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ASSESSMENT OF RADIOACTIVE METAL MELTING AS A VIABLE APPROACH TO REDUCING AND REUSING SCRAP FROM NUCLEAR INSTALLATIONS

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Abstract

Activities associated with nuclear power generation produce continuous amounts of low-to-intermediate level radioactive wastes that require long-term management solutions such as surface, near-surface or geological repository storage. While metallic waste (scrap) volumes are modest during normal operation, they increase dramatically when a facility is ultimately retired from operation and decommissioned.

Melting of scrap in a furnace immediately achieves waste volume reduction and potentially allows a majority of the metal to be recycled. Many European countries have already constructed and are successfully operating commercial metal melting facilities for radioactive waste management and new Japanese facilities are currently being developed in response to the 2011 Fukushima disaster.

This paper presents a high level overview of the environmental and socio-economic benefits that can be achieved by pursuing radioactive metal melting in North America, particularly in jurisdictions like Ontario, where numerous nuclear plants are scheduled for decommissioning over the coming decades.

1. Introduction

Melting of metallic low (LLW) and intermediate (ILW) level radioactive waste for partial decontamination and/or volume reduction has been practised for decades, predominantly in Europe and Japan. In North America, scrap melting has seen only limited application due to variety of political, social and economic factors. As a result, burial, storage (and occasional reuse of materials within the nuclear industry) continue to be the predominant waste disposal strategies.

While this trend is expected to persist in the near future, anticipated increases in the quantity of metallic waste produced, the rising cost of burial and storage, increasing public pressure to minimize radioactive waste inventories and the risk of contamination from geologically unstable repositories may soon push North America more towards the more sustainable European/Japanese model of waste management.

This paper explores some of the key drivers behind the varying waste management policies in North America and different jurisdictions around the world in an effort to improve industry awareness and better justify this complex and multi-faceted decision making process.

1.1 Radioactive waste generation

As a starting point, it is important to characterize and quantify the current and expected future sources of worldwide radioactive waste volumes. A summary of current global inventories is shown in Table 1.

Table 1: Global inventories of low (LLW) and intermediate (ILW) level radioactive waste[a] ($m^3 \times 10^6$ at Year End 2015)

	LLW	ILW
Canada	2.3	0.03
USA	22.7	0.2
Worldwide	30.1	0.59

[a]includes processed and unprocessed, storage and disposal (source: https://newmdb.iaea.org/dashboard.aspx)

Most of the above LLW and ILW inventory has been generated at facilities which are still in operation, and hence, it is estimated that only a small percentage (< 1 % by volume) of this waste is metallic. However, when a nuclear facility is decommissioned, large batches of both metal and concrete must be removed and demolished. It is estimated that at most 1% of the concrete in a demolished facility is potentially contaminated, but for metal this figure can approach 13% (by volume)[1], or approximately 1000 m^3 for a 1 GW facility.

Depending on the jurisdiction, even non-contaminated material originating from a nuclear facility may need to be segregated as 'radioactive waste', which would bring the metallic quantities involved closer to 8,000 m^3 for a 1 GW facility. To put this in perspective, ultimate decommissioning of the 440+ nuclear plants currently in operation will increase the global inventory of waste metal by more than an order of magnitude (and total LLW + ILW inventories by over 10%).

While these figures do not appear unmanageable, the ability to reduce waste volumes where economically viable should always be the considered the ‘benchmark’ standard of sustainable practice, consistent with ‘As Low As Reasonably Achievable’ (ALARA) waste generation protocols. Note that volume reductions of organic material can similarly be achieved by thermal processes (such as incineration), but this is outside the scope of the current paper.

2. Current waste management practices for metallic LLW and ILW

In many jurisdictions in North America, metallic scrap is treated in the same manner as other LLW and ILW radioactive waste, and as a result, many opportunities to reduce waste inventories are often overlooked.

2.1 Overview of technologies

The primary proven processes for metallic waste treatment are highlighted below. For the purposes of this paper, proven processes are limited to those regularly used in a current commercial application and would exclude technologies still in development or undergoing pilot trials.

