	Seitz (1979)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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)
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)

Metal	Slag										Final Metal Contamination		Reference
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant	Conc., ppm	
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		12	Pu	0.0063	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		10	Pu	0.0007- 0.00009	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O 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)
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)

Metal	Slag										Final Metal Contamination		Reference
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant	Conc., ppm	
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
Steel								No Flux			UO ₂	0.52	Heshmatpour (1981a)
Steel	Borosilicate	80		2		4	1	13 B ₂ O 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)
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)

Metal	Slag										Final Metal Contamination		Reference	
	Type	Composition, Nominal %						BI'	Amount, % ²					
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O			Other				
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	Pu	0.27-6.4	Seitz (1979)
Steel	Fluoride Containing, High Lime	25	60	10							5 CaF ₂	UO ₂	0.03	Heshmatpour (1981a)
Steel	High Silica	60	30	10								Pu	0.4	Copeland (1981)
Steel	Fluoride Containing, High Lime	35	60								5 CaF ₂	UO ₂	0.016	Heshmatpour (1981a)
Steel	Calcium-Aluminum-Silicate	40	40	20								U	<0.1	Abe (1985a)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
Steel	Borosilicate	80		2			1	13 B ₂ O 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 ₂ O ₃		10	Pu	0.001-0.003	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O 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)
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)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
Steel	Borosilicate	80		2		4	1	13 B ₂ O 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 ₂ O 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)
Steel	Calcium-Aluminum-Silicate	40	40	20					0.83	10	U	0.19	Uda (1985)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
Steel	Calcium-Aluminum-Silicate	15	55	30						9	UO ₂	2.04	Heshmatpour (1981a)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O 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 ₂ O ₃		11	Pu	0.00186	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		20	Pu	0.005-0.20	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		10	Pu	0.017-0.22	Seitz (1979)
Steel	Calcium-Aluminum-Silicate									10	Pu	0.09-1.6	Seitz (1979)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
Steel	Calcium-Aluminum-Silicate									10	Pu	NA	Seitz (1979)
Steel	Calcium-Magnesium-Silicate							CaMgSi ₂ O ₆		10	Pu	0.18-21.0	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O 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 ₂ O ₆		19	Pu	0.0037	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		11	Pu	0.001	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		7	Pu	0.002-0.03	Seitz (1979)
Steel	Calcium-Aluminum-Silicate							CaMgSi ₂ O ₆		15	Pu	0.0162	Seitz (1979)
Steel	Calcium-Aluminum-Silicate	10	40	40				10 NiO		10	U	0.005	Nafziger (1988)

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

2. % Slag in charge

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

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

5. NA = Not Available

TABLE 3.2. TYPICAL RESULTS OF SMELTING URANIUM-CONTAMINATED FERROUS SCRAP (From Mautz, 1975a)

Material	Product Ingot U Content, ppm*		
	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
* 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 ($\mu\text{g/g}$)			

TABLE 3.3. MELT/SLAG REFINING TEST WORK RESULTS FOR RADIONUCLIDE DECONTAMINATION OF METALLIC SCRAP

Metal	Slag						Final Radionuclide Contamination in Metal Product						Reference
	Type	Composition, Nominal %				Amount, % ¹	Co-60	Cs-137	Sr-85	Other	Other	Other	
		SiO ₂	CaO	Al ₂ O ₃	Other								
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 , Bl ² = 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 ₂ O, 5.0% K ₂ O	0.09-0.44	91-100%	0-15%	0-4%				Reimann (1991) quoting Larsen (1985)
S.S. and Steel (123 melts)	Unknown, probably as above						0-27 uCi/g	1-2 uCi/g		Eu-152, 0 uCi/g	Eu-150, 0 uCi/g	U-235, 0 uCi/g	Larsen (1985)
S.S.	Fluoride				75% CaF ₂ , 25% MgF ₂	3-6				Beta, Gamma: 3321 uCi/g	Alpha: 23 uCi/g		Jacquet-Francillon (1991)

Metal	Slag						Final Radionuclide Contamination in Metal Product						Reference
	Type	Composition, Nominal %				Amount, % ¹	Co-60	Cs-137	Sr-85	Other	Other	Other	
		SiO ₂	CaO	Al ₂ O ₃	Other								
Zircaloy/ 10% S.S.	Fluoride				50% CaF ₂ - 50% BaF ₂	9.5-10.5				NA ³	NA		Jacquet- Francillon (1991)
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)
S.S. and Steel	Unknown									Alpha: U- 235, U- 238, Pu- 241, all < D.L. ⁴	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)

Metal	Slag						Final Radionuclide Contamination in Metal Product						Reference	
	Type	Composition, Nominal %				Amount, % ¹	Co-60	Cs-137	Sr-85	Other	Other	Other		
		SiO ₂	CaO	Al ₂ O ₃	Other									
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 ⁵ , IF ⁶						BOF: 0.16 Bq/g, no activity in slag or dust. IF: to metal							Harvey (1990a)
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)

1. % Slag in charge

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

3. NA = Not Available

4. D.L. = Detection Limit

5. BOF = Basic Oxygen Furnace

6. IF = Induction Furnace

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 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.

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 für 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 3.4. 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 3.4 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 3.4) 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 3.1-3.4) 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						Contamination		Reference
Composition, Nominal %						Natural, ppm	Achieved, ppm	
SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	CaF ₂	Other			
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)

Slag						Contamination		Reference
Composition, Nominal %						Natural, ppm	Achieved, ppm	
SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	CaF ₂	Other			
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)
80		2			13 B ₂ O 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 ^a		
	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
<p>a. Data extracted from 10CF61, 1-1-88 ed., 61.55, Tables 1 and 2.</p> <p>b. ppm calculated from specific activity and estimated weight of stainless steel in 1 m³ of scrap, using equation from ref. 10 (Blatz, 1951) and half life data from ref. 11 (Klevin, 1956). 1 ppm = 1 g/metric ton.</p> <p>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.</p> <p>d. Units are nanocuries per gram.</p>			

3.3. 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. 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. At this time, however, optimum decontaminating slag compositions for the steels cannot be specified based solely on the presently available literature data.

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% $\text{Ca}_2\text{B}_6\text{O}_{11}$. 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..

DECONTAMINATION OF METALS BY MELT REFINING/SLAGGING

SECTION FOUR 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)
THERMODATA (France)	Cheyne (1988), Bale (1990)
THERDAS (Germany)	Barin (1980), Bale (1990)
UM/ROLLA-PYROMETALLURGY: STEPSOL, STGSOL (U.S.)	Morris (1993)

DECONTAMINATION OF METALS BY MELT REFINING/SLAGGING

SECTION FIVE SURROGATES

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 al (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).

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)

SECTION SIX 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. The bibliography (MONTANA TECH DATABASE) is available on computer disk (Paradox software required for use).

Bibliography

Abe M., Uda T., Iba H., "Melt Refining Method for Uranium-Contaminated Steels and Copper," Waste Management '85, Proceedings of the Symposium on Waste Management at Tucson, Arizona, Mar. 24-28, 1985a.

Abe M., "Melt Refining Method for Uranium Contaminated Metallic Waste," EDB-86-156814, Donen Giho, Japan, June 1985b.

Ackerman J.P., "Magnesium Transport Extraction of Transuranium Elements from LWR Fuel," U.S. Patent No. 5,147,616, Department of Energy, Oct. 3, 1991.

Ackerman J.P., Grove D., "Plutonium Recovery From Spent Reactor Fuel by Uranium Displacement," U.S. Patent No. 5,096,545, Department of Energy, 21, 1992.

Adelman S.L., "Niobium-Based Superalloy Compositions," U.S. Patent No. 5,028,390, San Francisco CA, July 27, 1989.

Allibert M., Delabbaye F., "Extraction of Cobalt from Stainless Steels," EUR-8966, France, Commission of the European Communities, Page 22, 1984.

Allibert M., Christin G., "Processing of Steel Containing Metallic Elements, Especially Cobalt," France Patent No. FR2553435 A, France, Dec., 1983.

American National Standard Institute, "Measurement of the Leachability of Solidified Low-Level Radioactive Wastes by a Short-Term Test Procedure," ANSI/ANS-16.1-1986, Apr. 4, 1986.

Anderson T.O., "Pilot Plant Studies of Slag Liners, Section VII of the Series, "Uranium Metal by Bomb Reduction", " NYO-1348, Mallinckrodt Chemical Works, St. Louis, Mo, Nov. 14, 1952.

Anderson T.D., "Hanford Waste Vitrification Plant Project Advanced Conceptual Design Summary Report," WHC-EP-0140, Department of Energy, Nov., 1988.

Andrieux C., Daniel F., Vendel J., "Filtration of Gaseous Wastes Released in a Furnace for Melting Contaminated Metals," CEA-CONF-8213, French, Jan., 1985.

Arnberg L., Karlsson A., Brandrup-Wognsen H., "Influence of Slag Particles on the Mechanical Properties and Corrosion Resistance of a P/M Austenitic Stainless Steel," 0361-3488/88 0215-7, The International Journal of Powder Metallurgy, Vol. 24, No. 3, 1988.

