CRC for Contamination Assessment and Remediation of the Environment

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no. 7 technical report

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G. Owens

Centre for Environmental Risk Assessment and Remediation (CERAR),
University of South of Australia

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Enquiries and additional copies:
CRC CARE, P.O. Box 486, Salisbury South, South Australia, Australia 5106
Tel: +61 (0) 8 8302 5038
Fax: +61 (0) 8 8302 3124
www.crccare.com

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Project summary

The Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE) asked the Centre for Environmental Risk Assessment and Remediation (CERAR) to provide a literature review of the current and existing polices for handling, disposal and potential beneficial reuse options for used foundry sands. The purpose of this review is therefore to examine the current industry and regulatory practice concerning the disposal and the potential options for beneficial reuse of used foundry sands and to identify data gaps requiring allocation of future focused research.

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Executive summary

A large amount of research conducted recently and practical experience gathered worldwide over the last 30 years has indicated that with very few exceptions, beneficial reuse of used foundry sand (UFS) is not detrimental to human health or the environment.

Characteristics

- UFS is not uniform and the type of contaminant issues that may be experienced varies both spatially and temporally. Spatial variation is due to the differences in procedures and foundry processes which vary from one company to another and from one application to another. The main differences occur between foundries that use green sands to produce moulds, as opposed to foundries which use resin sands with a higher content of organic contaminants due to the organic resin binders used to prepare moulds. Temporal variations in UFS consistency can occur even at the same location due to changes in foundry production.
- UFS is currently poorly characterised with regard to the type and extent of contaminants, especially organic contaminants including potentially unhealthy contaminants such as polyaromatic hydrocarbons (PAHs) produced during the foundry process at elevated temperatures due to pyrolytic reactions. There is a need to better understand how these reactions occur so they can be controlled and minimised.
- Most organic residues are present in UFS at low concentrations, usually below detection limits. When detected the organic residues are either PAHs (phenanthrene, naphthalene, fluorene, anthracene and pyrene) or phenolic compounds (phenol, 2-methyphenol, 3- and 4-methylphenol and 2,4-dimethyl phenol).

Beneficial reuses

- While a number of beneficial uses have been proposed, few are economically viable unless the foundry and the site of reuse are close and thus limit the costs associated with transporting UFS for treatment or reuse.
- Beneficial reuses that are well advanced include many construction applications, whereas agricultural application of UFS is limited, not due to any real environmental concern but rather the perception that UFS will be detrimental to human health. Indeed, substantial research conducted worldwide has indicated that metal contaminants in UFS, especially those derived from green sands, are not of environmental concern and are often present at levels comparable to native soils.
- Several studies have indicated that UFS from brass foundries are generally not suitable for beneficial reuse due to high levels of metal contaminants.
- For land application of UFS, greater research needs to be conducted to unequivocally demonstrate that UFS as part of a manufactured soil is completely safe.

Legislative aspects

- A number of legislative frameworks have been adopted worldwide. The more successful of these use some form of classification of UFS based on specified criteria for both metal and organic concentrations, usually TCLP (toxicity characteristic leaching procedure) extraction, and then define specifically what reuse is applicable to that classification.
- While the levels of metal contamination in UFS are normally well below any legislated levels of concern and are often comparable to the original clean sand, organic contaminants are poorly characterised in UFS and are consequently poorly legislated for. In part this results from the plethora of different potential organic binder technologies currently in use.
- Lack of clarification by the state EPAs as to what criteria would be suitable for classification of UFS is one of the major barriers to successfully reusing UFS. This is coupled with disagreement between states on clear legislative guideline levels for different contaminants.
- There is a need to streamline the approvals process to encourage beneficial reuse.
- Research is required to establish not only the types of UFS constituents, but also the magnitude of investigation levels for these constituents that would be required to ensure protection of the environment and human health.
- Legislative guidelines should include information on sampling plans and the frequency of sampling required.

Further research

In the short term the most pressing need for industries and regulators intent on the adoption of beneficial reuse of UFS is to focus on dialogue that fosters beneficial reuse. The development of regulatory guidelines which address the needs of industries in clear and unequivocal terms needs to be a priority. Generic guidelines are not required, rather, a clear statement of what is required on the quality of UFS fit for a specific purpose. There is a need for guidelines to be developed specifically for the reuse of UFS.

These guidelines should initially focus on land application, which would be the most difficult to define and implement due to the greatest potential risk associated with this reuse. However, reuse should not be limited to this avenue alone as many other applications such as road base and construction are relatively low risk alternatives that can quickly be used to demonstrate beneficial reuse.

1. Introduction

1.1 Background

Used foundry sand (UFS) contains a variety of inorganic and organic binding agents required for the production of sand casts in the foundry process. Large metal contaminants in the UFS can be removed by using screening or magnetic separators, which generally ensure that in terms of metal and inorganic contaminants, UFS can be classified as a non-hazardous industrial by-product. However, organic contaminants are also a major component of the binder and may be retained within the sand to various degrees depending on the foundry process. In particular aluminium casting, which generally occurs at lower temperatures, is likely to result in higher concentrations of organic residues. Depending on the particular foundry these organic residues could include phenolics, PAHs, isocynates and a variety of daughter organic compounds formed during the foundry process (Ji et al. 2001). There is also considerable variability in the contaminant profiles of UFS between foundries and often within a foundry due to temporal variations.

Foundries attempt to reuse as much of the sand as possible within the foundry process itself, but eventually a fraction becomes spent and unsuitable for further foundry processes. In the US, ferrous and non-ferrous foundries generate more than six million tonnes of UFS that can no longer be recycled in the foundry process (Dungan et al. 2006). At the moment 90% of this waste is disposed of to landfill as non-hazardous waste while only 10% is beneficially reused (US EPA 2002).

The practice of disposing of UFS to landfill is becoming increasingly cost prohibitive and is likely to become more difficult as legislation governing waste disposal becomes more stringent. A more cost-effective alternative is to utilise the spent foundry sand in a by-product that generates revenue for the foundry. Considerable savings to industry are therefore possible through development of a reuse application for UFS.

This literature review will examine the potential reuse alternatives for UFS and identify what research needs to be conducted to support new or existing policies on beneficial reuse of UFS.

1.2 Objectives

The purpose of this review was to examine the current industry and regulatory practice concerning the disposal and the potential options for beneficial reuse of used foundry sands.

The principle objectives of this project were therefore to:

1. Review the current international policies and legislation on the safe use, disposal and reuse of used foundry sands (UFS).
2. Identify potential 'value adding' options available for reuse of UFS.
3. Review the contaminant profiles (e.g. binding agents) of UFS and to identify which contaminants may limit potential beneficial reuse options.
4. Identify current scientific knowledge gaps and prioritise future research needs to support new or existing policies.

1.3 Scope of the literature review

This project reviews all readily available published literature pertinent to the project objectives up until March 2008. Some information was proprietary in nature and not readily available to the public and could therefore not be reviewed for the purposes of this project. Where possible some projects nearing completion were reviewed on the basis of presentations only, as the full reports were not available. While this approach may lack completeness of detail, the major conclusions drawn from the research should remain unchanged.

1.4 The foundry process and the origin of UFS

A foundry produces metal casts by pouring molten metal into a preformed cast usually made from sand. The sand used in the foundry process is a high quality product of uniform size often with superior physical characteristics to normal sands since poor quality sand will result in casting defects. Foundry sand is therefore a valuable resource for foundries who generally take great care to maximise the reuse of the sand within the foundry process. However, a small fraction of the casting sand after prolonged use becomes unusable within the foundry and is discarded. Thus a fraction of the foundry sand becomes an industrial by-product called used foundry sand (UFS).

Sand can be used in the foundry to produce both the external shape of the cast part or to fill the internal spaces of cast parts, the latter sometimes being referred to as 'core' sands. However, since sand grains do not usually stick together, moulds must be formed using some binder additive while molten metal is added, and remain intact until the molten metal has cooled. The cast is then destroyed and the cast object recovered.

There are two general types of binder systems commonly used for sand metal casting – clay-bonded systems termed 'green sands' and chemically-bonded systems termed 'resin clays'.

Green sands are made of high quality silica sand with bentonite clay as the binder and a small fraction of a carbonaceous additive and water. The green sands are usually black in colour due to the combustion of the carbonaceous material during casting. The term green does not imply any cleaner production value.

In comparison, resin sands are commonly made from high quality silica sand using an organic binder activated by a catalyst. In rare cases inorganic binders may also be used. Resin sands are most often used in core making where a higher binding strength is required to withstand the high temperatures of the molten metal. In addition, because they contain no carbonaceous material, resin sands are usually lighter in colour than green sands.

2. Review of existing information and reports

2.1 Foundries in Australia

The history of foundries in Australia dates back to the very early days of the colony. The first foundry, Sydney Foundry and Engineering Works, was established in Sydney before 1841 (Richard 2000). A rapid expansion of foundries occurred concurrently with the discovery of gold in Australia which resulted in the demand for picks and shovels and stimulated small manufacturing concerns. By 1861 Ballarat had 10 foundries producing primarily mining and agricultural equipment (Richard 2000). These early foundries eventually lead to an extensive foundry and engineering industry.

Since that time the foundry industry has expanded progressively with industrialisation and major foundries exist in all states throughout Australia. Today the Australian Foundry Institute estimates that annually over half a million tonnes of Australian metal castings are shipped to foreign markets (AFI 2007). The foundry industry in Australia includes a range of both large and small foundries involved in a variety of manufacturing techniques. Thus the volume and quality of UFS generated varies significantly between foundries, which limits the formulation of any simple generic approaches to their classification.

2.1.1 Queensland

In 1999, 40 of Australia's 200 foundries were located in Queensland (EPA 1999). The foundry sizes ranged from vary small operations to large companies employing over 400 people. Most foundries used modern electric furnaces (electric arc or electric induction) and 75% of the production by volume was ferrous. Approximately 46,000 tonnes of UFS were generated annually, of which 85% was disposed to landfill and only 15% was beneficially reused (Pagan et al. 1999).

The distribution of quantities of UFS by source from casting industries from south-east Queensland shows that UFS is derived predominantly from silicate bonded sand followed by green sands and resin phenolic sands which account for 71% of the solid foundry wastes (Figure 1).

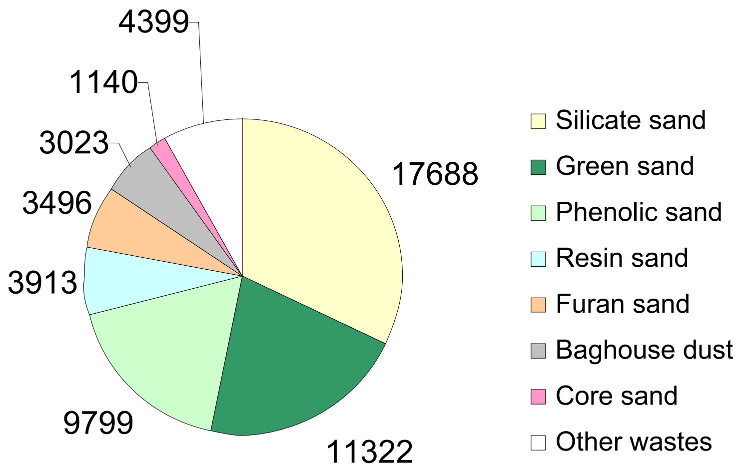

Figure 1. Quantities (tonnes per year) of solid foundry waste produced in ferrous foundries from south-east Queensland (source data: Queensland EPA 1999)

2.1.2 South Australia

The head office of Australia's largest iron foundry, Intercast & Forge, is located in Wingfield, South Australia, with other major foundries including Bradken, IonAutomotive (Castalloy) and McKechnie. The foundry industry in South Australia employs around 2000 people and is a key economic asset in the state essential to the supply of local industry (SA EPA 2003). A landfill survey conducted in 2004 indicated that UFS was a significant landfill component (Figure 2). At 5.86% (w/w) UFS was the seventh largest amount disposed to landfill in the state (Zero Waste SA 2004).