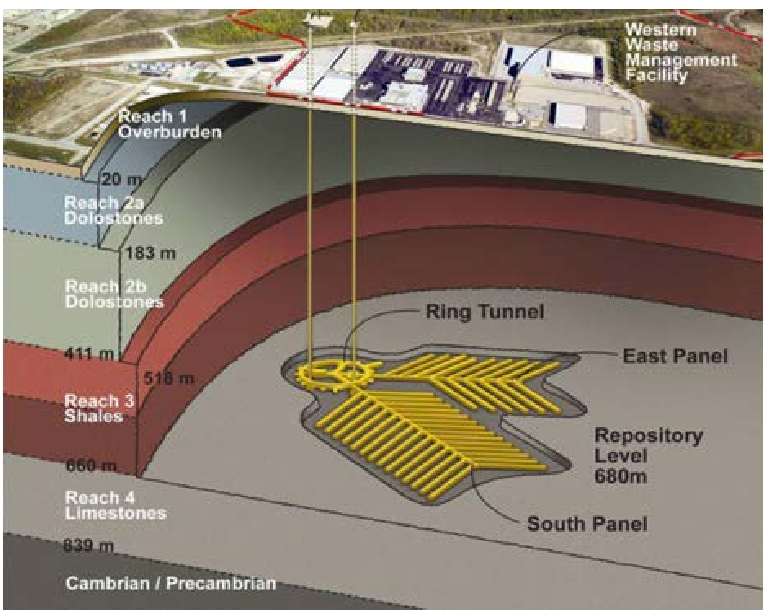

Figure 1: Deep geologic repository (Hatch design)

<u>Burial/storage</u>
Description: long term retention of scrap in the appropriate storage facility (ranging from surface, near surface, buried, deeper geological repository)

Applicability: all scrap depending on storage facility
Pre-treatment options: compaction, melting, surface decontamination
Final waste destination: indefinite isolation
Advantages: simple process, applicable to all types of scrap, currently low public resistance in North America
Disadvantages: containment and/or access risk due to natural disaster, risk of larger long term environmental liabilities, susceptible to increasing storage costs, challenging stakeholder management, sustainability issues

Surface decontamination
Description: cleaning of exterior surfaces of scrap using mechanical (such as abrasion) or chemical (such as acid oxidization) means
Applicability: bulk scrap with predominantly contaminated surfaces
Final waste destination: secondary treatment, reuse in nuclear industry, unconditional release
Advantages: low cost, fairly simple, generally most cost effective for lowest levels of contamination
Disadvantages: only applicable to certain types of scrap, creates secondary waste, worker exposure from additional processing

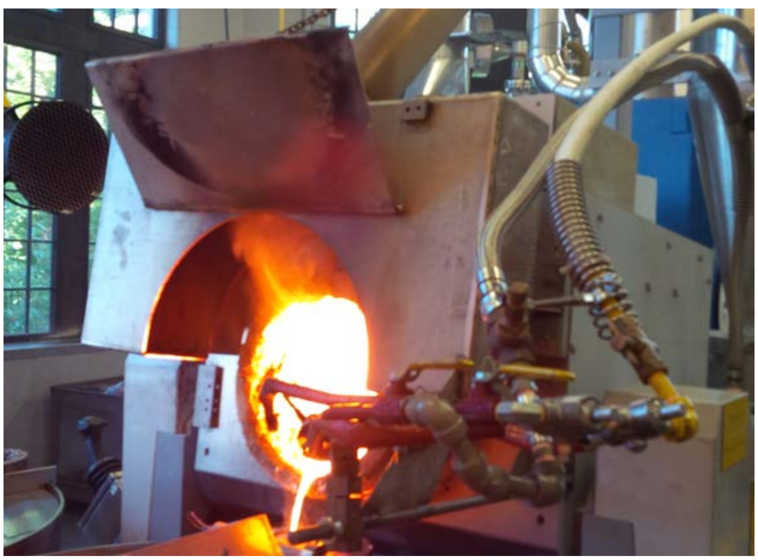

Figure 2: Induction Melting Furnace

Melting
Description: melting of scrap for decontamination and/or volume reduction
Applicability: most metals
Technology options: induction, plasma or electrode furnace, with separate processing of different metals
Final waste destination: burial/storage, reuse in nuclear industry, unconditional release
Advantages: some metal decontamination via slag separation, waste volume reduction, maximizes scrap recycling, recovery of higher value metals, surface contamination can be ‘blended’ to a lower average concentration for certain metals (i.e., lead in shielding applications)

Disadvantages: requires separate facility with associated costs, worker exposure from additional processing, creates secondary waste (though this is generally considered an overall benefit as the waste becomes concentrated), recycling options currently limited by regulations in North America

From an environmental perspective, there are clear benefits favouring both the volume reduction and potential recycling associated with metal melting. However, the selected waste treatment method must also be technically sound and justifiable on an economic basis.