Arnberg L., Karlsson A., "Influence of Slag Particles on the Mechanical Properties of a P/M High Speed Steel," 0361-3488/88 0203-9, The International Journal of Powder Metallurgy, Vol. 24, No. 3, 1988.

Bale C.W., Eriksson G., "Metallurgical Thermochemical Databases-A Review," Vol. 29, No. 2, Cand. Met. Quarterly, Jan., 1990.

Balukov R.V., Vasil'eva L.I., Zakharchuk G.A., "Electrochemical Decontamination of Stainless Steel," SU1556145, Russia, July, 1991.

Barin I., Frassek B., Gallagher R., Spencer P.J., "THERDAS," Erzmetall 33, 1980.

Barry T.I., Dinsdale A.T., Gisby J.A., "Predictive Thermochemistry and Phase Equilibria of Slags," JOM, Apr., 1993.

Bart G., Zwicky H.U., Aerne E.T., Graber Th., Z'Berg D., Tokiwai M., "Borosilicate Glass Corrosion in the Presence of Steel Corrosion Products," Materials Research Society Symposium Proceedings, Vol. 84, Page 459, Materials Research Society, 1987.

Bates J.K., Bradley C.R., Buck E.C., Cunnane J.C., Dietz N.L., Ebert W.L., Emery J.W., Ewing R.C., Feng X., Gerding T.J., Gong M., Han W.-T., Hoh J.C., Mazer J.J., Tomozawa M., Wang L.-M., Wronkiewicz D.J., "ANL Technical Support Program for DOE Environmental Restoration and Waste Management: Annual Report October 1990 - September 1991," ANL-92/9, Argonne National Laboratory, Chemical Technical Division, Mar., 1992.

Baxter R.G., "Design and Construction of the Defense Waste Processing Project at the Savannah River Plant," Proceedings of the Symposium on Waste Management at Tucson, Arizona, Vol. 2, High Level Waste, Post R.G. ed., Mar. 2-6, 1986.

Beall G.H., Rittler H.L., "Highly Refractory Glass-Ceramics Suitable for Incorporating Radioactive Wastes," U.S. Patent No. 4,314,909, Corning Glass Works, Feb. 9, 1982.

Bennett G.A., Burris L. Jr., Vogel R.C., "Halide Slagging of Uranium-Plutonium Alloys," ANL-6918, Argonne National Lab, Chemical Engineering Division, July, 1964.

Bergsman T.M., PNL Hanford, Washington, June 1991, Private Communication with R.E. McAtee, Hanford, WA, June, 1991, (as referenced in McAtee, 1991.)

Berry N.E. ed., "Compendium of Mallinckrodt Reports on Slag Processing," MCW-1387, Mallinckrodt Chemical Works, St. Louis, Mo, Feb., 1956.

Bickford Dennis F., Ondrejcin Robert S., "High-Temperature Materials for Radioactive Waste Incineration and Vitrification," Advances in Ceramics, Vol. 20: Nuclear Waste Management II, 1986.

Bjorklund W.J., McElroy J.L., Mendel J.E., "Method for Calcining Radioactive Wastes," U.S. Patent No. 4,152,287, Exxon Nuclear Company, May 1, 1979.

Blatz H., Harley J.H., Eisenbud M., "Investigation of the Potential Hazard in Releasing Scrap Steel Contaminated with Uranium to Commercial Channels," USAEC NYO-1558, Jan., 1951.

Blewett J.A., Van Dorpe M., "Recent Advances in Power Plant Radwaste Volume Reduction Systems and End Product Characteristics," CONF-820424, Richland, WA, Jan., 1982.

Boatner L.A., Sales B.C., "Lead Iron Phosphate Glass as a Containment Medium for Disposal of High-Level Nuclear Waste," U.S. Patent No. 4,847,008, Department of Energy, July 11, 1989.

Boggs S., Livermore D., Seitz M.G., "Humic Substances in Natural Waters and Their Complexation with Trace Metals and Radionuclides: A Review," ANL-84-78, Department of Energy, July, 1985.

Bonnaud R., Jacquet-Francillon N., Jouan A., Sombret C., Moore J.G ed., "Melting Process to Condition Decladding Hulls Generated by the Reprocessing of LWR and FBR Spent Fuels," CONF-801124-(Pt.1), Department of Energy, Jan., 1981.

Bouteillon J., Poignet J.C., Ramaeau J.J., "Cathodic Phenomena in Aluminum Electrowinning," JOM, Feb., 1993.

Bouzou G., "Process and Apparatus for the Recovery of Plutonium or Uranium," British Patent No. GB1,206,748, Jan., 1970.

Bray L.A., Elmore M.R., Carson K.J., Elovich R.J., Richardson G.M., Anderson L.D., "Decontamination Testing of Radioactive-Contaminated Stainless Steel Coupons Using a Ce(IV) Solution," PNL-8223, UC-721, Pacific Northwest Laboratory, Aug. 1992.

Briggs J.L., Younger A.F., "Materials Selection of Surface Coatings in an Advanced Size Reduction Facility," NTIS No. RFP-2989, Department of Energy, June 2, 1980.

Brouns R.A., Mellinger G.B., Nelson T.A., Oma K.H., "Immobilization of High-Level Defense Waste in a Slurry-Fed Electric Glass Melter," PNL-3372, UC-70, Pacific Northwest Laboratory, Nov. 1980.

Brumley W.J., "Defense Waste Processing Facility: The Vitrification of High-Level Nuclear Waste," DOE/SR-2002, Department of Energy, Jan., 1986.

Buist D.T., "Radioactive Decontamination," U.S. Patent No. 3,437,521, Purex Corporation, Apr. 8, 1969.

Burns W.G., Ewart F.T., Hobley J., Smith A.J., Walters W.S., Williams S.J., "Radiolytic Oxidation. Task 3. Characterization of Radioactive Waste Forms. A Series of Final Reports (1985-1989) No. 25," EUR-13670, United Kingdom, Jan., 1991.

Burris L., "The Melt Refining of Irradiated Uranium: Application to the EBR-II Reactor Fuel I. Introduction," Nuclear Science & Engineering, Vol. 6, pp. 493-495, Jan., 1959.

Cadden J.L., Lewis P.S. Jr., "Electroslag Remelting of a Uranium Alloy," NSA-32, Oak Ridge Y-12 Plant, May, 1975.

Caldwell J.T., Kunz W.E., Atencio J.D., "Apparatus and Method for Quantitative Assay of Generic Transuranic Wastes from Nuclear Reactors," U.S. Patent No. 4,483,816, Department of Energy, Nov. 20, 1984.

Cavendish J.H., "Treatment of Metallic Wastes by Smelting," IAEA-SM-234/14, National Lead Company of Ohio, Cincinnati, Ohio, 1978.

Cecillie L., Simon R.A., Oyen L.C., Platt A.M., Tosetti R.J., Feizollahi F., "Economic Evaluation of Various Management Strategies for Solid Plutonium Contaminated Waste," CONF-871102, ASME 1987, Jan., 1987.

Chamberlain H.E., Dalton J.T., Dawson R.K., Gaudie S.C., Turner A.D., "Experimental Study of the Recovery of Plutonium from Non-Combustible Wastes," EUR-10491, Commission of the European Communities, 1986.

Chapuis A.M., Luykx F., "Radiological Criteria for Unrestricted Release of Materials from Nuclear Installations," Advances in Ceramics, Vol. 20: Nuclear Waste Management II, 1986.

Chatterjee S., Moore H.H., "New Technologies for Recycling Radioactive Scrap Metals: A Technical Overview," Techno 92-04, post 1991.

Cheyne B., "International Symposium on Computer Software in Chemical & Extractive Metallurgy," Proc. Metal Soc. CIM, Jan., 1988.

Christensen D.C., "Pyrochemical Recovery of Plutonium from Calcium Fluoride Reduction Slag," APPL-6-482 372, Department of Energy, Apr., 1983.

Christensen D.C., Rayburn J.A., "Pyrochemical Recovery of Plutonium Fluoride Reduction Slag," LA-9655-MS, Department of Energy, July, 1983.

Chronister D.J., Scott S.W., Stickle D.R., Eylon D., Froes F.H., "Induction Skull Melting of Titanium and Other Reactive Alloys," Journal of Metals, Sept., 1986.

Clark D.E. ed., White W.B. ed., Machiels A.J. ed., Nuclear Waste Management II, The American Ceramic Society Inc., OH, 1986.

Colby J.W., Wise W.N., "Microprobe Analysis of Uranium Metal Recovered from Magnesium Fluoride Slag," NLCO-920, National Lead Co, OH, NSA-18-043380.
Coops M.S., "Lithium Metal Reduction of Plutonium Oxide to Produce Plutonium Metal," U.S. Patent No. 5,118,343, Department of Energy, June 2, 1992.

Copeland G.L., Heestand R.L., "Volume Reduction of Contaminated Metal Waste," CONF-800313-2, Department of Energy, Oak Ridge National Laboratory, Mar., 1980.

Copeland G.L., Heshmatpour B., Heestand R.L., "Melting Metal Waste for Volume Reduction and Decontamination," ORNL/TM-7625, Oak Ridge National Laboratory, Mar., 1981.