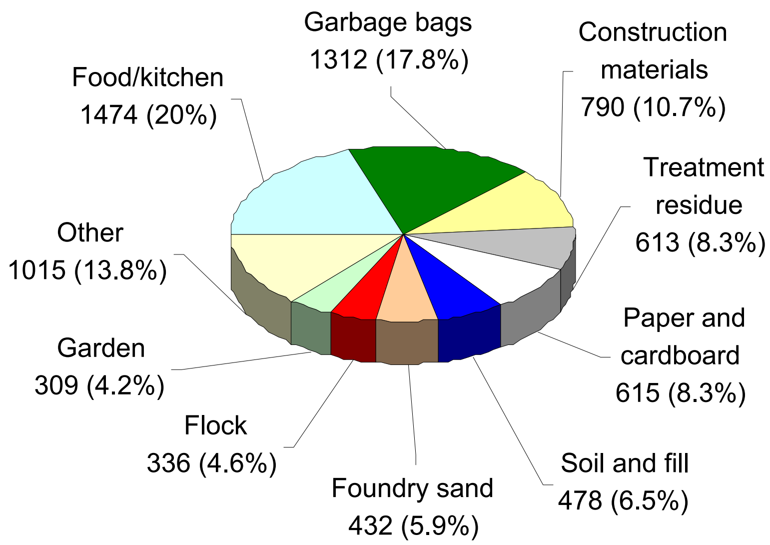

Figure 2. Quantities (kg) of commercial and industrial waste streams disposed to South Australian landfills in June 2004 (source data: Zero Waste SA 2004)

2.1.3 Victoria

Victoria produces about 89,000 tonnes of hazardous waste every year and some of this is UFS. Low-level contaminated soils together with low-hazard prescribed industrial wastes such as UFS are handled at 25 EPA licensed landfills across the state.

Geelong, located outside Melbourne, has a number of foundries casting metal products (Meinhardt Pty Ltd 1999). Ford Motor Company of Australia has its main manufacturing and assembly plant located in Geelong generating a number of industrial by-products including UFS. The Ford casting plant generates about 45 tonnes of UFS per day. Ford Australia has modified their production process to recover bentonite, steel and sand binders to ensure that the UFS is uncontaminated, and has therefore gained EPA approval for reuse applications potentially as concrete product manufacturers (Meinhardt Pty Ltd 1999).

2.2 Foundries in the USA and internationally

With the advent of the Industrial Revolution the number of foundries increased dramatically worldwide, transforming small cottage industries into large-scale and large-volume industrial operations. In 2006, foundries in Europe alone produced around 13.8 million tonnes of ferrous castings and 3.7 million tonnes of non-ferrous castings (CAEF 2008). In this section the worldwide distribution of foundries and foundry practice is briefly discussed.

2.2.1 Finland

Finland, like the majority of countries in Europe, produced less than 200,000 tonnes of foundry castings in 2006 (Figure 3). Yet despite this fairly modest production the amount of UFS produced was significant. Approximately 130,000 tonnes of UFS are produced annually in Finland primarily consisting of green sands or furan or ester-hardened phenolic sands (Mrouch & Wahlström 2002).

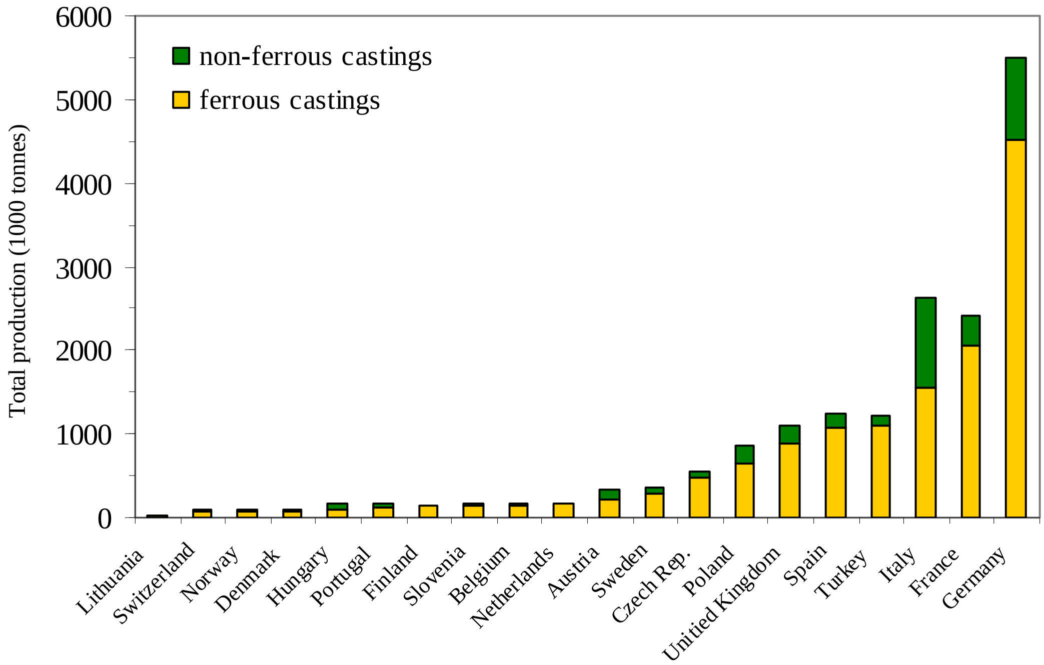

Figure 3. Total annual production of ferrous and non-ferrous castings (1000 tonnes) in 2006 from foundries from 20 different European counties (source data: CAEF 2008)

2.2.2 Germany

Germany is by far the largest producer of foundry castings in Europe (Figure 2.3). In 2006 total castings production was 5.5 million tonnes divided between ferrous (82.3%) and non-ferrous foundries (17.7%) from 619 foundries across the country (CAEF 2008). Today the foundry industry in Germany is the sixth largest producer of cast components in the world with around 700 foundries employing 75,000 people (CPG 2008). This significant foundry production would generate a large amount of UFS from a variety of delocalised sources.

In the former West Germany approximately 2 million tonnes of UFS were generated annually, and for many years this was not considered a hazardous waste. UFS therefore found a variety of uses in groundfill, landscaping and road construction (Lahl 1992). However, in the early 1980s it became apparent that there was a potential health concern with UFS due to the presence of a variety of PAHs including carcinogenic benzo(a)pyrene, which were formed as thermal reaction products during the foundry process. This led to the decline in reuse and increased moves to dispose of UFS to landfill in the new Federal Republic of Germany (Lahl 1992).

During the 1990s, German foundries were spending around 15% of their total investment on environmental protection measures, including waste recycling together with improving air quality and noise reduction (CPG 2008). While many of the projects funded in this time were related to resource and energy efficiency and the reduction of air and water emissions, some projects funded realised the necessity of ecologically sound methods of production in German foundries. These projects funded the development of environmentally friendly moulding material systems for the production of cores and moulds and the improvement of closed loop recycling and avoidance of wastes (CPG 2008). The German foundry industry, with government encouragement, has therefore focused efforts on prevention of waste generation rather than the beneficial reuse options. This may have primarily resulted from the classification by government authorities of UFS containing phenol as being hazardous and the few sites available for disposal (Morley 1991).

2.2.3 United Kingdom

The United Kingdom is one of the major producers of foundry castings in Europe (Figure 2.3) producing approximately 1.1 million tonnes of metal casting in 2006 from 459 operational foundries across the country (CAEF 2008). The United Kingdom has a long history of waste disposal of green sands especially in the West Midlands where it was used for land reclamation, and in the period 1971–1991 more than 17 million tonnes of UFS was used for land reclamation with no apparent ill environmental effects (Morley 1991). However, changes in English legislation and modern attitudes to environmental protection have led to a decline in such practices.

2.2.4 United States of America

The foundry industry in America reported over 27 billion dollars in sales in 2000 (US EPA 2002). Foundries in America include both ferrous (iron and steel) and non-ferrous (aluminium, beryllium, cobalt copper, zinc, lead, tin nickel, magnesium and titanium) foundries with over half of the foundries in the United States located in six states including Ohio, Michigan, Illinois, Wisconsin, Pennsylvania and California (US EPA 2002). The casting volume in the USA is about 90% green sands (FIRST 2003).

American foundries annually utilise about 100 million tonnes of sand. While the majority of this is reused on-site, between 8–12 million tonnes of UFS finds its way into landfill every year. It is conservatively estimated that Washington State foundries alone annually produce 22,000 tonnes of UFS (CWC 2008).

2.3 Characterisation of used foundry sands

The nature of contaminants present in the final UFS would depend largely on the type of foundry. Foundries can be divided into two main classes – ferrous and non-ferrous foundries. Ferrous foundries are primarily concerned with the casting of iron and steel moulds, while non-ferrous foundries are concerned with other metal casting including aluminium, brass/bronze, copper, gunmetal, lead, nickel, tin and zinc.

The foundries produce castings by pouring molten metal into moulds prepared from sand. The moulds are destroyed during manufacture of the casting and the sand after a number of reuses becomes no longer suitable for continued foundry purposes and is disposed.

The residuals in the UFS depend on:

- the metal being cast (iron, steel, aluminium, brass/bronze)
- the casting process (sand casting, investment casting)
- technology employed at the foundry (induction furnace, electric arc furnace, cupola furnace)
- the finish process (grinding, blast, cleaning, coating).

There are two main types of mixtures that are used during sand casting. The first mixture uses sand with a small percentage of clay with water to prepare casts known as 'green sand'. Another popular choice is 'o-bake' sand which mixes sand with a synthetic resin to produce casts. Since green sands use natural clay binders they often contain no synthetic organic resin binders. As a consequence the primary contaminants in UFS from 'green sands' is metals, while UFS from 'o-bake' sands would contain mixtures of both metals and organic residues. In general UFS consists predominantly of the parent sand and residual phenolic resins, clay and binding agents used in the manufacture of moulds.

2.3.1 Physical characteristics

The physical characteristics of UFS, including particle size distribution, pH and bulk density, are all important parameters that may restrict or even enhance certain reuse applications.

The grain size of UFS, regardless of the source, is uniform reflecting the high quality and uniformity of the parent sand. Typically 85–95% of UFS will be between 0.6–1.5 mm, with the remaining 5–12% < 0.075 mm. However the actual grain size distribution will vary with the foundry process. UFS has a moisture content usually < 2% (Siddique 2008).

Foundry sand is also called green sand when the sand used in the moulding process is mixed with a 'natural' clay binder such as bentonite rather than a synthetic resin binder. Green sands, like many of the sands used in the foundry processes, are uniformly graded fine sands with a percentage fines (< 75 μm) ranging from 10–16% (Lee et al. 2004a). Green UFS is typically black in colour and contains a large percentage of fine particles < 150 μm (100 sieve size). UFS from Geelong had almost 65.8% of the sand as fine particles < 0.300 mm (URS 2001) and about 60% of the US federal highways utilised UFS < 0.33 mm.

Foundry sand is typically 94% silicon dioxide (SiO_2). For green sands approximately 10% bentonite clay is often added to the sand to make it more workable for the foundry process with seacoal comprising 3%. Seacoal is a combustible coal mixed with the sand to prevent the sand sticking to moulding bit and has the side effect of turning the sand black during casting.

The pH of UFS varies depending on the type of foundry sand initially used to generate the UFS. When phenolic resins are used as binders the pH of the final UFS is normally alkaline, but pH can vary widely between 4 and 8 (Siddique 2008). A survey of 43 UFSs found that the pH varied from 6.7 to 10.2 with a median pH of 8.8 (Dungan & Dees 2007). The pH of the UFS is important for some beneficial reuse applications, such as soil amendments, where pH > 9 may result in nutrient deficiency if the growth media was composed exclusively UFS and not buffered with some other soil component.

The bulk density of 41 UFSs ranged from 1.57 to 1.66 g cm^{-3} with a mean of 1.64 g cm^{-3} (Basta et al. 2008) which is slightly higher than the typical bulk density of soils which would lie somewhere between 1.2 and 1.4 g cm^{-3}. Higher bulk densities may have negative implications such as lower porosity and poorer crop growth in soil applications but may be attractive in some other construction applications.

2.3.2 Metal contaminants

The potential metal contaminants within the UFS are related directly to the metal being cast at the foundry where the UFS was produced. This results in a wide variety of metal concentrations within individual sands. Some of the total metal concentration ranges from a number of UFS studies are summarised in Table 1 and are compared with the average background levels in soils from across the USA as determined by Shacklete and Beoerngen (1984). Generally, significant total metal concentrations are only observer for Al, Cu, Fe, Mg, Ni, Pb and Zn, and even then are more often comparable to the typical background levels observed in soils. In this comparison of studies, UFS derived from brass foundries were excluded because the total metal concentrations in UFS derived from brass foundries is significantly higher than all other types of foundries. indicating that brass foundries are a significant source of metal contaminated UFS.

The toxicity characteristic leaching procedure (TCLP) is most commonly used to assess the environmental impact of reusing foundry sand. This procedure tests the potential for various metal contaminants to leach from the UFS under acidic conditions. In general, TCLP extracts show that metal concentrations from UFS are below regulatory threshold values, and therefore TCLP assessment typically results in UFS being classified as a non-hazardous waste by-product. However, the adoption of the TCLP as a default test method of assessment is not universally accepted. Some regulatory bodies in the US prefer the Synthetic Precipitation Leaching Procedure (SPLP) or a total analysis of the sand composition in preference to TCLP.