2.2 Technical risks

The technical viability of using melt refining as a technique to separate active atomic species from the base metal has been clearly established and demonstrated from a thermodynamic and pyro-metallurgical chemistry perspective[2]. The remaining technical risks are mostly site/process specific, and can relate to target efficacy issues (i.e., problems with achieving the maximum decontamination efficiency), environmental performance (including the risk of unintentional contamination), and economic uncertainties with the design of a modern facility to ALARA radiation exposure principles.

Process risks with induction-based melting have been successfully addressed by European facilities over the last three decades of operation. Plasma furnace and electrode melting, while commercialized in at least two facilities[3] have not operated long enough to be considered truly low risk, though problems encountered to date have proven to be surmountable.

Environmental performance risks are expected to be low and can normally be dealt with by implementing the proper redundancy as per the governing standards. For example, furnace area exhaust systems can use dual filtration in series to prevent contamination due to filter failure. Design to standards for segregation, isolation and ventilation of facility areas is also necessary to minimize the risk of accidental release.

Finally risks related to ALARA exposure are generally well understood and appreciated by personnel in the nuclear industry and can be addressed in the same manner as all processes involving radioactive material handling. The melting application is well suited to operational mechanization/automation to keep worker exposure to a minimum.

2.3 Cost assessment

As with most waste treatment processes, economic justification for metal melting is made by comparison to prevailing and/or alternative treatment options. Simply put, from a purely economic perspective, the lowest cost option is the deemed the gold standard.

Since burial/storage is most prevalent in North America, a logical starting point would be to compare the total cost of melting radioactive scrap (including the amortized cost of the processing facility) to the equivalent cost to bury the same quantity of waste. Though most sites levy a host of charges and surcharges, the effective cost of burial can typically be expressed as a unit rate (i.e., US$/kg).

For metal melting, the ultimate cost primarily depends on the amortized capital cost of the facility (essentially a trade-off between the throughput of the facility and the maximum time to treat all the waste). For the purposes of the simplistic economic model presented in this paper, the following assumptions are made:

<u>Economic assessment assumptions</u>
Facility life: 30 years
Approximate cost of baseline facility: $40 Million*
Scaling factor for prorating the cost of larger/smaller facilities: 0.8 (exponent)
Volume of secondary waste produced (i.e., Slag): 5%
Facility operating costs per annum: 23% of CapEx**
Prevailing interest rate (for amortization): 10%
**based on in-house information (includes 30% general contingency)*
***consists of 5%, 3%, 2%, 8% and 5% for materials, labour, licensing, decommissioning budgeting and misc. items, respectively*

Based on these parameters, the cost curves shown in Figure 3 were generated for varying quantities of waste throughput and disposal costs.