Copeland G.L., Heestand R.L., Mateer R.S., "Volume Reduction of Low-Level Contaminated Metal Waste by Melting: Selection of Method and Conceptual Plan," ORNL/TM-6388, Oak Ridge National Laboratory, June, 1978.

Corbett R.A., Morrison W.S., Bickford D.F., "Corrosion Evaluation of Alloys for Nuclear Waste Processing," Nuclear Technology, Feb., 1987; National Association of Corrosion Engineers, 0094-1492/87/000976.

Couture R.A., Seitz M.G., "Physical Response of Backfill Materials to Mineralogical Changes in a Basalt Environment," Argonne National Laboratory, Conference Proceedings of NRC Research Annual Review Meeting of Nuclear Waste Management Research on Geochemistry of HLW Disposal, Reston, VA, CONF-8308126-5, Aug. 30, 1983.

Cregut A., Gregory A.R., "Decommissioning of Nuclear Power Stations in Community Countries Carried Out and Projected," EUR 9474, European Communities, Decommissioning Nuclear Power Plants, Page 15, May, 1984.

Davies R.H., et al., "Application of MTDATA to the Modeling of Multicomponent Equilibria," Vol. 26, High Temperature Science, Jan., 1990.

Davies R.H., Dinsdale A.T., Hodson S.M., Gisby J.A., Pugh N.J., Barry T.I., Chart T.G., "MTDATA-The NPL Databank for Metallurgical Thermochemistry-User Aspects of Phase Diagrams," Institute of Metals, Jan., 1991.

Davis D.M., Hart J.C., Warden A.D., "Hazard Control in Processing Stainless Steel and Copper Contaminate with Uranium," American Industrial Hygiene Association Quarterly, 18, pp. 235-241, 1957.

Dealy J.M., Pehike R.D., "Activity Coefficients in Binary Liquid Metallic Solutions at Infinite Dilution," Transactions of the Metallurgical Society, 1030-Vol. 226, Aug., 1963.

Deichman J.L., "Contaminated Metallic Melt Volume Reduction Testing," ORNL/NFW-81/34, Oak Ridge National Laboratory, 1981.

Diercks D.R., "Effect of Decontamination on Aging Processes and Considerations for Life Extension," Nuclear Engineering and Design, Vol. 115 (1989), pp. 207-218, North-Holland, Amsterdam; 0029-5493, Elsevier Science Publishers B.V., 1989.

Dillon R.L., Griggs B., Kemper R.S., Nelson R.G., "Chemical Decontamination and Melt Densification of Chop-Leach Fuel Hulls," IAES-SM-207/69, Battelle Pacific Northwest Laboratories, 1976.

Dillon R.L., Griggs B., Kemper R.S., Nelson R.G., "Chemical Decontamination and Melt Densification," CA86(8):48281v, Richland, WA, USA, Jan., 1976.

Dillon R.L., Griggs B., Kemper R.S., Nelson R.G., "Chemical Decontamination and Melt Densification," CONF-760310-5, Energy Research & Development Administration, Jan., 1976.

Echols R., Scientific Ecology Group, Inc. (SEG) Government Marketing, Private Communication with S. Worcester, Montana Tech, June 22, 1993.

Eickelpasch N., Stang W., Steiner H., "Waste Minimization and Scrap Recycling During Decommissioning Work of the KRB Nuclear Power Plant, Unit A" Proceedings of the International Topical Meeting on Nuclear and Hazardous Waste Treatment, Spectrum '92, American Nuclear Society, Boise, ID, 1992.

Elliott J.F., "Metallurgical Slags & Fluxes," Journal of Metals, Mar., 1985.

Elliott, "Process and Apparatus for Recovering and Purifying Uranium Scrap," U.S. Patent No. 4,591,382, May 27, 1986.

Eymery J.P., Laplanche G., Cahoreau M., Denanot M.F., "Structural Investigation of B.C.C. 304 Stainless Steel," 0040-6090, Elsevier Sequoia, Mar. 26, 1992.

Fujiki K., Hirabayashi T., Kanazawa K., Yasunaka H., "Decontamination and Melting Test for Metal Wastes in JPDR Decommission Project-Toward Recycling of LLW," Proceedings Waste Management, Tucson, AZ, USA, 1991a.

Fujiki K., "Present Status of Decommissioning Materials Reuse Research at JAERI," 1st JSME/ASME Conference on Nuclear Research, Jan., 1991.

Geimer R., Hertzler T., Gillins R., Anderson G.L., "Assessment of Incineration and Melting Treatment Technologies for RWMC Buried Waste," EGG-WTD-10035, EG&G, Idaho National Engineering Laboratory, Feb., 1992.

Geimer R., "Current DOE Initiatives in Plasma ARC Technology Development," Techno-92-001, SAIC, 1992.

Gelfort E., "Process for Decontamination of Radioactively Contaminated Iron and/or Steel Scrap," EDB-86-125993, Germany, May, 1983.

Geimer Ray, Batdorf Jim, Larson Milo M., "Plasma Arc Treatment of TRU and Mixed TRU Waste," Science Application International Corporation, Idaho Falls, Idaho, techno-92-002, 1992.

Glassner A., "The Thermochemical Properties of the Oxides, Fluorides, and Chlorides to 2500 K," ANL-5750, Argonne National Lab, 1957.

Gomer C.R., Lambley J.T., "Melting of Contaminated Steel Scrap Arising in the Dismantling of Nuclear Power Plants," EUR-10188, Commission of the European Communities, 1985.

Gomer C.R., Sappok M., Allibert M., Delabbaye F., "Treatment of Metal Waste by Melting," Decommissioning Nuclear Power Plants, CONF-840524, United Kingdom, May 22, 1984.

Grantham L.F., "Actinide Recovery," U.S. Patent No. 5,041,193, Rockwell International Corporation, Aug. 20, 1991.

Greenhalgh W.O., "Recoverable Immobilization of Transuranic Elements in Sulfate Ash," U.S. Patent No. 4,509,978, Department of Energy, Apr. 9, 1985.

Guon J., Hills W., Grantham L.F., Specht E.R., "Yttrium and Rare Earth Stabilized Fast Reactor Metal Fuel," U.S. Patent No. 5,112,543, Department of Energy, May 12, 1992.

Guy et al., "Process for the Radioactive Decontamination of Metal Surfaces, Particularly Portions of Primary Circuits of Water-Cooled Nuclear Reactors," U.S. Patent No. 5,093,072, Mar. 3, 1992.

Hanninen H.E., Jauhiainen E., Starkman T., "Oxidation and Decontamination Mechanisms of Stainless Steels Studied by Electron Spectroscopy."

Hannulk J., "Process for the Decontamination of Steel Surfaces and Disposal of Radioactive Waste," Swiss Patent No. 4,508,641, Zurich, Switzerland, Apr. 2, 1985.

Hanson M.S., Bjorklund W.J., "Vitrification of Radioactive High-Level Waste by Spray Calcination and in-Can Melting," PNL-3145, UC-70, Pacific Northwest Laboratory, July, 1980.

Harbour J.R., Plodinec M.J., "Exclusion of Foreign Materials from DWPF Canistered Waste Forms Compliance Activities for the WAPS," Westinghouse Savannah River Corporation, Waste Management, Vol. 1, 1991.

Harvey D.S., "Melting of Contaminated Steel Scrap from Decommissioning," or Advances in Ceramics, Vol. 20. Nuclear Waste Management II, 1986
Decommissioning of Nuclear Installations-1990, Brussels, Pfulgrad et al. editors, 1990a.

Harvey D.S., "Research Into the Melting/Refining of Contaminated Steel Scrap Arising in the Dismantling of Nuclear Installations," EUR-12605, Commission of European Communities, 1990b.

Hebrant P., "Key Parameters for the Safe and Economical Recycling of Contaminated Stainless Steel," Advances in Ceramics, Vol. 20: Nuclear Waste Management II, 1986.

Heimerl W., Ewest E., "Method of Filling a Metal Vessel with a Glass Melt Containing Highly Radioactive Fission Products," German Patent No. 4,690,781, Germany, Sept. 1, 1987.

Hempelmann W., "Treatment of Waste Metals from Decommissioning," Kernforschungszentrum Karlsruhe GmbH, Postfach 3640, D-7500 Karlsruhe, Federal Republic of Germany, 1987.

Heimerl W.C., "Device for the Production of Glass Drops from a Glass Melt Containing Radioactive Waste," German Patent No. 4,528,014, Germany, July 9, 1985.

Hermansson H.P., Bjoerner I.K., Christensen H., Ohe T., Werme L., "Static Leaching of Fully Radioactive Waste Glass at 90 Degrees in the Presence of Bentonite, Granite, and Stainless Steel Corrosion Products," Material Resource Society Symposium Proceedings, Vol. 50, Materials Research Society, 1985.

Heshmatpour B., Copeland G.L., Heestand R.L., "Disintegration and Size Reduction of Slags and Metals After Melt Refining of Contaminated Metallic Wastes," ORNL/TM-7671, UC-70, Oak Ridge National Laboratory, Apr., 1981.

Heshmatpour B., Copeland G.L., "The Effects of Slag Composition and Process Variables on Decontamination of Metallic Wastes by Melt Refining," ORNL/TM-7501, UC-70, Oak Ridge National Laboratory, Jan., 1981a.