In the USA Robert Dungan has studied foundry sand for many years. In his latest work he examined the total metal composition together with the leachable metal fraction from UFS collected from 43 foundries across the USA (Dungan & Dees 2007). The results indicated that in general metals were not of any environmental concern and had levels less than TCLP extractable limits and that the total metals in the UFS were less than or comparable to metal level in agricultural soils across USA (Dungan & Dees 2007). This study is perhaps the most comprehensive study of the metal characteristics of a large range of UFS and indicated that since none of the UFS exceeded TCLP toxicity characteristic guidelines, UFS have limited potential for leaching (Dungan & Dees 2007).

Table 1. Total metal(loid) concentrations (mg kg^{-1}) in UFS compared with background levels in soils from the USA. UFS data from brass foundries have been excluded.

Metal	Concentration (mg kg^{-1})						
	UFS Studies						US Soils
	A (n=1)	B (n=1)	C (n=3)	D (n=5)	E (n=9)	F (n=41)	G
Al	74 -1020	4240	425 - 1925	283 - 7803		< 311 - 10048	72000
As	< 0.5		< 0.30 - 7.50			0.04 - 4.8	7.2
B	0.7 -4.9			< 11.8		< 19.2	33
Ba			5.63 - 27.2	3.6 - 18.9		< 8.7 - 151	580
Be				< 0.3 - 0.7		< 1.2 - 3.1	0.92
Cd	< 0.2	10	< 0.4	< 2.6	< 0.1 – 0.2	< 5.9	-
Co				< 0.3 - 0.7	< 0.1 - 1.2	< 0.84 - 95.3	9.1
Cr	0.4 - 19.8	30	3.51 - 51.8	< 1.3 - 3.8	< 0.6 – 30	< 1.0 - 149	54
Cu	1.8 - 36	20	3.90 - 137	< 10.2 - 48.3	< 0.1 – 18.5	< 23.1 – 97.6	25
Fe	110 - 2610	1750	1001 - 47480	1207 - 6550	119 - 7652	< 352 - 44320	26000
Mg	4.4 - 19.8	140	252 - 909	< 1693	6.6 - 2178	< 720 - 51574	9000
Mn	0.8 - 17.8		16.8 - 47.6	12.9 - 150	0.5 - 69.7	< 45 - 671	550
Mo	< 0.08 - 0.17		< 0.5 - 6.97	< 1.7		< 4.4 - 9.6	0.97
Ni	< 0.5 -2.5	40	1.96 - 26.3	< 2.6 - 6.5	< 1.4 - 5.9	< 1.2 - 2328	19
Pb	0.6-3.0	30	0.86 - 2.42	< 16.2	< 1.9 - 2.3	< 7.7 - 25.7	19
Sb						< 4.5	0.66
V				1.4 - 3.2		< 7.4 - 9.1	80
Zn	2.5 - 9.6	30	5.32 -7.54	6.2 - 19.3	0.9 – 15.1	< 33.4 - 179	60

A – Owens et al. (2003). Single UFS sourced from an Australian aluminium foundry. 8 replicate samples collected over 28 days.

B – Guney et al. (2006). Single UFS sourced from Turkey.

C – Stehouwer (2006). Three UFSs sourced from foundries in America (two iron and one aluminium foundry).

D – Dungan, RS & Dees, NH (2006b). Five UFSs sourced from foundries in America (two aluminium, two iron and one steel) used to examine earthworm toxicity.

E – Dungan et al. (2006). Four UFS green sands (two iron and two aluminium) and five UFS core sands used to analyse the effect on dehydrogenase activity (DHA).

F – Dungan, RS & Dees, NH (2007). 41 UFS sources from a variety of different foundries across the U.S.

G – Shacklette, HT & Boerngen, JG (1984). Survey of soils of the U.S.

2.3.3 Organic contaminants

The binder system used in the manufacture of sand moulds is the primary source of organic contaminants in UFS and the use of green sand casting, which generally does not involve a synthetic organic binder, has a lower potential for leaching of organic contaminants. Where synthetic organic binders (core sands) are used the main contaminants detected in UFS tend to be acetone, 1,1,1-Tricloroethane and a variety of aromatic compounds (US EPA 2002). Some of the more common organic compounds detected in UFS are summarised in Table 2. Of these only a small number of compounds are currently of legislative concern and routinely screened during testing of UFS and other regulates wastes (Table 3).

Table 2. Organic compounds detected in foundry sand cores (US EPA 2002)

Acetone	Formaldehyde
Benzene	Isopropylbenzene
2-chlorphenol	1-and 2-Methylnapthalene
m/p-Cresol	Napthalene
1,2-Dichlorobenzene	Phenol
1,4-Dichlorobenzene	Tetrachloroethane
Diethyl benzenes	Toluene
Dimethylnapthalenes	1,1,1-Trichloroethane
2,4-Dimethylphenol	1,2,4-Trimethylbenzene
Ethylbenzene	1,2,5-Trimethylphenol
p-Ethyltoluene	Xylenes

Analysis of UFS for organic constituents is challenging. One of the main challenges in determining the potential organic constituents present in UFS is initially identifying the exact formulation of the organic binder system used. Due to the proprietary nature of the foundry sand binders, public information on the composition and relative proportions of common binder and resin constituents is often lacking. The other main problems facing organic analysis of UFS is that some of the organic binder can potentially be altered from its original composition during the foundry process, making analytical quantification of contaminants in a UFS problematic. The casting temperature would be one of the most critical factors determining the fate of organic residues associated with UFS. At sufficiently elevated levels the majority of organic residues would be completely destroyed and this process offers one means of UFS reclamation (Section 3.3.8). However, at lower casting temperature significant proportions of organic binders are likely to survive the casting process. Since aluminum foundries tend to use lower casting temperatures, less organic binders are likely to be burnt off during the casting process and consequently greater concentrations of organic residues would be expected in UFS from aluminum foundries.

Table 3. Selected total organic concentrations (mg kg^{-1}) detected in UFS

Compound	UFS Studies (mg kg^{-1})				
	A (n=10)	B (n=8)	C (n=11)	D (n=4 -34)	E (n=43)
Phenol		5.51 – 7.20	< 0.05 – 12	0.8 -10	< 0.07 - 186
2-chlorophenol					< 0.11
o-cresol (2-methylphenol)					< 0.21- 14.9
m/p cresol (3 and 4-methylphenol)					< 0.08 - 6.11
2,4-Dimethylphenol		0.62 – 2.60			< 0.08 - 4.57
PAH (Total)	0.4 - 228.9		0.22 - 28.7	0.2 - 2.7	
Anthracene					< 0.1 - 0.91
Benz(a)anthracene		0.15	0.01 – 0.33		< 0.1 - 0.19
Fluorene					< 0.04 - 0.83
Naphthalene		1.93 – 4.60	0.05 - 8.3		< 0.03 - 48.1
2-Methylnapthalene			0.01 - 6.3		
1-Methylnapthalene			0.01 - 5.6		
Phenanthrene		0.64 - 1.8			< 0.03 - 1.81
Pyrene		0.32			< 0.03 - 0.53
Formaldehyde	-	< 0.1 - 11.9	< 10		
Diphenylmethane-di-isocyanate			< 1	< 5	

A – Lahl, U (1992)
B – Winkler & Bol'shakov (2000)
C – Ji et al. (2001)
D – Mroueh, U-M & Wahlstrom, M (2002)
E – Dungan, RS (2006)

Although there are a large range of potential organic contaminants the main contaminants in terms of a legislative framework are PAHs and phenols. The studies of Dungan on PAHs and phenols in UFS (Dungan 2006) suggest that neither chloro- nor nitro- phenols are significant constituents of UFS. Similarly, although a large number of PAHs could potentially be found in UFS, the predominance of PAHs decreased with the number of rings in the PAH. Thus while 2 and 3 ringed PAHs such as acenaphthene, acenaphthylene, anthracene, fluorine, naphthalene and phenanthrene were detected, 4 ringed PAHs were just above detection limits and 5 and 6 ringed PAHs were not detected at all (Dungan 2006).

Polyaromatic hydrocarbons (PAHs) are a large group of organic contaminants which consist of at least two conjugated aromatic rings of which naphthalene is probably the most commonly known. PAHs contain a variety of persistent contaminants including the carcinogenic benzo(a)pyrene. The PAHs are formed as a direct consequence of pyrolytic reactions occurring during the foundry process at high temperatures (300–700^{o}C) and reducing conditions where organic binders, such as furan or phenol resins present at 1–10% (w/w), are in part converted to PAHs at high temperatures (Lahl 1992). Thus UFS can potentially contain a number of different PAHs. At least 32 different compounds were detected from 11 different UFS, where although PAHs were detected in all UFS, the level varied with the type of UFS with naphthalene being the most important PAH accounting for about 30% of the total PAHs in all sands (Ji et al. 2001).

The total concentrations of individual PAHs and phenolic compounds determined in 43 UFSs collected from 37 different foundries across 13 American states did not generally exceed regulatory guidelines (Dungan 2006). Only nine of the 43 UFS samples were considered unacceptable for beneficial reuse without remedial treatment. The most commonly detected PAHs were phenanthrene (95%) > naphthalene (93%) = fluorene (93%) > anthracene (79%) >> pyrene (49%), with most of the 16 PAHs screened below detection limits. Naphthalene was generally present in higher concentrations than all other PAHs with the highest individual concentration of 48.09 mg kg^{-1} followed by a maximum phenanthrene concentration of only 1.60 mg kg^{-1}. The maximum permissible concentrations (MPC) in Wisconsin's beneficial reuse guidelines are 600 and 0.88 mg kg^{-1} for naphthalene and phenanthrene respectively (Dungan 2006), indicating that for these sands phenanthrene was more of an environmental concern than naphthalene despite the naphthalene's generally higher concentrations.

The main phenolic compound detected was phenol, which was found in 91% of the UFS studied at concentrations ranging from 0.12–186 mg kg^{-1} (Dungan 2006). Other common phenolic compounds detected were 2-methyphenol, 3- and 4-methylphenol and 2,4-dimethyl phenol at the maximum concentrations of 14.9, 6.1, 12.3 mg kg^{-1} respectively (Dungan 2006). Assuming that 100% of the phenolic compounds are leachable, only 9.3% of the UFSs studied would exceed a 1.2 mg L^{-1} TCLP extractable limit for phenol.

TCLP extraction of a selected number of UFS collected from a range of foundries across the US indicated that generally leachable organic concentrations were < 25 μg kg^{-1} for the majority of potential organic constituents screened for and that only acetone (100 $\pm$ 10 μg kg^{-1} (n=4)) and naphthalene (570 $\pm$ 60 μg kg^{-1} (n=2)) were present in any detectable amounts (Deng & Tikalsky 2007). Similarly, phenolic urethane and phenolic isocyanate binder systems contributed the highest organic content in laboratory leaching tests but none were above 1 ppb (US EPA 2002), and Winkler and Bolshakov (2000) reported that of the 45,000 compounds tested for in groundwater in foundry landfills in Wisconsin none were found to be above 1 μg L^{-1}. These results generally indicated that leachability of organic constituents from UFS may not be a significant issue.

2.3.4 Toxicity testing

To date limited toxicological testing of UFS has been conducted. Microtox™ bioassays conducted on UFS from 13 American foundries when compared to virgin sands collected prior to the foundry process indicated that in general most of UFS from iron foundries had little or no adverse toxicity (Bastian & Alleman 1998). Of the 13 UFS examined, toxicity was observed in only four of the iron foundry sands and was potentially related to the use of a synthetic organic binder rather than a clay-based binder in at least one of these cases. Significant bacterial inhibition and hence inferred toxicity was also observed from two other UFS, one from a steel foundry and the other from an aluminium foundry. Since the bacteria used in the Microtox™ assay (*Vibrio fisheri*) did not usually respond to short-term metal exposure the authors attributed the observed bacterial inhibition (inferred toxicity) to the presence of organic contaminants (Bastian & Alleman 1998). However, no chemical analysis of the UFS studied was undertaken.

Although the relevance of using the Microtox^{TM} test which uses a marine bacterium for assessing terrestrial toxicity is questionable, the bioassay does provide a quick and simple method of assessing relative toxicity of samples and may find applications as a screening tool.

Another measure of toxicity is the dehydrogenase activity (DHA) which is a general indicator of soil microbial health. When UFS was blended with an agricultural soil the DHA decreased, and this was attributed largely due to a reduction in micro-organism populations due to metal toxicity (Dungan et al. 2006). For the five green sand amended soils, green sands containing no origin resin binders, the greatest reduction in DHA was observed for a UFS from a brass foundry that also contained significantly higher levels of metals including Cu, Pb and Zn (Dungan et al. 2006). However, for UFS-containing resin binders the DHA was generally similar to, and in some instances enhanced, relative to controls. This was attributed to the ability of the microbial communities to utilise the resin binders as a carbon source (Dungan et al. 2006). This study indicated that while DHA could find application as a screening tool for beneficial reuse of UFS, its applicability would need to be tested especially where organic binders were used in the foundry process.