Heshmatpour B., Copeland G.L., "Metallurgical Aspects of Waste Metal Decontamination by Melt Refining," Nuclear and Chemical Waste Management, Vol. 2, pp. 25-31, 1981; 0191-815x/81/010025-07, Pergamon Press Ltd., 1981b.

Heshmatpour B., Copeland G.L., Heestand R.L., "Decontamination of Transuranic Waste Metal by Melt Refining," ORNL/TM-7951, 1981; Nuclear and Chemical Waste Management, Vol. 4, pp. 129-134, 1983.

Heshmatpour B., Copeland G.L., Heestand R.L., "Granulation of Slags and Metals After Melt Refining of Contaminated Metallic Wastes," Nuclear and Chemical Waste Management, Vol. 2, pp. 33-37; 0191-815X 81 010033-05, Pergamon Press Ltd., 1981.

Hobbick C.W., Schatz D.R., Aden G.D., "Distribution and Removal of Radionuclides in Molten Stainless Steel," RHO-CD-1444, June, 1981.

Hooker R.L., "Incinerator Carryover Tests with Dysprosium as a Stand-In for Plutonium," DPST-81-603, 1991.

Hopkins H.H. Jr., "Solubilization of Actinide Metal-Containing Slag," NSA-14-002504, US Atomic Energy Commission, Aug., 1959.

Horie et al., "Method of Treatment of High-Level Radioactive Waste," U.S. Patent No. 5,082,603, Jan. 21, 1992.

Hoshi T., Seiki Y., Kato K., "Management of Waste from the JPDR Decommissioning," Japan Atomic Energy Research Institute, Tokai-mura, Ibaraki-ken 319-11, Japan.

Huber B., "The European Community's Programme of Research on the Decommissioning of Nuclear Power Plants: Objectives, Scope and Implementation," EUR 9474, Decommissioning Nuclear Power Plants, May, 1984.

Hundley G.L., Davis D.L., "Recovery of Critical Metals from Superalloy Scrap by Matte Smelting and Hydrometallurgical Processing," Report of Investigations 9390, U.S. Bureau of Mines, 1991.

Igarashi H., "Electric Melting Furnace with Partitioned Melting Cavity for Solidifying Highly Radioactive Waste in Glass," Japanese Patent No. 4,903,277, Doryokuro Kakeunenryo Kaihatsu Jigyodau, Tokyo, Japan, Feb. 20, 1990.

Iseghem Van P., De Grave E., Peters L., De Batist R., "Incorporation of Fe_2O_3 , FeO and Al_2O_3 in Silicate Glasses and Its Effect," BLG-560, Belgium, NTIS No. PB84-203306, Sept., 1983.

Ivanov N.I., Vachaeu A.V., Gorokhov A.V., "Heating of Metal Scrap Under Protective Coating of Slag," Ferrous Metals & Analysis, 1992.

Ivanov L.I., Bystrov L.N., Platov Yu.M., Lazorenko V.M., Bondarenko G.G., Kasyanov O.M., Ustinovshchikov V.M., "Electron Irradiation-Induced Structure-Phase Transformation in Low Radioactivation Chromium-Manganese Steel," CA118(2):13004j, Moscow, Russia, Journal of Nuclear Materials, pp. 191-194 (1992), 733-736 North-Holland, 1992.

Jacquet-Francillon N., Piccinato R., Roux J.P., Jouan A., Puyou M., "Hull Melting," CEA-CONF-10552, Sendai, Japan, Apr., 1991.

Jamrich J., Soos F., Chlobystina E., Strba J., "Prospects of Remelting Metal Materials from Shutdown Nuclear Power Installations," INIS-MF-11312, Czechoslovakia, 1987.

Janberg K.G., Rittscher D., "Comparison of Decontamination and Melting with Direct Disposal," Decommissioning of Nuclear Installations-1990, GNS Gesellschaft fur Nuklear-Service, Germany, 1990.

Jantzen C.M., Bibler N.E., Beam D.C., Ramsey W.G., Waters B.J., "Nuclear Waste Glass Product Consistency Test (PCT)-Version 5.0 (U)," WSRC-TR-90-539 Revision 2, UC -721, Westinghouse Savannah River Site, Jan., 1992.

Jeffers T.H., "Separation and Recovery of Cobalt from Copper Leach Solutions," Journal of Metals, Jan., 1985.

Johnson T.R., Ackerman J.P., Tomezuk Z., Fischer D.F., "Process to Separate Transuranic Elements from Nuclear Waste," U.S. Patent No. 4,814,046, Department of Energy, Mar. 21, 1989.

Kalmar E., Tar J., Lucaks J., "Testing the Dissolution of Ferrochrome with an Inactive Method, and the Inverse Reduction of Chromium with a Radioactive Method During the Production of Acid Resistant Steels," 1992.

Katsuta H.M., Mito S.I., Mito M.S., Mito S.K., Kobe F.K., Ibaraki I.T., Kobe T.S., "Method of Compacting Radioactive Metal Wastes," Japanese Patent No. 5,063,001, Japan, Nov., 1991.

Kellogg D.R., Mack J.E., Thompson W.T., Williams L.C., "Metal-Smelting Facility," CONF-820418-13, Oak Ridge, 1982.

Kerr W.B., "Production Test 235-5 Plant Process Evaluation Reduction of Plutonium Tetrafluoride with Calcium and Sulfur," HW-26676, G.E., Hanford, Feb., 1953.

Kimmitt R., "Separation of Uranium from Mixed Solid Wastes," Y/IA-202, DE91 012046, Spring Semester, 1989.

Kirk - Othmer Encyclopedia of Chemical Technology, 2nd edition, Vol. 1, pp. 946-947, 1963.

Klein M., Weyers C., Goosens W.R.A., "Behavior of Ruthenium, Cesium, and Antimony in High Temperature Processes for Waste Conditioning," EDB-86-156774, Belgium, Radioactive Waste Management and the Nuclear Fuel Cycle, Vol. 6(No. 3-4), pp. 255-276, Dec., 1985.

Klevin P.B., Harris W.B., "Remelting May Permit Reclaiming Uranium Contaminated Metals," Nucleonics, Apr., 1956.

Kluk A.F., Hocking E.K., "Considerations in Recycling Contaminated Scrap Metal and Rubble," ANL/CP-75817, DE92, 016188; Department of Energy Facility Deactivation, Decontamination, Decommissioning, and Dismantlement-A Pressing Need for Technology Development, Workshop, Charleston, South Carolina, Mar., 1992.

Konovalov E.E., Lastov A.I., Petrekhin G.N., "Sorption of a Cesium-137 Radionuclide by Steel from a Sodium Melt," Ca101(16):139097j, USSR.

Kuhn K.D., Scheffler K., Koch G., "Recovery of Plutonium from Scrap and Wastes. 5.5 Recovery of Neptunium-237, Plutonium-238, and Plutonium-242," RFP-Trans-206.

Lacroix J.P., Tailliez M., "STMI's Industrial Experience in Low Activity Steel Waste Processing by Melting," STMI, France, Waste Management' 85, 1986.

Large D., SEG, Oak Ridge, Tennessee, Personal Communication with Sam Worcester, Montana Tech, June, 1993.

Larsen M.M., Davis J.N., Logan J.A., "Sizing and Melting Development Activities Using Contaminated Metal at the Waste Experimental Reduction Facility," EGG-2411, Idaho National Engineering Laboratory, Feb., 1985a.

Larson D.E., Blair H.T., Bonner W.F., Garrett A.A., Hanson M.S., "Conceptual Design of a Nuclear Waste Vitrification Facility," PNL-2690, Department of Energy, May, 1978.

Lasch M., Schaller K.H., Stang W., Watzel G.V.P., "Estimation of Radioactive Waste Quantities Arising During Decommissioning," EUR-9474, Decommissioning Nuclear Power Plants, Apr., 1984.

Lau T., Weatherly G.C., Lean MC, "Gas/Metal/Slag Reactions in Submerged Arc Welding Using CaO-Al₂O₃ Based Fluxes," Welding Research Supplement, Feb., 1986.

Lauris B.G., Martigues C.C., Gauchon J.P., "Process for the Radioactive Decontamination of Metal Surfaces, Particularly Portions of Primary Circuits of Water-Cooled Nuclear Reactors," French Patent No. 5,093,072, Mar., 1992.

Lefort H.G., Selby C.L., Price J.R., "Soluble, Vitreous Ceramic Coatings for Decontaminating Stainless Steel Canisters Filled with Radioactive Glass," Nuclear Waste Management IV, Page 551, 1991.

Leister P., "Method for the Treatment and Conveyance of Feed Sludge," German Patent No. 4,906,409, Germany, Mar. 6, 1990.

Levitz N., Gerding T.J., Winsch I.O., Cannon T.F., Steindler M.J., "Volume Reduction and Salvage Considerations for Plutonium-Contaminated Ferrous Metal," CONF-750902-9, Argonne National Lab; AIChE Symposium Series, Vol. 72, No. 154, Jan. 1, 1975.

Lewis P.S. Jr., "Electroslag Refining of Uranium Alloys," Y-DA-5858, Fifth International Symposium on Electroslag and Other Special Melting Technology, Mellon Institute, Pittsburgh, PA, 1974, CONF-741078-1; Oak Ridge Y-12 Plant, Sept. 17, 1974.

Lewis P.S. Jr., Agee W.A., Bullock J.S. IV, Condon J.B., "Process for Electroslag Refining of Uranium and Uranium Alloys," 533111, United States Energy Research & Development Administration, Dec., 1974.

Liddell K., "Understanding the Processing and Properties of Actinide Elements," JOM, Feb., 1993.

Lilly M.J., Bierman G.R., Phillips J.W., "Radioactive Scrap Metal Recycling: A Doe Assessment," Waste Management '92, Waste Processing, Transportation, Storage, and Disposal, Technical Programs and Public Education, Vol. 2, Technology Program for Radioactive Waste Management and Environmental Restoration, 1992.

Lograsso T.A., Delaney D.W., Parker G.W., Mailen J.C., "Purification of Waste Uranium for Recycle," IS-M--705, DE92 013562, CONF-920851, 1992.

Lohr H.P., "Method of Inclusion Melting Glass with Radioactive Components, and Furnace for Carrying Out Such Method," German Patent No. 4,139,360, Germany, Feb. 13, 1979.

Lore J.D., "Electrical Conductivity Measurements of Molten-Salt Fluxes from an Electroslag Remelting Process," Oak Ridge Y-12 Plant, NTIS No. Y-1947, July, 1974.

Lucia A., "Analysis and Computer Tools for Separation Processes Involving Nonideal Mixtures," Techno-92--005F, DE 015298, DOE/ER/13552--7, May, 1992.

Macedo P.B., Simmons J.H., Litovitz T.A., "Fixation of Radioactive Materials in a Glass Matrix," U.S. Patent No. 4,224,177, Silver Spring, MD, Sept. 23, 1980.

Macedo P.B., Simmons J.H., Litovitz T.A., "Fixation of Radioactive Materials in a Glass Matrix," U.S. Patent No. 4,362,659, Silver Spring, MD, Dec. 7, 1982.

MacToth L., Bond W., Avens R., "Aqueous and Pyrochemical Reprocessing of Actinide Fuels," JOM, pp. 35-39, Feb., 1993.

Makarov G.S., "Thermodynamic Evaporation of Highly Volatile Components in the Vacuum Degassing of Melted Aluminum Alloys," techno 94-004f, WSRC-tr--146, DE92 015315, 1970.

Malek R.I.A., Roy D.M., Licastro P.H., Langton C.A., "Slag Cement Low-Level Radioactive Waste Forms at Savannah River Plant," American Ceramic Society Bulletin, Vol. 65, No. 12, 1986.

Mautz E.W., "Ferrous and Common Nonferrous Metals Industries and Associated Scrap Metals: A Review," NSA-3307, Technical Division National Lead Company of Ohio, Contract No. E(30-1)-1156, Nov., 1975.

Mautz E.W., Briggs G.G., Shaw W.E., Cavendish J.H., "Uranium Decontamination of Common Metals by Smelting: A Review (Handbook)," NSA3204, National Lead Company of Ohio, Cincinnati, Ohio, Feb., 1975a.

Mautz E.W., "Uranium Decontamination of Common Metals by Smelting- A Review," NLCO-1113, Feb., 1975.

May A., Boyle J.R., "Assessment of Ra^{226} and Toxic Element Distribution at Tennessee Valley Authority Phosphate Slag Stockpiles, Muscle Shoals, AL," Report of Investigations 9288, Bureau of Mines, 1990.

Mazoyer R., Vernaz E., "Conditioning of Waste Cladding Hulls by Eutectic Melting and Embedding in Glass," EUR-10702, Commission of the European Communities, Luxembourg, 1986.

McAtee R.E., Beal M., "Comparison of the High Temperature Chemistry of Plutonium and Rare Earths, a Review Study," EGG-WTD-9801, Idaho National Engineering Laboratory, Sept., 1991.

McCall J.L., Tenaglia R.D., Gibson G.W., Benedetti R.L., "Coreless Induction Melting of Simulated Transuranic Wastes," Proceedings of the ANS Topical Meeting on the Treatment and Handling of Radioactive Wastes.

McGright R.D., Halsey W.G., Van Konynenburg R.A., "Progress Report on the Results of Testing Advanced Conceptual Design Metal Barrier Materials Under Relevant Environmental Conditions for a Tuff Repository," UCID 21044, Lawrence Livermore National Laboratory, Dec., 1987.

Menon S., Hernborg G., Andersson L., "Melting of Low-Level Contaminated Steels," Decommissioning Nuclear Installations-1990, Studsvik AB, Sweden, 1990.

Mies H.P., Stang W., "Decommissioning of Nuclear Power Plant Gundremmingen Unit A," Kernkraftwerke Gundremmingen Betriebsgesellschaft, Germany, 1991.

Miller W.E., Welch J.M., Flinn J.E., "Uranium Recovery from a Nuclear Fuel Waste Form," Mineral & Metallurgical Processing, Feb., 1985.

Miller W.E., Ackerman J.P., Battles J.E., Johnson T.R., Pierce R.D., "Uranium Chloride Extraction of Transuranium Elements From LWR Fuel," U.S. Patent No. 5,141,723, Department of Energy, Aug. 25, 1992.

Miller S.M., "Ultratrace Analysis of Transuranic Actinides by Laser-Induced Fluorescence," U.S. Patent No. 4,724,217, Department of Energy, Feb. 9, 1988.

Mishra B., Pritchett S., Moore J.J., Murray A.M., "Salt Scrub Reduction Alloys for Actinide Recovery," Proceedings of Symposia Sponsored by the Extraction and Processing Division, TMS Annual Meeting in Denver, Colorado, Feb. 21-25, 1993.

Mito M.H., Yoneya M., Fukumoto M., "Method of Treatment of High-Level Radioactive Waste," Japanese Patent No. 5,082,603, Japan, 1992.

Miyao et al., "Method of Compacting Radioactive Metal Wastes," U.S. Patent No. 5,063,001, Nov., 1991.

Miyata Kazuyoshi, Ohtsuka Katsuyuki, "Electro-Slag Melting of Plutonium-Contaminated Metallic Waste," PCNT-N-831-82-01, Japan, Sept., 1982.

Mizia R., Idaho National Engineering Laboratory, Montana Tech, Butte Montana, Private Communication with A. Liby, Manufacturing Sciences Corporation, June, 1993.

Montgomery D.R., Nesbitt J.F., "Review and Evaluation of Metallic TRU Nuclear Waste Consolidation Methods," PNL-4754, UC-70, DE84 001919, Pacific Northwest Laboratory, Aug., 1983.

Montgomery D.R., "Consolidation of Simulated Nuclear Metallic Waste by Vacuum Coreless Induction Melting," PNL-5254, UC-70, Pacific Northwest Laboratory, Oct., 1984.

Moreau J.C., "S.T.M.I. Several Years of Experience in Nuclear Plant Dismantling," EDB-86-093371, CEA-75 Paris, Jan., 1986.

Morris A.E., Stephenson J.B., "Computer Software for Chemical and Extractive Metallurgy Calculations," 1993 Apr., JOM, Apr., 1993.

Mullins L.J., Leary J.A., Johnson K.W.R., Wilkinson W.D., "Removal of Fission Product Elements from Plutonium by Liquation," Los Alamos Scientific Laboratory, 1960; Extractive and Physical Metallurgy of Plutonium and Its Alloys, Wilkinson W.D. ed., Interscience Publishers, New York, 1960.

Mullins L.J., Leary J.A., Maraman W.J., "Removal of Fission Product Elements by Slagging," NSA-14-010537, Los Alamos Lab, 1960; Industrial and Engineering Chemistry, Vol. 52, No. 3, Mar., 1960.

Murphy J.E., Morrice E., Wong M.M., "A Comparison of Sublimation and Vaporization for Purification of Samarium Metal," Report of Investigations 7466, Bureau of Mines.

Music S., Gotic M., Popovic S., "Corrosion of Stainless Steel in Contact with a Melt of a Phosphate Glass," Journal of Materials Science Letters, Vol. 8, pp. 1389-1390, 1989.

Nafsiger R.H., Elger G.W., "Fluorspar Substitutes in Steelmaking," New Steelmaking Technology from the Bureau of Mines, IC 9195, pp. 23-27, 1988.

Nakajima K., "Annual Progress Report of Power Reactor and Nuclear Fuel Development Corporation," Tokai Works, Apr., 1981-Mar., 1982, PNCT-N-831-82-01, DE85 780801 F6200, Sept., 1992.

Nakamura H., Fujiki, "Radioactive Metal Melting Test at Japan Atomic Energy Research Institute," Japan Atomic Energy Research Institute, 1992.

Nakamura Haruto, Kikkawa Shizuo, Sato Mamoru, Kamizono Hiroshi, Senoo Muneaki, Tashiro Shingo, "Volatilization of Cs¹³⁷ and Sr⁹⁰ from Simulated High-Level Waste Glass," JAERI-M-84-141, Japan Atomic Energy, July 13, 1984; CEA-TR-2444, France, June, 1988.