Terrestrial dwelling organisms such as earthworms have long been considered good indicators of soil toxicity because of their intimate contact with the soil environment. Standard bioassays, such as those endorsed by the OECD (OECD 1984), exist for assessing both chronic and acute toxicity.

Dungan and Dees (2006) studied the toxicity of a range of UFS using earthworms. UFS was collected from six different foundries and blended with an artificial soil at three ratios 10, 30 and 50% (w/w) on a dry weight basis. The UFS collected included samples from all of the major foundry types including UFS derived from two aluminium, one brass and two iron green sand foundries as well as one UFS derived from a phenolic urethane resin sand foundry. Toxicity of the UFS-artificial soil mixtures to adult earthworms (*Eisenia fetida*) was assessed after 28 days' exposure by monitoring earthworm survival and metal uptake. For five of the UFS there was no statistically significant difference between earthworm survival in the UFS-soil blends and the control soil. However, for the UFS-soil blend from the brass foundry statistically significant earthworm mortality was observed increased with the percentage of UFS incorporated into the blend. The increase in toxicity was associated with a significant increase in the DTPA extractable Cd, Cu, Pb and Zn from these UFS-soil blends when compared to all other UFS-soil blends. Dungan and Dees (2006) concluded that UFS from aluminium, iron and steel foundries did not pose a significant ecotoxicological threat but UFS from brass foundries was not suitable for beneficial reuse unless the material was completely encapsulated to prevent metal leaching.

2.4 Current international regulatory practice

The current international regulatory practice for UFS disposal and reuses varies widely. In this section some of the ways in which the issues of UFS reutilisation are being handled are discussed on a country-by-country basis.

2.4.1 Finland

Some of the legislative practice in Finland relating to by-products and recycled materials was reviewed by Mrouch and Wahlström (2002). The legislative requirements under the Finnish Environmental Protection Act generally require an environmental permit to be granted for the utilisation of waste which is what the legislation classes all industrial by-products as. These permits are granted by the local environment authority for amounts < 5000 tonnes and by the regional environmental authority for larger amounts (Mrouch & Wahlström 2002).

However, the road to granting a permit is long and tedious, taking more than four months, where the onus is on the applicant to supply sufficient information on the properties of the waste and to investigate environmental compliance. The applicant also has to develop plans to prevent environmental and occupational hazard with the aim of showing that the waste utilisation has no issues. Mrouch and Wahlström (2002) attribute the long and complicated permit process as being one of the biggest barriers limiting the use of industrial by-products. One encouraging aspect of the Finnish legislation is that short-term pilot studies are exempt from permit applications, which is a positive move to encourage attempts at beneficial reuse.

The Finnish government identified phenol as being a contaminant of particular concern for UFS, requiring that UFS with a phenol content > 100 mg kg^{-1} could not be disposed of to a normal licensed landfill and that special arrangements had to be made (Morley 1991).

2.4.2 Germany

The hazardous site commission of Northrhine-Westfalia set a limit value for benzo(a)pyrene (BAP) as 1 mg kg^{-1} on a dry weight basis in 1988 (Lahl 1992).

2.4.3 United Kingdom

The United Kingdom has some of the most advanced and holistic policies in terms of waste reuse in the world (Harris 2007). Recent changes in legislation have been driven by European legislation particularly the EU Landfill Directive and the EU Waste Directive.

The EU Landfill Directive resulted in a landfill tax being introduced to the UK in 1996. The landfill tax progressively increases annually, being £24 per tonne in 2007 and rising by £8 per year until at least 2010 (Harris 2007). Thus the landfill tax acts as a driver for change over a defined time period. The revenue from the landfill tax was utilised by the UK Government to implement the Business Resource Efficiency and Waste (BREW) program designed to assist industry to reduce waste by providing free advice, support and longer term research programs. The BREW program therefore returns the landfill tax to the industries and simultaneously encourages them to reuse their waste streams.

In comparison, the EU Waste Directive led to barriers for reuse by labelling a wide variety of industrial by-products as 'waste' and introduced bureaucracy and financial burden that accompanied handling 'wastes'. The UK Environmental Agency responded by moving to develop a series of waste protocols whereby industrial by-products would not be considered 'waste' if they met certain criteria. To date limited numbers of protocols have been developed and UFS is not one of them.

2.4.4 United States of America

The United States suffers from regulatory inconsistencies across America with regard to industrial by-product reuse. Some states had generic requirements for all industrial by-products while other states have developed specific guidelines for selected by-products including foundry sand (US EPA 2002).

An overview of the framework used by 18 states in America to regulate non-hazardous industrial solid waste and the industrial waste re-use programs was conducted by the US EPA in partnership with American Foundry Society (US EPA 2002). States were chosen for inclusion in the review based on the following criteria:

- states had the largest number of foundries
- states had **active** industrial waste reuse programs
- states had developed guidance specific to the beneficial reuse of UFS
- states had worked collaboratively with the foundry industry.

While 11 of the states studied required rules developed generally for industrial solid wastes, seven states had developed rules and policies specifically for beneficial reuse of UFS.

There was some commonality between all states. For instance all states required some form of testing to initially characterise the UFS as being non-hazardous, although the exact testing required varied with each state (Table 4). The testing usually required a leaching test such as TCLP, but five states also required a total analysis of the waste itself and five states required a detailed sampling and analysis plan (SAP). With the exception of three states, all states compared to the results of testing to specified thresholds values to ascertain whether the UFS could be classified as non-hazardous. In the majority of cases this was either direct to the Resource Conservation and Recovery Act (RCRA) levels or some variable percentage of these values or alternative via comparison to the federal drinking water guidelines.

Seven states had introduced a waste classification system in an attempt to encourage beneficial reuse of UFS. The idea was that there would be few restrictions on using an industrial waste to manufacture another product such as cement, because this would have a very low potential for adverse environmental impact. However, the application of UFS to agricultural soils would have greater restrictions and greater potential for adverse environmental or human impacts. By classifying wastes into categories based on waste quality, 'cleaner' wastes can be reserved for specific applications and cleaner wastes have fewer restrictions on reuse.

Some of the disadvantages of a waste classification system for UFS are that there would be an initial need to commit resources and time to develop a classification structure and this would remove some of the flexibility allowed when reviewing UFS use on a case-by-case basis. However, once developed, a waste classification system would allow for streamlined approvals and review processes. The main challenge would be to ensure that the waste classification levels for UFS constituents are stringent enough to provide environmental protection for all possible reuse scenarios or to predefine what UFS reuse scenarios may be adopted. The waste classification system must also allow for the known constituents of UFS that are potentially of environmental concern now and that may become of concern in the future. This may be problematic with the development of new organic binders.

In Illinois, UFS can be classified as beneficially usable, potentially usable, low risk or as chemical waste depending on a range of maximum leachate concentrations for each constituent associated with each label, and only UFS that qualifies as being ‘beneficially usable’ can be reused.

Table 4. Characteristics of United States industrial waste reuse programs including exemption and permit techniques for UFS

State	Reuse program	Testing required			Threshold concentrations	Waste classification categories	Authorisation process
		Leachate	Total	SAP			
Alabama	General	TCLP			50% of RCRA	No	Prior notice
California	General	TCLP			RCRA	No	
Illinois	UFS	TCLP			DWS	Yes	Prior notice Waste exemption
Indiana	UFS	TCLP		Yes	Variable % of RCRA	Yes	Prior notice Waste exemption
Iowa	UFS	TCLP			90% of RCRA	No	Waste exemption
Louisiana	General	TCLP	Yes		NO	Yes	General permit
Maine	General	TCLP	Yes	Yes	Not specified	No	General permit
Massachusetts	General	TCLP			NO	No	
Michigan	General	TCLP		Yes	10% RCRA	Yes	
Minnesota	General	TCLP			RCRA	No	
New York	General	TCLP			RCRA	No	
Ohio	UFS	TCLP			30 x state DWS	Yes	Prior notice Waste exemption
Pennsylvania	General	TCLP	Yes	Yes	Variable % or RCRA	No	General permit
Rhode Island	General	Not specified			NO	No	
Tennessee	UFS	TCLP			10x DWS	No	Prior notice Waste exemption
Texas	General	TCLP			Unknown	Yes	Prior notice
West Virginia	General	TCLP	Yes	Yes	DWS	No	
Wisconsin	UFS	TCLP	Yes		Variable multiple of DWS	Yes	Prior notice Waste exemption

RCRA TC Levels = Resource Conservation and Recovery Act (RCRA) Toxic Characteristic Threshold Levels (TCLP extractable)
DWS = Drinking Water Standards
SAP = Sampling Plan Required

In Ohio, new beneficial reuse guidelines are being proposed, but previously Ohio had allowed several beneficial reuse programs including application to land as manufactured soil by setting non-toxic threshold levels from a TCLP extract at 30 times the Ohio maximum allowable concentration in drinking water Table 5.

Table 5. Regulatory metal levels for UFS in the United States of America

Element	TCLP USA (mg L^{-1})	TCLP Ohio EPA 1994 (mg L^{-1})	NPDWS (mg L^{-1})	NSDWS (mg L^{-1})
Ag	5.0			0.1
Al				0.05
As	5.0	1.5	0.01	
B			2.0	
Ba	100	60	0.004	
Be				
Cd	1.0	0.15	0.005	
Co			-	-
Cr	5.0	3.0	0.1	
Cu			1.3	1.0
Fe			-	0.3
Hg	0.2	0.06	0.002	
Mg			-	-
Mn				0.05
Mo			-	-
Ni				
Pb	5.0	1.5	0.015	
Sb			0.006	
Se	1.0	1.0	0.05	
Tl			0.002	
V				
Zn				5.0

NPDWS = National Primary Drinking Water Standard

NSDWS = National Secondary Drinking Water Standard

In Indiana, a simple number system is used to classify waste into four categories (Type 1, Type II, Type III and Type IV), again based on exceedance of predefined leachate concentrations for each constituent, with Type IV wastes being the cleanest and therefore having the most potential reuse options.

For regulatory agencies the burden is to develop tables of constituents and associated safe reusable levels either based on totals or leachate concentrations. Several American authorities do precisely this. However once this is established the burden of compliance switches to the manufacturer who must via ongoing testing ensure that the UFS is compliant with regulations.

Research is required to establish not only the types of constituents that must be detected but also the magnitude of the values to ensure protection of environmental and human health.

As with the UK, the most streamline procedure for beneficial reuse adopted in the US is waste exemption which exempts by-products from waste requirements provided stringent criteria are met. The criteria can be set at different levels depending on the end-use. For example in Illinois UFS meeting the leachate concentration thresholds can be used without notifying the state unless the UFS is to be reused for land application.

Across the USA a variety of waste reuse programs have been implemented by state authorities. The majority of these are general reuse programs where the UFS is only one of many waste or industrial by-products considered by the legislation, while in a few states specific waste reuse programs have been instigated specifically for UFS (Table 4).

In many of these states effort has been made to streamline the process of approvals for waste reuse. These streamline processes in order of increasing speed and simplicity include: (i) Project Specific Permits, (ii) General Permits, (iii) Prior Notice and (iv) Waste Exemption. The simplest of these processes, waste exemption, simply means that the waste is exempt from classification as an industrial waste. At least six states (Table 4) have adopted waste exemption where waste meeting the leachate concentrations can be used without notifying the state provided the reuse is not for land application. Prior notice is also popular in some states, requiring that the state be notified of the proposed reuse and that the UFS be assessed and classified following TCLP extraction of metals, but no permits are granted. General permits are issued by some states which allow multiple applicants to engage in a specified reuse application. For example, in Louisiana a land application permit will allow UFS to be permitted for beneficial reuse at multiple locations provided set criteria are met and it is only one waste stream.

Based on the Smith et al. database (2005) results, guidelines soon to be released suggest that UFS should contain concentrations no higher than the 95th percentile of background U.S. soils if they are to be reused in soil applications (Table 6). It is likely that in the future this methodology will be adopted in the US as a simple screening method for all UFS beneficial reuse applications.

Table 6. Guidance limit (mg kg^{-1}) equivalent to 95th percentile of the USA background soil levels

Element	Guidance limit (mg kg^{-1})	Element	Guidance limit (mg kg^{-1})
Al	74600	Mn	1630
As	12	Mo	2.2
Ba	840	Na	19400
Be	2.3	Ni	37.5
Ca	66600	Pb	38
Cd	0.6	Sb	1.39
Co	17.6	Se	1
Cr	70	Sn	2.5
Cu	30.1	Sr	458
Fe	42.6	Tl	0.7
Hg	0.08	V	119
K	28400	W	1.6
Mg	18800	Zn	103

Source: Dungan et al. 2008

2.5 Current Australian regulatory practice

In Australia the NEPM (NEPC 1999) provides clear generic guidelines, both HILs and EILs, for a variety of contaminants that may be potentially present in soils and waters. However, the NEPM guidelines in themselves are generally insufficient for classifying UFS and consequently there is an overall lack of clarification by the state EPAs as to what criteria would be suitable for classification of UFS.

Recently, some moves have been made to push for a national approach to the beneficial reuse of industrial residues for land application (EPHC 2006). This article does not specifically mention UFS, although it does mention a large number of other materials, and no details are given. The push seems to be to direct enquiries to the state government agencies.

The application of metals in agricultural practice is well established via biosolid guidelines especially in relation to biosolid applications, but does not well address the issue of organic contaminants. For instance, endocrine-disrupting chemicals have been completely ignored and in all likelihood organic residues resulting from the use of sand binders in UFS have not even been considered.

The states and territories generally characterise and regulate industrial residues in different ways and there is in general no consensus. Some of the regulatory techniques used in different Australian states are discussed below.

2.5.1 New South Wales

The Department of Environment and Conservation NSW (DEC), together with NSW Department of Primary Industries (DPI), have jointly developed the *Residual Wastes Regulation* which became effective on 1 December 2005 as a precautionary approach to land application of wastes to land for the application of growing plants. Under this regulation foundry sands and foundry filter bag residues are specifically prescribed as residue wastes and are prohibited from being applied to land for growing plants. Furthermore, any substance which incorporates the waste residue, such as a compost or horticultural product, is also prohibited from land application unless the DEC issues an exemption to the regulation.

In the case of UFS application to land for agricultural use the DEC may grant an exemption to the regulation if:

1. The application of UFS to lands is beneficial for growing plants.
2. The likely contaminants present in the UFS need to be fully identified and it must be shown that these contaminants and the UFS effect on soil (pH, salinity and soil structure) are not detrimental or in any other way cause harm to the environment or to humans.
3. UFS needs to have industry associations that develop QA and QC programs that ensure that all UFS is well characterised and of a consistent quality.
4. The application for exemption maybe permitted if application has been permitted in another Australian jurisdiction.

An exemption guideline was developed for foundry sands by the DEC NSW which exempted the land application of UFS from waste regulations provided the responsible parties complied with the relevant exemption (EPA NSW 2006). However, the exemption 'known as the foundry sand exemption 2005' commenced on 1 December 2005 and was only valid until 1 April 2006 (NSW Government Gazette 2005). The exemption only applied to UFS from iron and/or aluminium foundries and had to be mixed or blended into compost or an artificial soil at a rate not greater than 10% dry volume and could not be directly applied to land (NSW Government Gazette 2005). It is not known if further exemptions were made subsequently or why the exemption was allowed for such a short space of time. It is likely that recent changes to legislation have replaced any former exemptions.

There appears to be no guidelines by which to not classify the UFS as a waste and ALL foundry sand generated by a foundry is considered waste under the regulation. Ideally it would be beneficial if an environmental guideline such as *Use and Disposal of Biosolids Products* (SA EPA 1999) was developed for UFS. DEC policy claims that 'the potential contaminants in waste materials are almost infinite and there is currently insufficient knowledge to set acceptable limits for all potential contaminants'. However specifications for contaminants such as UFS could be submitted to DEC for approval by an industry group should they be developed.

The Department of Environment and Climate Change (DECC) NSW recently changed the requirements for waste management and regulation. These changes became effective on 28 April 2008 and principally resulted in replacement of the *Environmental Guidelines: Assessment, Classification and Management of Liquid and Non-liquid Wastes with the Waste Classification Guidelines*, which was divided into two parts:

- Part 1: Classifying Wastes
- Part 2: Immobilisation of Waste

The most relevant of these to the re-use of UFS is the waste classification guideline. The guideline is extensive but is applicable to wastes in general and makes no specific reference to UFS. The guideline indicates that waste should be classified into 6 groups that pose risk to the environment and human health:

1. special waste
2. liquid waste
3. hazardous waste
4. restricted solid waste
5. general solid waste (putrescible)
6. general solid waste (non-putrescible).

UFS would not be considered a special waste as this category is reserved for clinical and asbestos waste as well as waste tyres, nor could UFS be classified as liquid waste due to its physical properties. Similarly UFS would not be considered a hazardous waste under the guideline nor would UFS be considered general solid waste as this category is predominately reserved for household wastes. Therefore UFS would typically initially be classified as a restricted solid waste category depending on the assessment of total and extractability contaminant levels. Chemical testing would then be applied to ascertain if the waste should be classified as general, restricted or hazardous waste.

In order to classify a restricted waste further, the guideline recommends that samples should initially be screened using a specific contaminant concentration (SCC) test. This is a simple determination of the total contaminant concentration of the material under review compared to two contaminant concentration thresholds (CT1 and CT2) specified in Table 1 of the guideline for an array of contaminants of concern, where CT1 < CT2 and in general CT2 = 4 x CT1.

Based on the SCC test alone a waste can be classified as either a general solid waste or a restricted solid waste, dependent on how individual test parameters compare with threshold concentrations as given below:

General solid waste	Waste ≤ CT1
Restricted solid waste	Waste ≤ CT2

Further to this classification a combination of total contaminant concentration (SCC) in combination with a TCLP extractable contaminant concentration (TCLP) could be used to classify wastes further, especially if CT guidelines were not available. Two threshold levels for both extractable (TCLP1 and TCLP2) and total (SCC1 and SCC2) individual contaminants are tabulated in Table 3 of the guideline. Waste can be classified via measuring the level of contaminants in the waste relative to these threshold criteria as given below (where SSC2 > SSC1 and TCLP2 > TCLP1 and in most cases TCLP2 = 4 x TCLP1 and SSC2 = 4 x SSC1).

$$\text{General solid waste} \begin{cases} \text{Waste} \le \text{SCC1} \\ \text{Waste} \le \text{TCLP1} \end{cases}$$

$$\text{Restricted solid waste} \begin{cases} \text{SCC1} < \text{Waste} \le \text{SCC2} \\ \text{TCLP1} < \text{Waste} \le \text{TCLP2} \end{cases}$$

$$\text{Hazardous solid waste} \begin{cases} \text{Waste} > \text{SCC2} \\ \text{Waste} > \text{TCLP2} \end{cases}$$

The option of a screening level for the classification of waste based on total concentrations is a useful tool for waste generators who can utilise a simple total contaminant assessment prior to leachability testing. However, the rationale is not clear behind the simple four-fold increase in contaminant levels that would see a waste become classified as restricted over general, nor do the CT screening values seem to be uniformly related to SCC values.

Comparing the typical levels of contaminants found in UFS from around the world in Section 2.3 with the DECC guideline for waste classification would see UFS simply classified as a general solid waste in the vast majority of cases.

2.5.2 South Australia

In South Australia, the state EPA has issued guidelines for the classification and disposal of UFS into two classes based on both total metal and organic constituent concentrations, as well as maximum leachate concentrations (SA EPA 2003). Class 1 UFS can be disposed of to landfill while Class 2 UFS must be disposed of to clay-lined landfills with a leachate collection system. This guideline does not encourage recycling or reuse of UFS since it sets no levels at which the UFS would be certified as fit for reuse; it only states that UFS must be classified and subsequently disposed of to landfill unless it is recycled or reused, but no further details are given. This guideline does mention levels for a few organic compounds such as total phenols and specifically benzo(a)pyrene, but does not mention other organic binders that may have been used in the foundry process.

The South Australian guideline specifically concerned with the general environmental management of foundries (SA EPA 2003) indicates that most UFS is disposed to landfill, but does indicate that where feasible, sand reclamation or on-site recycling should be considered. This guideline also encourages consideration of recycling UFS for external applications such as road base but gives no guidance on how to actually do this.

2.5.3 Queensland

The Queensland EPA seems to have advised for at least one project that a criterion of phenol (leachable fraction) of 0.2 mg L^{-1} would apply (URS 2001) but this value did not appear in any EPA publication. Under this recommendation UFS having an extractable phenol concentration < 0.2 mg L^{-1} could be classified as Solid Inert and therefore classed as non-hazardous industrial wastes used for any purpose.

Queensland EPA developed an environmental guideline, *Beneficial re-use of ferrous foundry by-products* (EPA 1999). It is not known if a similar guideline was developed to cover non-ferrous foundries. This guideline also acknowledged that while by-products such as UFS from green sands, alkali phenolic, silicate and furan-bonded sands may present little potential harm and may be suitable for use in any capacity, this should not be presumed and needed to be verified with TCLP and total contaminant testing across a stockpile over a period of time to confirm that levels were well within acceptable levels (EPA 1999).

This draft guideline also discussed ways to address the potential environmental impacts and threshold levels of various contaminants based on threshold levels established by ANZECC/NHMRC for contaminated soils because many of the foundry products have soil-like characteristics (Harris 2007). This guideline also indicated three levels of investigation corresponding to background levels, environmental health investigation levels and health investigation levels as described under the NEPM (NEPC 1999) with some modifications.

The Queensland EPA in a guideline for waste management entitled *Seeking an EPA exemption for trackable wastes* give tables of contaminant threshold values adapted from the New South Wales Environmental Protection Authority *Guidelines for Solid and Liquid Waste*, the Australian and New Zealand Environment and Conservation Council, the National Health and Medical Research Council *Contaminated Soil Investigation Thresholds* and the United States Environmental Protection Agency criteria. These tables are simple to use. When the concentration in the trackable waste is above threshold value a more detailed study, such as TCLP, is required otherwise the waste can be exempt from tracking. This is of limited use because exemption from tracking does not mean the waste is no longer classified as a waste material that still needs approvals and licences to be disposed of or recycled. However, it does allow for easier deregulated transportation of UFS from foundries to other end-users for recycling or reuse.

2.5.4 Victoria

EPA Victoria seems keen to substantially reduce industrial waste production and disposal to landfill by 2020. In 1999 the Victorian government imposed a modest $10/tonne levy on hazardous waste going to landfill which rapidly increased to $130/tonne and is scheduled to be $250/tonne by mid-2008. Some of the $30 million dollars in revenue from this levy is expected to be put into projects and technologies on waste minimisation. This is a dedicated push by the government to encourage industries to have a financial incentive to recycle or reuse industrial waste, including UFS.

EPA Victoria uses a three-tiered classification of solid industrial wastes which requires waste generators or treaters to classify waste as either category A, B or C based on comparison of both total and TCLP extractable concentrations with a table of guidelines levels (VIC EPA 2005).

The tables are extensive and list 25 inorganic and 45 organic contaminants, as is appropriate for a general classification guide for all potential industrial wastes, but not all of the prescribed contaminants would be found in UFS. The table includes two TCLP thresholds ($ASLP_1$ and $ASLP_2$) and two total thresholds (TC_1 and TC_2) and the wastes are characterised into categories, B or C as described below in relation to these four thresholds.

$$\text{Category A:} \quad \begin{cases} \text{Waste} > TC_2 \\ \text{Waste} > ALSP_2 \end{cases}$$

$$\text{Category B:} \quad \begin{cases} TC_1 < \text{Waste} < TC_2 \\ ALSP_1 < \text{Waste} < ALSP_2 \end{cases}$$

$$\text{Category C:} \quad \begin{cases} \text{Waste} < TC_1 \\ \text{Waste} < ALSP_1 \end{cases}$$

Category A waste is extremely hazardous and cannot even be moved to long-term containment facilities without prior treatment, while Category B waste is still hazardous, requiring a high degree of control, but can be moved to long-term containment facilities without prior treatment. Neither Category A nor category B waste can be disposed of to landfill without significant prior treatment. Category C wastes pose only a low hazard and can be disposed of to an EPA-licensed municipal landfill. Category C waste is further divided into two classes, C(1) waste which is highly odorous, dusty or contains non-persistent organic wastes and C(2) all other low environmental risk waste. UFS would normally be categorised as a Category C(2) waste.

2.5.5 Western Australia

In Western Australia the Department of Environmental and Conservation (DEC) is responsible for administering legislation pertinent to by-product reuse under the *Environmental Protection Act 1986*. As with other states, while the application for biosolids to land is well catered for in Western Australia by the *Draft Guidelines for the Direct Land Application of Biosolids and Biosolid Products* (2002) there is no current procedure for gaining approval for the reuse of a by-product. Approval for specific application can be obtained from the EPA by lodging a 'Notice of Intent' which triggers a formal 'Public Environmental Review', or alternatively DEC considers cases on a case-by-case basis.