Nelson R.G., Griggs B., "Chop-Leach Fuel Bundle Residues Densification by Melting," BNWL-2132, Energy Research & Development Administration, Nov., 1976.

Nelson R.G., Schlienger M.P., Tiesenhausen E.V., "Selection of a Melting Furnace for Consolidation of Nuclear Fuel Hulls," BNWL-1968, Battelle, Pacific Northwest Laboratory, July, 1976.

Newby B.J., "Method for Calcining Nuclear Waste Solutions Containing Zirconium and Halides," U.S. Patent No. 4,164,479, Department of Energy, Aug. 14, 1979.

Newman D.F., Ross W.A., "Battelle Radioactive Waste Melter," U.S. Patent No. 4,919,190, Battelle, Richland, WA, Apr. 24, 1990.

Oak Ridge National Laboratory, "Metal Decontamination and Volume Reduction for Trans-uranium Contaminated Metals," Department of Energy, Sept., 1982.

Ochiai A., Yamamoto T., "Method of Volume-Decreasing and Decontaminating Radioactive Metal," Japanese Patent No. JP 57-132522, Japan, July, 1982.

Ochiai A., Kitagawa K., Sawada Y., "Treatment of Plutonium-Contaminated Metallic Waste by the Electro-slag Melting Method," IAEA-SM-261/20; EDB-84-020441, Japan: Kobe Steel, June, 1982.

Ochiai A., Nagura K., Noura T., "Treatment of Radioactive Metallic Waste by the Electro-slag Melting Method," EDB-84-071668, Japan: Kobe Steel, Jan., 1983.

Office of Technical Services/Weston & H&R, "Radioactive Scrap Metal Recycling: A Doe Assessment," paper 92-001 (Unpublished), Department of Energy, Aug., 1991.

Osamu K., Takao K., Makoto K., "Decontamination of Radioactive Metal Surfaces by Plasma Arc Gouging," Nuclear Technology, Vol. 61, Apr., 1983.

Oziraner S.N., Minaev A.A., Kuznetsov D.G., Prokhorova N.P., "Comparison of Some Properties of Phosphate and Silicate Glasses Intended for Vitrification of Aluminum Containing Radioactive Wastes," Conference On Processing and Disposal of Radioactive Wastes and on Decontamination of Surfaces, Moscow, USSR, CONF-761260, Dec. 20, 1976; INIS-mf-5571, 1978.

Passant F.H., Ward R.D., "Decommissioning Waste Arisings in the European Community and Western Europe," Advances in Ceramics, Vol. 20: Nuclear Waste Management II, 1986.

Peulve J., "Treatment of Dismantled Materials by Fusion," Techno-992-022, 1992.

Peulve J., & colleagues, "Dismantling of Nuclear Facilities Scrap Steel Management of G2 and G3 Reactors at Marcoule," UDIN, Commissariat A L'Energie Atomique, Marcoule ie Apr. 16, 1993.

Pick M.E., "The Nature of PWR Stainless Steel and Inconel in Relation to Decontamination in Permanganate Based (NP & AP) Processes," H2O Chem Nuc R.S. VI3, Berkeley, United Kingdom, 1983.

Pierce et al., "Salt Transport Extraction of Transuranium Elements from LWR Fuel," U.S. Patent No. 5,160,367, Department of Energy, Nov. 3, 1992.

Pierce R., Johnson T., McPheeters C., Laidler J., "Progress in the Pyrochemical Processing of Spent Nuclear Fuels," JOM, pp. 40-44, Feb., 1993.

Piper, "Method of Inclusion Melting Glass with Radioactive Components, and Furnace for Carrying out such Method," U.S. Patent No. 4,139,360, Feb. 13, 1979.

Price M.S.T., "Large Transport Containers for Decommissioning Waste," EUR 9474, Decommissioning Nuclear Power Plants, May, 1984.

Proceedings of the 1980 UCC-ND and GAT Waste Management Seminar, CONF-800416, Prepared by Oak Ridge National Laboratory, Shawnee State Park Lodge, Friendship, Ohio, Apr. 22-23, 1980.

Rackley J.M., Vecchi S.J., "Cyclone Furnace for Hazardous Waste Incineration and Ash Vittrification," U.S. Patent No. 5,052,312, Babcock & Wilcox Company, Oct. 1, 1991.

Rajan J.B., Kumar R., Vissers D.R., "Process for Direct Conversion of Reactive Metals to Glass," U.S. Patent No. 4,898,692, Department of Energy, Feb. 6, 1990.

Reimann G.A., "Technical Assessment of Processes to Enable Recycling of Low-Level Contaminated Metal Waste," EGG-MS-9879, Idaho National Engineering Laboratory, Oct., 1991.

Reimann G.A., Grandy J.D., Eddy T.L., Anderson G.L., "Summary of INEL Research on the Iron-Enriched Basalt Waste Form," EGG-WTD-10056, Idaho National Engineering Laboratory, Jan., 1992.

Robinson R.A., Fekete L., Janke D.S., Peters R., "Conceptual Design of a Joule-Heated Ceramic Melter for the DOE Fernald Silos 1,2, and 3 Wastes," FEMP/SUB--051, DE92 016516, Spectrum '92 Conference, Boise, ID, Aug. 23-27, 1992.

Roine A., "International Symposium on Computer Software in Chemical & Extractive Metallurgy," Proc. Metall. Soc. of CIM, Montreal 1988, Vol. 11, p. 15, 1988.

Rosen C.L., Chellew N.R., Feder H.M., "The Melt Refining of Irradiated Uranium: Application to the EBR-II Fast Reactor Fuel. IV. Interaction of Uranium and Its Alloys with Refractory Oxides," Nuclear Science and Engineering, Vol. 6, pp. 504-510, July 6, 1959.

Sappok M., "Recycling of Metallic Materials from the Dismantling of Nuclear Plants," Kerntechnik, Vol. 56, No. 6, Germany, 1991.

Sappok M., Rettigelt G., "Results of Melting Large Quantities of Radioactive Metallic Scrap," Proceedings of the International Topical Meeting on Nuclear and Hazardous Waste Management, Spectrum '92," American Nuclear Society, La Grange Park, Illinois, 1992.

Sappok M., Graebener K.H., "Melting of Radioactive Scrap. A. Experience Gained by SGR and Siemens with the Melting of Radioactive Scrap B. First Results Obtained with the Melting of Alpha-Contaminated Steel Scrap," EUR-14363, European Community, Sept., 1991.

Sappok M., "Melting of Radioactive Scrap from Nuclear Installations," Decommission of Nuclear Installations, 1990a.

Sappok M., Tarcza G.A., "Results of Metallic Waste Treatment by Melting," Siemplekamp Giesserei GmbH & Co., Germany; CONF-874048 Vol. 1, Westinghouse Hanford, Oct., 1987.

Sauer N.N., Watkin J.G., "Actinide Metal Processing," U.S. Patent No. 5,098,677, Department of Energy, Mar. 24, 1992.

Schanker E., "Processes for the Decontamination of Surfaces," Swiss Patent No. 5,093,073, ABB Reaktor GmbH, Mannheim, Switzerland, Mar. 3, 1992.

Schuster E., Trummer K.H., Stang R., Post R.G., "Non-Hazardous Re-use of Components Removed from Nuclear Facilities by Melting Processes," Waste Management '87, CONF-870306, Tucson, AZ, Mar., 1987.

Schuster E., Haas E.W., "Behavior of Difficult to Measure Radionuclides in the Melting of Steel," EUR-12690, Belgium, Decommissioning of Nuclear Installations, Elsevier Applied Science, 1990, or Advances in Ceramics Vol. 20: Nuclear Waste Management II, 1986.

Scientific Ecology Group, Inc.(SEG), SEG Commercial Pamphlet on "Metal Processing," and Industrial Portfolio, Scientific Ecology Group P.O. Box 2530, 1560 Bear Creek Road Oak Ridge, TN 37830, 1993.

Seitz M.G., Vandegrift G.F., Bowers D.L., Gerding T.J., "Effect of Aged Waste Package and Basalt on Radioelement Release," CONF-8308126-4, Department of Energy, Jan., 1983.

Seitz M.G., Bowers D., Fortney D.R., "A Groundwater Stream Experiment for the Waste Isolation Pilot Plant," DE 82003231, NTIS, Dec., 1981.

Seitz M.G., Gerding T.J., Steindler M.J., "Decontamination of Metals Containing Plutonium and Americium," ANL-78-13, UC-70, UC-10, Argonne National Laboratory, June, 1979.

Sennewald G., David C., Wurm J.G., "Halide Slagging of Rare Earth Fission Products in Molten Uranium," EUR-4184e, European Atomic Energy Community - EURATOM, 1968.

Seymour W.C., "Migration of TRU-Containing Slag into Candidate Refractories for Waste Management," EGG-RE-M-78-034, UNCLAS, 70-4 UNLTD DIST, EG&G Idaho, Inc., Idaho Falls, Idaho, Nov., 1978.

Shaw W.E., "Study for Disposal of Uranium Contaminated Ferrous Scrap," NLCO-1110, Apr., 1974.