2.5.6 Interstate comparisons and national guidelines

There are currently no national guidelines governing UFS reuse or even general waste disposal and each state develops its own guidelines independently. Comparison of selected state legislative guidelines for UFS or general wastes indicated that there was considerable variation in the total permissible levels of both metallic and organic residues between states (Table 2.7). While the New South Wales and Victorian guidelines were generally similar, the guidelines set by the South Australian and Queensland EPAs were normally lower than either the Victoria or New South Wales values. The state values also differed significantly from national soil investigation levels and in general the values set for UFS at the state level were significantly higher than those of the relevant EIL or HIL. This may have been due to the assumption of some dilution of the UFS when reused, since it is unlikely that UFS would be applied to a soil or elsewhere at concentrations greater than 10%, and so some practical dilution of the UFS is expected. Only the Queensland EPA had adopted values similar to the national guidelines for soil contamination investigation (Table 7).

Table 7. Variation in legislative guideline values for selected metal(loid) and organic chemical content of biosolids, soil, industrial waste, UFS, and ($mg\ kg^{-1}$). All values are on a dry weight basis.

Element	SA EPA Class 1 ($mg\ kg^{-1}$) UFS	NSW DECC SCC1 ($mg\ kg^{-1}$) General Waste	VIC EPA TC_1 ($mg\ kg^{-1}$) Hazard Waste	QLD EPA ($mg\ kg^{-1}$) UFS	National MPC[a] ($mg\ kg^{-1}$) biosolid	National EIL[b] ($mg\ kg^{-1}$) soil	National HIL[c] ($mg\ kg^{-1}$) soil
Arsenic (As)	200	500	500	20	20	20	100
Beryllium (Be)	40	100	100	-	-	-	20
Cadmium (Cd)	30	100	100	3	3	3	20
Cobalt (Co)	170	-	-		-	-	100
Chromium (Cr)	12%	1900	500	300	-	400	12%
Copper (Cu)	2000	-	5000	60	200	100	1000
Lead (Pb)	1200	1500	1500	300	200	600	300
Manganese (Mn)	6000	-	-	500		500	1500
Mercury (Hg)	30	50	75	1	1	1	15
Molybdenum (Mo)	-	1000	1000	-	-	-	-
Nickel (Ni)	600	1050	3000	60	60	60	600
Selenium (Se)	-	50	50		-	-	-
Zinc (Zn)	14000	-	35000	500	250	200	7000
Benzo(a)pyrene	2	10	5			1	
Benzene	5	18	4	1			
Ethylbenzene	100	1080	1200				
Formaldehyde				10			
Toluene	50	518	3200				
PAH (Total)	40	200	100				
Phenolics (Total)	17000	518	560	10		8500	
TPH (C1-C9)	100	650 [d]	650[d]				
TPH (> C9)	1000	10000[f]	10000			61690[e]	
Xylene	180		2400				

a. Maximum permissible concentration (MPC) of contaminants in soils for food production which is equivalent to the upper limit of metal(loid) concentration in Grade A biosolid (SA EPA 1999).

b. EIL = Ecological Investigation Levels (NEPC, 1999; ANZECC/NHMRC 1992)

c. HIL = Health-based Investigation Levels (NEPC 1999)

d. TPH (C6-C9)

e. Total TPH C16-C35 (NEPC, 1999; ANZECC/NHMRC 1992)

f. Total TPH C10-C36 (DECC waste guideline 2008)

2.6 Summary and conclusions

The information reviewed in this section indicated that UFS sand had a range of total metal and leaching characteristics which varied widely with the foundry producing the UFS. While total metal analysis has been widely determined on many UFS and along with TCLP is routinely performed for assessing UFS suitability for number of applications including landfill disposal, analysis of the organic components of UFS is less widely observed. This probably relates to the predominance of green sands for casting which contain no resin-binding materials. Toxicity testing of UFS is limited, but studies to date indicate that UFS derived from iron or aluminium green sand foundries is safe while UFS derived from brass foundries is potentially toxic and should not be beneficially reused.

Likewise legislative controls vary widely worldwide. Most legislation is phrased in terms of monitoring either total concentration or TCLP extractable metals, or a combination of both scaled with respect to the local environmental guidelines. These guidelines can either be a background soil level or in the case of TCLP extractable contaminates are more often related to some scalar factor of the local drinking water guidelines.

3. Disposal and options for beneficial reuse

3.1 Introduction

While there are a large number of beneficial reuses for UFS, the adoption of these value-adding alternatives has been slow because of the expediency and relative cheapness of UFS disposal to landfill. In the future as landfill becomes an increasingly more expensive option due to decreasing space at current landfills, it is likely that reuse options will become increasingly more attractive.

3.2 Disposal options

UFS is an industrial by-product that is normally classified as a waste unless specific criteria are met. When classified as a waste unless treated, reused or recycled the UFS will typically be disposed of to landfill. Pending classification most regulatory frameworks would require the UFS to be treated as a regulated waste. This would typically require segregation of UFS from other wastes and stockpiling or storing of the UFS, preferably in covered areas to avoid the movement of dust off-site until disposal.

If classified as a regulatory waste UFS would also require permits to transfer the waste off-site to landfill or to any further reuse application. However, some regulatory bodies may allow applications for tracking exemption for UFS that meets predefined criteria.

Disposal of UFS is only to EPA-licensed municipal landfills and strict penalties are imposed for any non compliance. In Victoria, Consolidated Waste Bulk Bin and Transport Pty Ltd was fined $7,500 and ordered to pay $2,000 in costs for dumping 200 tonnes of foundry sand to a pistol club when the originating foundry had paid for the UFS to be disposed of to a licensed landfill. Vic EPA issued a clean-up notice and the waste was removed from the pistol club and deposited at licensed landfill.

3.3 Beneficial reuse options

A large range of beneficial reuse options have been suggested throughout the literature including:

- agricultural soil conditioner
- bedding sand
- bitumen production
- brick and paver manufacture
- cement and concrete production
- compost additive
- cover material
- drainage sand
- flowable fill (replacement for stabilised sand)
- landscaping
- loam production (related to soil conditioner function above)

- roadbase and highway construction
- sand reclamation
- sand bags (for emergency flood control)
- topsoil manufacturer
- novel sorbent options (remediation practice)
- mineral wool products.

These potential applications can be subdivided into three main categories: (i) manufacturer products, (ii) geotechnical applications, and (iii) soil-based applications. Under the manufactured product category the UFS is used as a substitute for another fine aggregate sand used to produce commercial materials. The most common manufactured product applications include cement and asphalt production. Geotechnical applications include all construction type work where UFS is used as a component and as such, UFS has found a home in a number of applications including flowable fill, retaining walls and embankments as well as road base. The final class involves the reuse of UFS as a component of soil. In these cases UFS is blended or composted with organic matter to obtain a soil capable of being utilised by the landscape or nursery industry. This latter use is the most contentious and regulatory bodies have the most cautious approach to this because of the direct association of humans via direct exposure to the product or indirectly to the food cultivated using the product.

In America, funding from the Wisconsin Cast Metals Association and the State of Wisconsin Recycling Market Development Board led to the development of a database on beneficial reuse of foundry by-products (Abichou et al. 1998). This database included a technical review of 90 projects from across 14 American states and two locations in Canada, and covered a variety of projects including many of those detailed above. The purpose of the database was to identify materials and markets that could utilise UFS and any areas requiring further research (Abichou et al. 1998). The major findings from this review have been incorporated and discussed under the relevant headings below.

One thing to note is that in order to move UFS off-site, the UFS would generally need an exemption if it is still classified as a waste. There would therefore be a reason to keep the process on-site until levels are acceptable, or exemptions applied for to allow movement off-site for recycling and reuse.

3.3.1 Soil conditioner and manufactured soils

UFS can be used to produce a manufactured soil for agricultural and horticultural applications (Jing & Barnes 2002). The dark colour of the UFS sand, especially product derived from green sands may be appealing for manufactured soil applications. For green sand derived UFS the presence of clay from bentonite also increases the capacity of the manufactured soil to retain nutrients and therefore has indirect fertiliser improvement. The advantages for using UFS as a component of a manufactured soil would be the access to trace elements and the conversion of compost into a loamy topsoil and to increase the drainage characteristics of clayey soils. The pH of the sand, especially when alkaline can also be used for pH adjustment of otherwise acidic soils. UFS can also act as a bulking agent for composted yard waste to produce topsoil.

Thus, replacing natural sand with UFS for agronomic applications has been suggested as an excellent market for beneficial reuse, and the nursery industry presents an excellent opportunity from both small and large foundries (Abichou et al. 1998).

Saturated hydraulic conductivity, which is a measure of the ability of a soil to transmit water, is an important physical characteristic of agricultural soils and addition of UFS could potentially improve a poor soil's hydraulic conductivity. Dungan et al. (2007c) blended four agricultural soils with a range of UFS at 10% increments of UFS (w/w) on a dry weight basis, up to a maximum UFS of 50%. The UFS was derived from three iron green sand foundries, three aluminium green sand foundries and two steel phenolic urethane resin sand foundries. In general, the addition of UFS increased the hydraulic conductivity of all the agricultural soils and hydraulic conductivity increased with the percentage of UFS present, except when the UFS contained a significant sodium bentonite component. In this case, the lower hydraulic conductivity was attributed to swelling of the sodium bentonite (Dungan et al. 2007c).

The American Agricultural Research Service (ARS), which is an arm of the US Department of Agriculture (USDA), initiated a review to assess the safety of UFS for soil-related application in 2003. The ultimate goal was to produce a guidance document to assist regulatory authorities in developing or improving beneficial reuse regulations. The draft was completed by April 2008 and was undergoing peer review by the US EPA (Dungan 2008, personal communication). A joint workshop held in conjunction with FIRST, AFS, USDA and US EPA was scheduled for 23 July 2008. The Ohio State University will host the forum at its Columbus, Ohio Campus and the recent USDA research will be highlighted. This research indicates that ferrous and aluminium UFS can safely be used to manufacture speciality soils (Dungan et al. 2008).

Recently, as a prelude to the Ohio workshop, a Beneficial Reuse of Industrial Materials Summit was held in Denver, Colorado (31 March – 3 April 2008) where four eminent scientists discussed the Beneficial Use Guidelines Development – Foundry Sands, where the development of guidelines for the application of UFS to agricultural soils was specifically discussed. This venue was where Dungan unveiled their beneficial guidelines. The actual guideline document is under review by the US EPA so cannot be released. However, the presentations given at the Denver Summit and discussions with Dungan (2008) indicate that the proposal is that UFS can be used in manufactured soils or other soil-related applications as long as trace element concentrations do not exceed the 95th percentile concentrations of background soils (Dungan et al. 2008, personal communication). This approach would seem to be valid and applicable to local conditions in other countries as it builds on existing knowledge regarding local soils.

A number of plant studies have been used to assess the metal availability of UFS. Dungan and Dees (2007) used three plant species, spinach, radish and perennial ryegrass, to assess metal uptake from sand blends containing up to 50% UFS. A total of six UFS including two sands from iron, two aluminium green sand foundries and two phenolic urethane resin sands derived from UFS were examined. They concluded that for all plant species and UFS considered, heavy metal uptake was generally not of concern (Dungan and Dees 2007). Similarly, plant studies conducted in Australia using three plant species, carrot, silverbeet and tomato, and a single UFS from an aluminium foundry incorporated into potting media up to 8% UFS showed that metal uptake by plants was not different to controls having no added UFS (Owens et al. 2003).

Stehouwer (2006) conducted greenhouse experiments on the utility of using green UFS from two iron and one aluminium foundry in manufactured soils. The UFS were chosen because they represented three different binder systems commonly used in casting: (i) phenolic urethane, (ii) furfuryl alcohol, and (iii) Shell. The final UFS blends, obtained by mixing UFS with compost and subsoil on a dry weight basis in the ratio 12:3:4 (UFS:organic matter:subsoil), had a sandy loam texture. Ryegrass was grown in the UFS blends and the leachate monitored. Ryegrass grew well in all UFS blends in comparison to control topsoils and there was no evidence to suggest that the presence of UFS increased plant uptake or leaching loss of trace elements of environmental concern (Stehouwer 2006). As with many previous studies limited organic analysis of plant uptake was conducted, but preliminary investigations did indicate that phenol concentrations in leachate from the pots was low (Stehouwer 2006).

One disadvantage of UFS derived from resin sands is a non-wetting character sands which tend to be hydrophobic that may restrict some soil applications. This non-wetting character can be reduced by composing (Owens et al. 2003).

UFS has been successfully incorporated into the growing mixes for ornamental flowers and shrubs where it was concluded that UFS (50%) should be mixed with coarse amendments such as compost (50%) to obtain mixtures of sufficient porosity (Dunkelberger & Regan 1997). However, this study did not formally test the toxicity of the mixtures.