Shaw P.G., EG&G Idaho Inc., Idaho Falls, Idaho, Private Communication with R.E. McActee 1988, Referenced in EG&G report, EGG-WTD-9801, Authored by R.E. McAtee and M. Beal (1991), Jan., 1988.

Shaw P.G., Loomis G.G., "Plutonium Contamination Control Studies During A Glove- Box Scale Simulated Evacuation of TRU Buried Waste," EGG-WM-8289, Oct., 1988.

Shirato K., Kitamura M., Asano H., Sakai A., "Ruthenium Release Rate from the Pilot Scale Melter," The Third International Conference on Nuclear Fuel Reprocessing and Waste Management RECOD'91, Vol. 2, Japan, Apr. 14-18, 1991.

Silverman L., "Uranium Dioxide in Stainless Steel. Determination in Solution by X-Ray Fluorescence Spectrometry," Bohl Analytic, Reinhold Corporation, 1963.

Skillern C.G., Vogel R.L., "Production Prove-out of a Process for Remelting Depleted Uranium Machining Chips By Vacuum Induction," United States Army Armament Research and Development Center, AD-A165-790, Feb., 1986.

Smith T.H., Tolman C.R., "Annual Technical Report Transuranic Waste Program at EG&G Idaho, Inc.," EGG-WM-5295, EG&G, Idaho National Engineering Laboratory, Dec., 1980.

Snyder T.S., Gass W.R., Worcester S.A., Ayers L.J., "Decontamination of Radioactive Metals," U.S. Patent No. 5,156,722, Westinghouse Electric Corporation, Oct. 20, 1992.

Snyder T.S., Whitlow G.A., "Integrated Decontamination Process for Metals," Statutory U.S. Patent No. H970, Department of Energy, Oct. 1, 1991.

Spendlove M.J., "Bureau of Mines Research on Resource Recovery, Reclamation, Utilization, Disposal, and Stabilization," BUMINES-8750, Maryland, 1977.

Starkey R.H., Quigley J.A., McKelvey J.W., "Health Aspects of the Commercial Melting of Radium-Contaminated ferrous Metal Scrap," American Industrial Hygiene Association Journal, 22, pp. 489-493, 1961.

Starkey R.H., McKelvey J.W., Held B.J., Alpaugh E.L., "Health Aspects of the Commercial Melting of Uranium-Contaminated Ferrous Metal Scrap," American Industrial Hygiene Association Journal, Vol. 21, pp. 178-181, 1960.

Stearn Dr. S.M., "The Recycle and Reuse of Components Arising from Decommissioning Nuclear Installations: An Overview," HM Inspectorate of Pollution, London, England, 1987.

Stoots P.R., "In Situ Vitrification Intermediate-Scale Sampling and Analysis Plan," EGG-WM-8661, 1990.

Sturchio N.C., Seitz M.G., "Behavior of Nuclear Waste Elements During Hydrothermal Alteration of Glassy Rhyolite in an Active Geothermal System: Yellowstone National Park, Wyoming," CONF-844157-13, DE85 002730, Department of Energy, 1984.

Sundman B., "International Symposium on Computer Software in Chemical & Extractive Metallurgy," Proc Metal Soc CIM, 1988.

Suwa T., Kuribayashi N., Tachikawa E., "Corrosion Behavior of Stainless Steel in Sulfuric Acid-Cerium Solution," Japan Atomic Energy Commission, Tokia Research Establishment, Boshoku Gijutsu, Vol. 37, pp. 88-96, 1988.

Suzuki Osamu, Ishizaki Kanjiro, Kushida Shizuko, "Multilayer Containers for Radioactive Wastes," Japanese Patent No. JP 85-292982, Japan, Dec. 26, 1985.

Tanaka M., Nakamura H., "A Research Program on the Recycling of Decommissioning Materials at JAERI," Proceedings of the St. Michaels Workshop on Residual Radioactivity and Recycling Criteria, St. Michaels, Maryland, Sept. 27-28, 1989.

Tanaka M., Nakamura H., "Research Program of Decommissioning Materials Reuse in JAERI," Joint International Waste Management Conference, Vol. 2, ASME/JSME/AESJ, 1989.

Tanimoto Shigemi, Eguchi Yoshiaki, Shimabara Yoshiko, "Stainless Steel Apparatus and Method for Analyzing Slag in Molten Metal," Japanese Patent No. JP 90-107048, Showa Aluminum Corporation, Japan, Apr. 23, 1990.

Teimer R., Batdorf J., Larsen M.M., "Plasma Arc Treatment of TRU and Mixed TRU Waste," Techno-92-002, Department of Energy, UCID-21044, 1992.

Terabe S., Otsuka K., Ichikawa K., Tsuchiya A., Ando T., "Electrodeposition of Actinides in a Mixed Oxalate-Chloride Electrolyte," American Chemical Society, Analytical Chemistry, Vol. 56, No. 1, pp. 113-116, Jan., 1984.

Thoma A., "First Results of the Melting of Radioactive Waste in the EIRAM Plant," Decommissioning of Nuclear Installations-1990, Commission of the European Communities, CEA, Germany, 1990, or Advances in Ceramics, Vol. 20: Nuclear Waste Management II, 1986.

Thompson W.T., Pelton A.D., Bale C.W., "F*A*C*T Facility for the Analysis of Chemical Guide to Operations," McGill University Computer Center, 1985.

Thompson W.T., Eriksson G., Pelton A.D., Bale C.W., "International Symposium on Computer Software in Chemical & Extractive Metallurgy," Proc Metal Soc CIM, 1988.

Thomson P., Edwards J.O., Uranium in Non-Ferrous Metals, Department of Mines and Technical Surveys Report R-97, USAEC report NP-12164, July, 1962.

Thomas T. ed., "Database000," WINCO, INEL, Mar. 23, 1993.

Timmerman C.L., "System for Enhanced Destruction of Hazardous Wastes by In Situ Vittrification of Soil," U.S. Patent No. 5,024,556, Battelle Memorial Institute, June 18, 1991.

Tingey J.M., Elliott M.L., Larson D.E., Morrey E.V., "Laboratory Characterization and Vitrification of Hanford Radioactive High-Level Waste," Nuclear Waste Management IV, 1991.

Tokumitsu, Naoki, Sakurai, Daihachiro, Anabuki, Yukitaka, "Method of Melting Iron Scrap Contaminated by Radioactive Material," Japanese Patent No. JP 3-293599A, Japan, Apr., 1990.

Turner A.D., Pottinger J.S., Junkison A.R., "Electrochemical Decontamination of Pu Contaminated Stainless Steel," UKAEA Atomic Energy Research Establishment, Harwell, England; AERE-R-10506, DOE/RW-83.089, NTIS No. DE84701715, Aug., 1983.

Uda Tatsuhiko, Miura Noboru, Tsuchiya Hiroyuki, "Method of Melting for Decontamination of Radioactively Contaminated Metals," Japanese Patent No. JP 59-127000 A, Hitachi Ltd., Japan, Jan. 12, 1983.

Uda T., Iba H., Tsuchiya H., "Decontamination of Uranium-Contaminated Mild Steel by Melt Refining," Written in Japan 1985, Nuclear Technology, Vol. 73, Apr., 1986.

United States Bureau of Mines-Department of Interior, "Mineral Commodity Summaries 1993," 1993.

Voigt A.F., Clark R.G., Gonser J.G., Haes D.L., Lutz G.J., Malaby K.L., "Removal of Plutonium from Uranium by Molten Metal Extraction," IS-470, Ames Laboratory, Iowa, May, 1962.

Voorde Van de N., Taeymans A., Hennart D., Vanbrabant R., Balleux W., Geenen G., Gijbels J., "High-Temperature Incineration of Radioactive Waste, Exploitation of the FLK-60 Slagging Incinerator for the Treatment of Different Waste Streams Contaminated with Plutonium," EUR-10411, Commission of the European Communities, 1986.

Voorde van de N., Claes J., Taeymans A., Hennart D., Gijbels J., "High Temperature Incineration. (a) Incineration of Solid Wastes Contaminated with Plutonium (b) Densification of Granules from High-Temperature Incineration (Final Report)," EUR-7675-EN, Commission of the European Communities, 1982.

Wadsley M., Personal Communication with Twidwell L.C., CSIRS/MONASH, MONASH University, 1993.

Ward C.R., "Experimental Canister Frit Blaster: Final Report," DPST-86-219, Savannah River Corporation, Jan. 9, 1986.

Watrous R.A., Kruger O.L., "Recycle Stream Impacts on Feed Treatment Flowsheets and Glass Formulations for the Hanford Waste Vitrification Plant," WHC-SA-1240, Westinghouse Hanford, Feb., 1991.

Wcislo Sygmut, Talbai Abiodun Adeleye, Fedko Jozef, Krucinski Marian, "Titanium mass transfer in the metal slag system during electroslag refining," Metal. Odlew 17(2), Krakow, Poland, Jan., 1991, or Institute of Metallurgy, Jan., 1991.

Weidner J.R., EG&G Idaho, Inc. Idaho Falls, Idaho, Private Communication with R.E. McAtee June 1997, Referenced in EG&G report EGG-WTD-9801, Idaho Falls, June, 1991.