Kurtz Brothers Inc., a custom soil blending company in Cleveland, Ohio, has been a strong advocate of beneficial reuse of UFS since the late 1980s. Over the past 30 years they have beneficially reused 6 million tonnes of UFS. They typically blend alkaline foundry sands (pH 9) to give pH 7 blends via addition of ammonium sulfate, aluminium sulfate or sulfur. The UFS makes up about 30% of their commercial mix and is blended with concrete sand, biosolid compost and manufactured topsoil. The Pro-Blend produced by Kurtz Brothers containing UFS was found to be superior to the local clayey topsoil, being less compact and more permeable and since the reuse was approved. The Ohio EPA is not aware of any environmental damage resulting from the reuse nor is Kurtz brothers aware of any environmental problems from end-users (US EPA 2006). This continued use over a prolonged period indicates that beneficial reuse of UFS in blended soil mixtures is practical and environmentally sustainable in the long-term.

3.3.2 Bitumen (asphalt) production

The substitution of virgin sand with UFS has considerable cost savings for manufacturers of products containing sands such as bituminous concrete. UFS has been used in the production of asphalt or bitumen in Ontario, Canada since the early 1980s and over 15 years of experience indicated that up to 15% UFS could be substituted for the asphalt concrete fine aggregate without loss of final product quality (Leidel et al. 1994). Larger percentages of UFS could also be potentially be reused in asphalt manufacture if foundries pre-processed the UFS to remove the finer (< 75 um) particles that tend to reduce the strength of the final product (Abichou et al. 1998).

3.3.3 Bricks and pavers

UFS can be incorporated into bricks that encapsulate the sands and any residual organic material. Limited studies conducted by the Cherokee Environmental Group indicated that the clay-baked bricks made from UFS from iron, steel and aluminium foundries contained no elevated levels of metals or organic residues (EPA 1999).

3.3.4 Cement manufacture and concrete production

Cement manufacture requires access to large quantities of sand. UFS can be used in cement production because it is composed largely of silica, alumina and iron oxide which are all key ingredients of cement. Cement is delineated from concrete as being the powder product that when mixed with water hardens to form concrete, while concrete is the finished product usually mixed up and formed on-site. Thus while the terms are often used interchangeably, cement is actually an ingredient of concrete.

Portland cement concrete typically compromises a mixture of sand (30%), gravel (50%), cement (15%) and water (55%) and can either be precast off-site to produce pipes, bricks or blocks or cast in place on larger constructions (Javed & Lovell 1994).

As with most manufactured materials cement production using UFS is attractive due to the lower cost of UFS when compared to virgin sand where it can be substituted for virgin sand at low percentages. Portland cement manufactured with <13% UFS showed higher compressibility strengths than conventionally produced cement with no other detrimental effects (CWC, 2008). The primary requirements for cement industry reuse are that UFS has >80% silica content, has a low alkaline level and is of uniform particle size (Abichou et al. 1998). For the majority of foundries seeking to supply to cement companies this would basically involve simple sieving or segregation of UFS to ensure uniformity and also matching supply of UFS to the needs of the cement manufacture. Thus depending on the sand needs of the cement manufacturers, this may exclude smaller foundries which only have limited quantities of UFS suitable for reuse.

Studies involving concrete blocks, where the fine aggregate was replaced with increasing amounts of UFS (15–45%) during construction, indicated that the compressive strength decreased with increased amounts of UFS in the mix but were still within acceptable strength criteria. However, replacing fine aggregates with 15–20% UFS produced cylinders with the same strength as control cylinders prepared using normal sand (Abichou et al. 1998). The recommendations from this study were that UFS from different sources needed to be segregated because UFS from resin sands could replace as much as 45% of the fine aggregate in concrete while UFS from green sands could only replace up to 15% (Abichou et al. 1998). They also observed that concrete darkened with increasing amounts of UFS and this was probably attributable to the amount of green sand present since resin sands generally have little coloration. This coloration may be attractive in some applications removing the need for oxide additions to give colour.

3.3.5 Construction – flowable fill

Flowable fill is a mixture of sand, fly ash or cement and water mixed to form a pourable slurry with a variety of construction uses. Flowable fill is useful because it is a self-levelling and self-compacting material that, like concrete, increases in strength with time and finds application in the construction industry as backfill for trenches around sewers and utilities. UFS can be used as a low cost substitute for the stabilised sand normally used in the manufacture of flowable fill.

The advantage of reuse of UFS as flowable fill is that the fill incorporates a large percentage of the UFS and flowable fill can be used on either a small scale or large scale depending on the construction process, meaning that even small foundries may be able to supply sand for smaller projects.

Beneficial reuse of UFS as a component of flowable fill is one of the most advanced uses being commonly adopted in at least three US states, Iowa, Ohio and Wisconsin, which have all developed recommended starting mixes (Abichou et al. 1998) where the percentage of UFS ranged from 81–96% of the dry weight composition of the flowable fill.

The geotechnical and leaching properties of flowable fill incorporating a range of different UFSs from 17 foundries from across America indicated that the geotechnical properties conformed to those desirable for flowable fill in both hardened and fresh phases when incorporating UFS, and that the toxicity of the flowable fills were below regulated criteria (Deng & Tikalsky 2007). This indicated that there was neither engineering nor environmental reasons for not adopting UFS as a component of flowable fill.

3.3.6 Construction – earthworks

The reuse of UFS in earthworks including embankments and retaining walls is attractive because of the relatively large volumes involved and the cost effectiveness. The US Department of Transport indicated that contractors could save 25–30% using UFS rather than virgin sand in construction (US DoT 2003). It concluded that UFS presented no environmental problems, and that the UFS was suitable for highway embankments and was cost effective when the highway project was located in the vicinity of the foundry. However, limited work has been done in testing the compressibility and strength of UFS for a full range of earthworks applications.

3.3.7 Construction – roadbase

The reuse of UFS in roadway construction is attractive because of the high volumes required during construction, and the reuse of UFS can provide considerable cost savings. Laboratory studies have indicated that foundry sand can be utilised safely as a component in highway sub-bases with good geomechanical properties and that leaching tests indicate that water passing through such sub-bases will not become contaminated with undesirable compounds (Guney et al. 2006).

3.3.8 Sand reclamation

Under sand reclamation a greater effort would be directed towards reconditioning and reusing the UFS on-site within the foundry process. This option is capital intensive and must be balanced against the long-term costs for continued purchase of virgin sand compared to the ongoing cost of sand reclamation. Reclamation can be either mechanical or thermal.

Mechanical reclamation involves sieving to remove sand clumps high in binder agents. It is not particularly technology intensive and is well within the scope of many foundries. However, compared to thermal reclamation, mechanical reclamation is generally inefficient because unlike thermal reclamation, mechanical reclamation cannot remove organic binders from the individual sand grains, limiting its application to green sands.

Thermal reclamation involves removing binder constituents from the sand particles via heating after particulation and removal of extraneous material via sieving. The temperature can be as high as 720^{o}C using gas fired burners, which ensures that the binding agents are completely combusted. Thermal reclamation can also be conducted at low temperatures in a process called cold reclamation where the binders are separated from the sand at low temperatures, < 0^{o}C. Thermal reclamation may not be generally applicable to all situations. A Brazilian foundry found that while low temperature reclamation at 450–550^{o}C resulted in removal of phenol resins from the sands, at higher temperatures a liquid phase formed resulting in partial agglomeration of the fine fraction (Andrade et al. 2005). This study did not examine the UFS for PAH or other organic residuals.

Other technical limitations of the technology indicate that the thermal reclamation is not suitable for all UFS and cannot be used for alkaline phenolic sands (URS 2001) and is not generally useful for inorganic binders as these are not burnt off during thermal reclamation (EPA 1999). Nat Tec developed a microwave UFS reclamation process that can be applied to any type of UFS at a cost of $10–20 per tonne but has not been developed for full scale operation (URS 2001).

The operating costs for thermal reclamation were estimated to be £3.96 per tonne in 1994 operating on a throughput of 0.5 tonnes per hour (Triplex Alloys 1994). At that time virgin sand cost £16.80 per tonne and the disposal cost was £7.10 per tonne for a total cost of £23.90 per tonne assuming no reclamation. Thus thermal reclamation involved a cost saving of about £19.94 per tonne which would pay for a reclamation unit with 6–9 months (Triplex Alloys 1994).

In Bielefeld, Germany, the city's foundry industry consisted of 15–20 small foundries and so the local authorities supported the design of a private plant commencing in 1991 to conduct UFS regeneration within the region (Lahl 1992). The plant used thermal reclamation, where the temperature in the fluidised bed reactor was between 600–800^{o}C and all gases produced were combusted at 800^{o}C to prevent PAH release from the effluent stack at a cost of 95–105 DM per tonne (Lahl 1992). At the time reclamation was not economically feasible because new sand cost only 30–35 DM per tonne, but this was misleading because it did not include transportation costs, and waste disposal tax was as little as 28 DM per tonne (Lahl 1992). When the cost of reclamation becomes comparable to the cost of virgin sand purchase + transport + disposal, reclamation would result in savings of the order of 40 DM per tonne.

Whether sand reclamation will be financially attractive for a particular foundry or indeed a consortium of foundries would depend on the location of the foundry and local transportation and supply costs. However, as landfill prices rise there may come a time when reclamation becomes an increasingly attractive option.

3.3.9 Contaminant sorbent

The unique properties of UFS may make them useful for the sorption of a variety of contaminants including nutrients and pesticide. Robert Dungan has developed a number of projects examining the benefits and risks of UFS for agricultural and horticultural applications claiming that the Fe and Al oxides formed in the UFS can serve as a sink for nutrient P. UFS may also be useful for reducing agricultural non-point source pollution by intercepting and sorbing nutrient and pesticide run off. This is an emerging area of research with a wide variety of potential applications to contaminant sorption.

For instance, UFS may also be useful in permeable reactive barriers for the clean up of TCE (Lee et al. 2004b) and for the removal of Zn from water (Lee et al. 2004a). However, in both of these applications the UFS tested was from iron foundries and at least some of the reactive properties could be attributed to residual iron rather than a specific interaction with the UFS. Zero-valent iron is widely used in reactive barriers for promotion of redox and precipitation reactions. The studies did however show that UFS has a high sorption capacity for TCE with partition coefficients ranging from 4–41.6 L kg^{-1} for the twelve sands studied (Lee et al. 2004b). However none of these studies discussed the possibilities of leaching of organic contaminates into the environment and so should be viewed with caution, as obviously by using UFS to clean up one contaminant issue it would be undesirable to potentially create another. However, in the longer term some use of UFS may find applications in permeable reactive barriers and this is a worthy future application provided the full environmental effects are all considered.

3.3.10 Cost effectiveness

It is not generally possible to ascertain whether a particular reuse option is more or less economically viable than another because the local financial conditions will dictate to a large extent what is viable. In general, since UFS is used as a replacement in the manufacturing industry for products that use virgin sand as a component the cost effectiveness of using UFS as a replacement of virgin sand would depend on:

- the cost of the virgin sand
- the final cost of the produce material as determined by market demand
- the cost of transporting UFS to the manufacturer's site
- the cost of processing or recycling the UFS.

For example, consider reuse of UFS as a soil conditioner. The sand is mixed with compost to produce a manufactured soil. The soil manufacturer may pay between $5–12 per tonne for virgin sand and the end product could be sold for $18 per tonne as topsoil, however the compost costs $10–12 per m^3 while the cost of local transport might reasonably be $4–7 per tonne (URS 2001). So even if the UFS was free, the costs to transport in this example appear to be comparable to the costs of purchase of virgin sand indicating that reuse as a soil condition may not always be economically viable, and certainly in today's climate would in all likelihood become increasing uneconomical as the costs of petrol and transport increase. This example highlights that it is important for foundries to consider a range of reuse options for their UFS to allow for changing financial situations in their local environment.

3.4 Summary and conclusions

The information reviewed in this section on beneficial reuse options for UFS indicated that the reuse options could be classified into three broad areas: (i) manufactured products, (ii) geotechnical applications, and (iii) soil-based applications.

The application of UFS in construction appears to be well advanced, with beneficial reuses in cement production and flowable fill being developed to the extent that mix designs are becoming available, although many of these specifications are still proprietary and therefore not commonly available. The lack of available details on particular applications, especially practical field performance is one of the major barriers which restricts uptake and adoption of the technologies. However, other applications such as asphalt and brick production were not developed as much as they could have been. In particular, while some work has been performed on soil applications much more research needs to be performed to convince legislative bodies of the safety of this application.

4. Limitations restricting beneficial reuse of used foundry sand

4.1 Introduction

While in general foundries go to great lengths to reuse onsite what is considered to them a valuable resource, it inevitable that a small fraction of foundry sand eventually becomes unusable, and is therefore classed as industrial waste by-product and marked for disposal. However, this 'waste' is still of significant high physical quality such that it could potentially be reused beneficially in many other processes. However, the adoption of UFS as a valuable resource is sporadic and in this section we examine the major limitations restricting the uptake of UFS reuse.