Weiling N., Hoffman P.J., Boothby R.M., Williams T.M., "Reduction of Exposure to Radiation by Substitution of Co Alloys and Reduction of the Concentrations of Co, Nb and Other Companion Elements in Steel," EUR 9474, Decommissioning Nuclear Power Plants, May, 1984.

Welch J.M., Sill C.W., Flinn J.E., "Leach Tests of Simulated Low-Level Transuranic Waste Forms Containing Transuranic Elements," EGG-FM-6153, Department of Energy, 1983.

Wendt K.M., "Identification of Alternative Decontamination Technologies for Use at the ICPP," techno 92-021, Idaho National Engineering Laboratory, Techno-92-021, Sept. 30, 1992.

Westerman R.E., Mackey D.B., "Effect of HNO_3 -Cerium (IV) Decontamination on Stainless Steel Waste Canisters," PNL-SA-18551, Pacific Northwest Laboratory, Apr., 1991.

White D.A., "Development of Reagents for the Decontamination of Stainless Steel Plant Scrap by Bulk Dissolution," Department of Chemical Engineering and Chemical Technology, Imperial College of Science and Technology, London; C394/88, IMechE 1988, London, Engineering, Jan., 1988.

Whitworth C.G., MSE, Butte, MT, Private communication with L.G. Twidwell, Montana Tech, Butte, MT, 1993.

Whitworth C.G., "Plutonium Processing in a Plasma Processing Environment," Component Development Integration Facility, MSE, Butte, Montana, Dec. 20, 1991.

Whitworth C.G., Twidwell L.G., Jenkins T.W., Wyss G.F., "Slag Chemistry and Metals Volatilization in the Plasma Arc Furnace Experiment," Department of Energy, Spectrum'92, 1992.

Wilhite E.L., Ebra M.A., Stone J.A., Stevens W.R. III, "Processing and Disposal of Defense Nuclear Waste at the Savannah River Plant," Savannah River Laboratory, CONF-870435, ASME, 1987.

Wilkinson W.D., Jenkins I.L., Keen N.J., Wain A.G., "Alternative Routes for the Conversion of Plutonium Salts to Metal and Their Recovery Problems," NSA14, Atomic Energy Establishment, 1960.

Williams L.C., Mack J.E., "Design Requirements for a Metal-Smelting Facility," CONF-820424-19, Department of Energy, Apr., 1982.

Windt N.F., Williams J.L., "Method for Decontamination of Nickel-Fluoride-Coated Nickel Containing Actinide-Metal Fluorides," U.S. Patent No. APPL-6-453-983, Dec., 1982.

Windt N.F., Williams J.J., "Method for Decontamination of Nickel-Fluoride-Coated Nickel Containing Actinide-Metal Fluorides," U.S. Patent No. 4,421,556, Department of Energy, Dec. 20, 1983.

Wood C.J., Bradbury D., "Process for Removing Radioactive Burden from Spent Nuclear Reactor Decontamination Solutions Using Electrochemical Ion Exchange," U.S. Patent No. 5,078,842, Electric Power Research Institute, Jan. 7, 1992.

Wormsbecher R.F., Chapman A.T. Jr., Hill D.N., "Process for the Immobilization and Volume Reduction of Low Level Radioactive Wastes from Thorium and Uranium Processing," Statutory U.S. Patent No. H1013, W.R. Grace & Company, New York, Jan. 7, 1992.

Zhu B.F., Clark D.E., Hench L.L., Wicks G.G., Werme L., "One Year Leaching of Three SRL Glasses in Granite," Materials Research Society Symposium Proceedings, Vol. 44, Materials Research Society, 1985.

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

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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	Hexachloreth- -ane degasser							Cl ₃ CCCl 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 ₂ O 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)

Metal	Slag										Final Metal Contamination		Reference
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant	Conc., ppm	
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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)
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 ³ =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)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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)
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 ₂ O ₃		9	UO ₂	1.36	Heshmatpour (1981a)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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 ₂ O 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)
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)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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 ₂ CO 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 ₂ CO ₃ , 50 NaNO ₃ , 10 PbO		9	UO ₂	0.26	Heshmatpour (1981a)
Lead	Sodium Slag							60 Na ₂ CO ₃ , 30 NaNO ₃ , 10 PbO		9	UO ₂	0.49	Heshmatpour (1981a)
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)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
Lead	Sodium Slag							80 Na ₂ CO 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 ₂ O 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 ₂ O 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)
Nickel	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		10	Pu	0.068	Seitz (1979)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
Nickel	Borosilicate	80		2			1	13 B ₂ O 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)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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	$\lambda = 226$	Snyder (1991)
S.S.	Borosilicate	80		2		4	0.5	13 B ₂ O 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 ₂ O 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 ₂ O ₃		10	Pu	0.60	Hobbick (1981)
S.S.	High Silica	60	30	10						10	Pu	0.42	Hobbick (1981)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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 ₂ O 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 ₂ O 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 ⁴	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 ₂ O ₃		NA ⁵	Pu	0.0012	Seitz (1979)

Metal	Slag										Final Metal Contamination		Reference
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant	Conc., ppm	
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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 ₂ O 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)
Steel	Calcium-Aluminate		40	60						9	UO ₂	0.42	Heshmatpour (1981a)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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 ₂ O ₃		12	Pu	0.0063	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		10	Pu	0.0007- 0.00009	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O 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)
Steel	Calcium- Ferric- Silicate	25	50		25						UO ₂	0.05	Heshmatpour (1981a)

Metal	Slag										Final Metal Contamination		Reference
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant	Conc., ppm	
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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 ₂ O 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)
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)

Metal	Slag										Final Metal Contamination		Reference
	Type	Composition, Nominal %						BI ¹	Amount, % ²	Contam- inant	Conc., ppm		
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O					Other	
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									5	Pu	0.27-6.4	Seitz (1979)
Steel	Fluoride Containing, High Lime	25	60	10						9	UO ₂	0.03	Heshmatpour (1981a)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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 ₂ O 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 ₂ O ₃		10	Pu	0.001- 0.003	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O 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)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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 ₂ O 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 ₂ O 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)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
Steel	Hearth Slag							CaFeSiO ₄ , Minor SiO ₂		10	Pu	NA	Seitz (1979)
Steel	High Lime	10	60		30						U	λ = 583	Snyder (1991)
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 ₂ O 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 ₂ O ₃		11	Pu	0.0019	Seitz (1979)

Metal	Slag										Final Metal Contamination		Reference
	Type	Composition, Nominal %						BI ¹	Amount, % ²	Contam- inant	Conc., ppm		
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O					Other	
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		20	Pu	0.005- 0.20	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O 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		Seitz (1979)
Steel	Calcium- Magnesium- Silicate							CaMgSi ₂ O ₆		10	Pu	0.18- 21.0	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O 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 ₂ O ₆		19	Pu	0.0037	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		11	Pu	0.001	Seitz (1979)
Steel	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		10	Pu	0.002- 0.03	Seitz (1979)
Steel	Calcium- Magnesium- Silicate							CaMgSi ₂ O ₆		15	Pu	0.016	Seitz (1979)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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 ₂ O ₃		10.7	Pu	0.0015-0.0012	Seitz (1979)
Steel-4% Copper	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		9.3	Pu	0.0004-0.0002	Seitz (1979)
Steel-4% Copper	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		10	Pu	0.0637	Seitz (1979)
Steel-45% S.S.-9% Brass	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		10.9	Pu	0.0005-0.0004	Seitz (1979)
Steel-45% S.S.	Borosilicate	80		2		4	0.5	13 B ₂ O ₃		10.4	Pu	0.0014-0.0011	Seitz (1979)
Tin	Sodium Slag							25 NaNO ₃ , 25 NaOH, 25 NaCl, 25 Na ₂ CO ₃		9	UO ₂	0.06	Heshmatpour (1981b)
Tin	Sodium Slag				5			50 NaNO ₃ , 45 Na ₂ CO 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)

Metal	Slag									Final Metal Contamination		Reference	
	Type	Composition, Nominal %							BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	Other					
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)
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	1 = 8	Snyder (1991)
Zinc	Sodium Slag				5			50 NaNO ₃ , 45 Na ₂ CO ₃		9	UO ₂	2.10	Heshmatpour (1981a)
Zinc	Sodium Slag				5			50 NaNO ₃ , 25 NaOH, 25 NaCl, 25 Na ₂ CO ₃		9	UO ₂	0.54	Heshmatpour (1981a)
Zinc	Sodium Slag				5			50 NaNO ₃ , 45 NaCl		9	UO ₂	0.14	Heshmatpour (1981a)

AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

2 of 2

Metal	Slag								Final Metal Contamination		Reference	
	Type	Composition, Nominal %						BI ¹	Amount, % ²	Contam- inant		Conc., ppm
		SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O					
<div>1. BI = Basicity Index = wt.% basic oxides/wt.% acidic oxides</div> <div>2. % Slag in charge</div> <div>3. Partition Ratio, λ, is defined as the ratio of concentration of constituent in the slag phase/concentration of constituent in the metal phase</div> <div>4. X = Constituent is present in the slag, but concentration is unknown</div> <div>5. N.A. = Not Available</div>												

**DATE
FILMED**

9/12/94

END