4.2 Barriers to UFS reuse

4.2.1 Perception of UFS as a 'waste'

One of the major barriers to economically viable reuse of UFS is the legislative labelling of UFS as a waste and the consequential cost associated with 'waste' handling. The continued perception of UFS as a waste material needs to be shifted towards the perception of UFS as a highly valuable material resource which is currently under-utilised by foundries and manufacturers worldwide. This points to the need for an education program being instigated to raise the profile of UFS as a valuable resource, with the specific aim of increasing demand for UFS.

The crux of the legislative issue which is hampering UFS beneficial reuse is simply the identification of UFS as an industrial waste material where increasingly research is showing that UFS with a few exceptions is generally of higher quality than most soils and as such should not be viewed as waste but as a valuable resource.

In general, regulations were burdensome to industries and impeded innovation (Cote & Smolenaars 1997) but these could be overcome collaboratively by opening a dialogue between industries and regulatory authorities (Mangan et al. 2003). In a supportive legislative paradigm, policy would need to meet the following four criteria suggested by Harris and Pritchard (2004):

1. be predictable, stable in the long-term and transparent to industry
2. use a mix of policy instruments to provide clear incentives for industry to engage
3. be supportive of the removal of barriers that impede reuse adoption
4. promote knowledge and information dissemination to build trust and industry collaboration.

Many industries intent on beneficial reuse of UFS tend to be frustrated by the regularity limits and processes required to allow use. There is a need to streamline the approval process to encourage safe and responsible reuse options for UFS.

4.2.2 Legislative approval

One of the main barriers to beneficial reuse is the legislative approval process that can be often challenging and long winded. Even when an approval process is undertaken, there is a legislative burden upon the legislative authority that must oversee and continue to monitor the reuse program throughout the lifetime of the program. The question is, how willing is the state or local authority to commit resources to review beneficial reuse options and monitor reuse activities? Often legislative authorities have limited financial resources to either approve or monitor programs and the easiest option for many is to simply restrict or ban reuse entirely.

Secondly, clear guidelines need to be developed for the sampling of UFS, including the UFS pile and the frequency of sampling to ensure that a representative sample is being tested for environmental compliance.

As encouraged under the Finnish legislation, small scale, short-term pilot projects should be exempt from legislation and actively encouraged to allow reuse applications to be rapidly trialled and developed. The success of these pilot projects should be reviewed by the environmental authority that would still need to give final approval prior to continued full-scale operation.

4.2.3 Cost effectiveness and economic viability

The triple bottom line limiting UFS reuse options will be cost effectiveness, availability of supply and the consistent quality of the UFS feedstock for the reuse application. Some of the restrictions previously shown to limit the cost effectiveness of UFS have included:

- consistency of UFS supply of regular large volumes for appropriate applications
- consistency of the quality of the UFS
- close proximity of the foundry to the reuse site
- the ability to treat UFS on site since travel costs and haulage can increase cost of processing and delivery.

Relatively low total volumes are produced by any one foundry. To meet the demands of industrial applications, especially construction, it is desirable that consortiums of foundries be formed to deliver the volume of UFS required on a consistent basis.

One of the major limitations of reuse of UFS is the distance from the foundry to the end use site. Transport costs for UFS need to be weighed against potential income from resale of UFS products. Transportation costs and logistics mean that generally only uses found within close proximity of foundries would be cost effective.

The main cost normally associated with beneficial reuse of UFS is not the sand itself, but rather the transportation and logistics costs. This normally means that cost-effective beneficial reuse programs for UFS must be located in close proximity to the originating foundry. Similarly the often small volumes of UFS produced mean that for larger projects UFS would need to be stockpiled for a period to obtain enough volume or consolidated from a number of smaller different foundries. This has costs associated with the consolidation, transport and logistics, and may involve some blending of UFS sources from different regions to obtain a uniform UFS.

Foundries and UFS recyclers need to be matched with their UFS needs and proximity. It would be necessary to identify foundries' locations and the type, volume and quality of UFS that they produce and then have this UFS targeted for resale to local industries with the ability to take the foundry sand.

4.2.4 Quality and consistency of UFS

One of the major challenges is not the environmental quality of UFS but rather the non-uniformity of UFS. Generally, because UFS is derived from a number of different foundries and different sand binder systems, the chemistry and physical characteristics vary significantly from foundry to foundry making it difficult to obtain large volumes of uniform UFS for a specific application.

Even when obtained from a single foundry over a period of time, all UFS suffer to some extent from temporal non-uniformity depending on the site and the foundry processes being conducted during any given work period. The challenge for industry is to supply UFS of sufficient and consistent quality to meet the requirements of potential recyclers and end-users. In this respect, particle sieving or magnetic removal and physical separation of extraneous material from the waste stream, should all be considered as simple and readily implementable measures as part of any foundry process to attain a highly quality uniform product.

In general UFS are normally low in metal contaminants, and metals present in UFS would not normally preclude future reuse. However, in some limited cases high levels of metal contaminants may preclude any future reuse. In particular UFS from brass foundries may be unsuitable for recycling due to the high metals observed.

The first information gap in the reuse of the UFS that needs to be filled is the complete characterisation of the UFS. While the metallic composition of UFS is usually well defined and of limited concern, UFS may contain a variety of organic compounds that need to be identified and evaluated for toxicity and associated health effects. UFS may contain a number of sand-binding agents including phenols, diphenyl-4-4'di-isosyanate, hexamine and formaldehyde as well as a plethora of as yet uncharacterised new compounds produced via combustion in the casting process. These all need to be characterised and evaluated as potential environmental contaminants.

For organics contamination even potentially high levels of phenols or PAHs would not necessarily preclude future beneficial uses, as unlike metal contamination, the organic contamination would be amenable to a variety of bioremediation options including simple aeration. However, these would generally need to be conducted on site to minimise transport costs, and would add additional expense to the manufacturer of the UFS.

Bioremediation techniques such as landfarming utilise simple equipment and blending of UFS with an organic product. A simple aeration treatment showed that the levels of leachable phenol could be reduced from 0.4 to 0.2 mg L^{-1} within four weeks (URS 2001). Other options to consider could include accelerated composting on a smaller scale in compost bins of suitable size to match expected UFS production using optimised conditions of moisture, temperature and nutrients. Other options may also include the use of worms (vermiculture) to assist in the composting.

The real question to consider is, does the foundry have the necessary space or expertise to conduct bioremediation of UFS on-site together with all its other ongoing activities? Clearly it is unlikely that foundries would embrace the processing of UFS on-site. Legislation or exemptions need to be considered to allow transport of UFS from one site to another to allow preparation of UFS for reuse to proceed and there is a need to foster relationships between UFS producers and UFS recyclers.

4.2.5 Management practice

The first challenge for a foundry intent on finding a beneficial reuse option for its product is to completely characterise the UFS so that all potential contaminants are quantitatively known. In this regard, due to temporal variation in feed to a UFS stockpile, a suitable sampling regime must be initially developed so that the samples taken are representative of the characteristics of the UFS over a period of time. This endeavour will require management willing to dedicate resources to sampling and continued monitoring of their stock piles with the goal of obtaining a high quality and consistent supply of UFS.

Detailed information on sampling of UFS appears not to be available and given the inconsistencies and temporal variation of UFS, output guidelines need to be developed to allow consistent sampling of UFS yielding homogeneous and representative samples of waste streams or piles.

Foundries also need to ensure that metallic contaminants such as metal and litter do not contaminate the UFS waste stream. A simple management practice that should be implemented at all foundries is the segregation of different types of UFS and sieving to remove extraneous material and obtain UFS of a uniform particle size.

5. Summary and conclusions

5.1 Introduction

Overall UFSs are valuable under-utilised resources that can potentially be used in a range of beneficial ways. However, many legislative entities worldwide are not supporting beneficial reuse of UFS and are choosing to take a precautionary approach. This will not change until comprehensive beneficial reuse documents are available.

Recent extensive research conducted by the US Department of Agriculture indicates that in general UFS has metal concentrations comparable to or lower than native US soils, has relative low concentrations of PAHS and phenols, is non-toxic to earthworms and soil microbes, and is not accumulated in excessive amounts in edible crops. It therefore concluded that UFS derived from iron, aluminium and steel foundries presented little risk to humans whether via dietary exposure or direct ingestion of soil (Chaney 2008). This report suggested that if UFS had trace elements < 95 percentile of the USGS then there was no risk, and that only if the 95th percentile was exceeded would further investigation be required. Further investigation would involve practical examination of bioavailability or phytoavailability which would invariably reduce the real threat to humans due to the soil-plant barrier.

Thus, with the possible exception of UFS derived from brass foundries, metal contaminants in UFS are of no significant environmental concern if the UFS is utilised responsibly. Thus, there is no environmental concern associated with UFS derived from green sands which utilise no organic binder systems. This category accounts for the vast majority of UFS.

In contrast the characterisation of organic residues present in UFS has been poorly examined, presumably due to the large number of binder systems available and variation in foundry conditions from site to site. The major environmental concerns would be from organic contaminants present in UFS derived from core sands, which use organic binder systems at relatively low moulding temperatures. There is currently a lack of understanding regarding the chemical composition of such UFS, and foundries who have invested research into proprietary formulations for UFS are reluctant to share that information with regulators who are subsequently unwilling to issue permits for reuse (Chaney 2008). The challenge for the future is to characterise the levels of organic contaminants in these UFS. Little research has been conducted to date and more research needs to focus on the development of cleaner sand-binding systems, to modify existing processes to eradicate excessive levels of contaminants and to understand the foundry process that leads to higher concentrations or organic residues including their nature and amounts.

5.2 Knowledge gaps and future research

The long-term goals of any environmental legislation for any industrial by-product, such as UFS, should be to encourage the use of the industrial by-product beneficially as a substitute for existing raw materials, and consequently as much as possible make reasonable use of existing natural resources and reduce disposal to landfill. Little is currently being done to encourage reuse of UFS due to some existing knowledge gaps and this need to be addressed.

The main knowledge gaps limiting beneficial reuse of UFS are:

1. poor complete characterisation of UFS
2. limited understanding of the nature and dynamics of organic and metallic compounds derived from UFS in the environment, especially in plant systems
3. unclear legislative requirements and a lack of well defined management strategies for beneficially reusing UFS.

Currently, especially in regard to organic contaminants of UFS, there is a lack of understanding as to how the foundry process contributes to different levels of organic contaminant and other UFS characteristics. Future research needs to focus on fully characterising the nature of UFS within Australia. While international research indicates that the levels of metal contaminants are not generally an issue, the level and range of different organic binders present in UFS is normally an unknown quantity and needs to be identified. Therefore additional testing of UFS to more fully characterise the composition of UFS beyond metal contaminants is required.

Foundries need to sell their product. For instance, foundries should produce data sheets describing their UFS product and distribute this widely to prospective interested end-users. The data sheets should include information on particle size distribution, clay content, sand content, compaction curves, total metal and organic concentrations and where appropriate TCLP-extractable metal concentrations. Terrestrial toxicity tests could also be established as proof of the safety of the product. The objective should be to sell a high quality UFS product for reuse applications and to foster a change in perception via suitable education programs that values UFS not as a waste, but as a valuable resource.

House keeping and management at foundries need to be upgraded to ensure that the UFS waste stream is not compromised. Efforts need to be made to ensure that a uniform and high quality waste stream is maintained. This will encourage confidence in a resource from end-users. To facilitate quality control, ongoing analysis of UFS needs to be encouraged and guidelines developed for the frequency and manner in which these analyses is conducted to ensure representative sampling of UFS is achieved with minimal cost. Expenditure into online sampling and assessment using FTIR for instance may be an attractive approach for larger foundries, but simpler and less costly sampling regimens need to be developed for smaller foundries.

There are a limited number of growth studies conducted with plant uptake of UFS blends (Dungan 2007; Owens 2003) and for only a limited number of plant species and types of UFS. If UFS is to be generally utilised for agricultural applications much greater research must be performed including study of both the uptake of metals and organics by a variety of crops and a range of UFS. Likewise, limited studies using soil blends utilising UFS have been conducted. More studies need to be conducted to identify quality mixtures and to document the beneficial use and economic savings together with the safety of these blends for the growth of a variety of commonly edible crops.

For beneficial reuse, applications involving soil application of UFS research should concentrate on:

- determining the extent of leaching of potential contaminants from blended soils containing UFS from a variety of green and resin sand foundries
- determining the extent of plant uptake of UFS contaminants from these blended soils
- comparing the characteristics of plant growth and crop quality on blended soils with commercially available topsoils
- demonstrating the utility of UFS soil blends to foundries, end-users and EPAs.

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CRC CARE Pty Ltd
ACN 113 908 044
University of South Australia
Mawson Lakes
South Australia 5095

P.O. Box 486
Salisbury South
SA 5106
Australia

Tel: +61 (0) 8 8302 5038
Fax: +61 (0) 8 8302 3124
Email: admin@crccare.com
Web: www.crccare.com

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