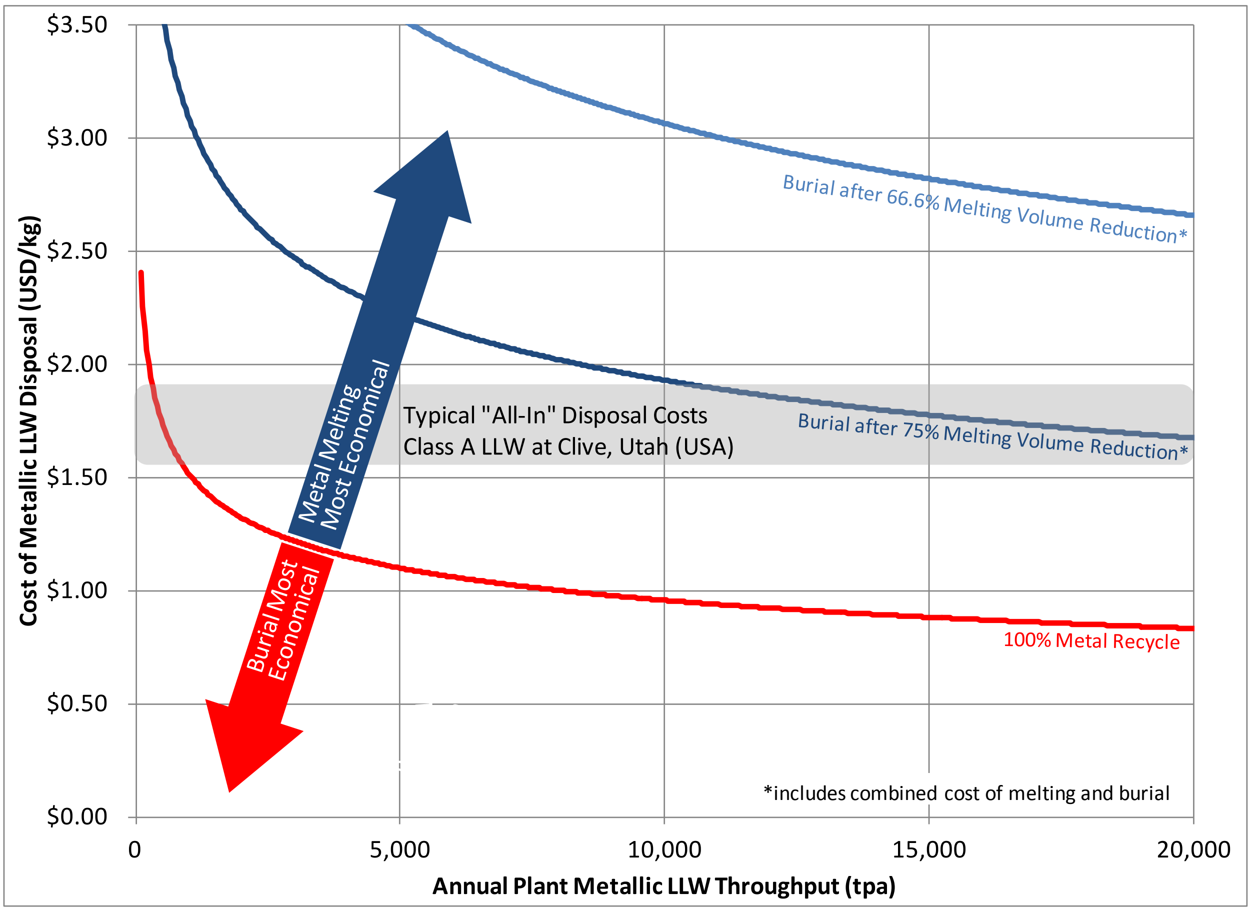

Figure 3: Breakeven cost of metal melting vs. burial

Case 1: 100% recycle

The lowest curve (shown in red), represents the breakeven point between burial and melting. That is, for any combination of annual scrap throughput and unit disposal rate residing above the red curve, the cost of melting will be less than the cost of burial. Note that this economic advantage depends on 100% of the metal being recycled, which, as described in Section 3, may be restricted in certain jurisdictions.

Case 2: Volume reduction and burial

The other two cost curves in blue represent similar breakeven points for the scenarios where scrap is melted to reduce volume by 75% and 66%, respectively, beyond any other volume reduction methods (such as mechanical compaction) being employed prior to burial. For example, if a 2500 tpa facility reduces the volume of metallic scrap by an additional 75% prior to burial, it will require a waste disposal cost of about $2.5/kg or higher to be worthwhile from a combined cost basis. Breakeven points for other volume reductions between 100% and 66% can be roughly interpolated from the curves above.

Disposal costs vary by region, but current price quotes for disposition of Class A LLW at the non-compact disposal facility located in Clive, Utah suggest that melting is becoming economical even in North America. Costs can be significantly higher in jurisdictions where governments would operate both melting and disposal facilities, including Ontario, however, market-based unit rates are usually the better input for sensible decision making.

While the above model is crude in nature and the absolute figures/assumptions represented in Figure 3 can change over time, a number of important trends are evident:

- Metal melting can still be worthwhile for volume reduction in some cases, even if the melted product is buried.

- Higher throughputs favour metal melting (though volume discounts offered at certain burial sites can offset this trend).

- Very high burial costs encourage recycling of metal, and eventually may lead to regulatory changes. This has already occurred in Europe and Japan.

An interesting example of the latter trend is apparent with lead. Local disposal costs for lead are typically well above $US 5/kg, since encapsulation of the metal in plastic is required in North America. It is easy to see how these high disposal costs would discourage burial, and indeed, melting and repurposing lead (for controlled reuse as shielding products and shipping containers within the industry) is currently one of the most popular metal recycling practices, despite the fact the throughputs involved are extremely low.

Economics are obviously an important consideration in the development of efficient waste management strategy and often dictate eventual policy. But costs must be evaluated in conjunction with other net benefits which cannot be easily monetized such as social/environmental advantages and impacts on public welfare.

3. Political, regulatory, social, and environmental considerations

Strategies for dealing with LLW and ILW vary significantly across the globe. While in practice there are only two possible 'end games' for this waste: burial or reuse, in reality it is important to recognise the multitude of political and regulatory requirements that dictate socially acceptable paths towards either option and appreciate the key differences between North America and the rest of the world.

Against this backdrop, the most prevalent treatment practices can be broadly cast into six different categories as shown in Figure 4, which highlights both the technical processing route and the associated societal perception.

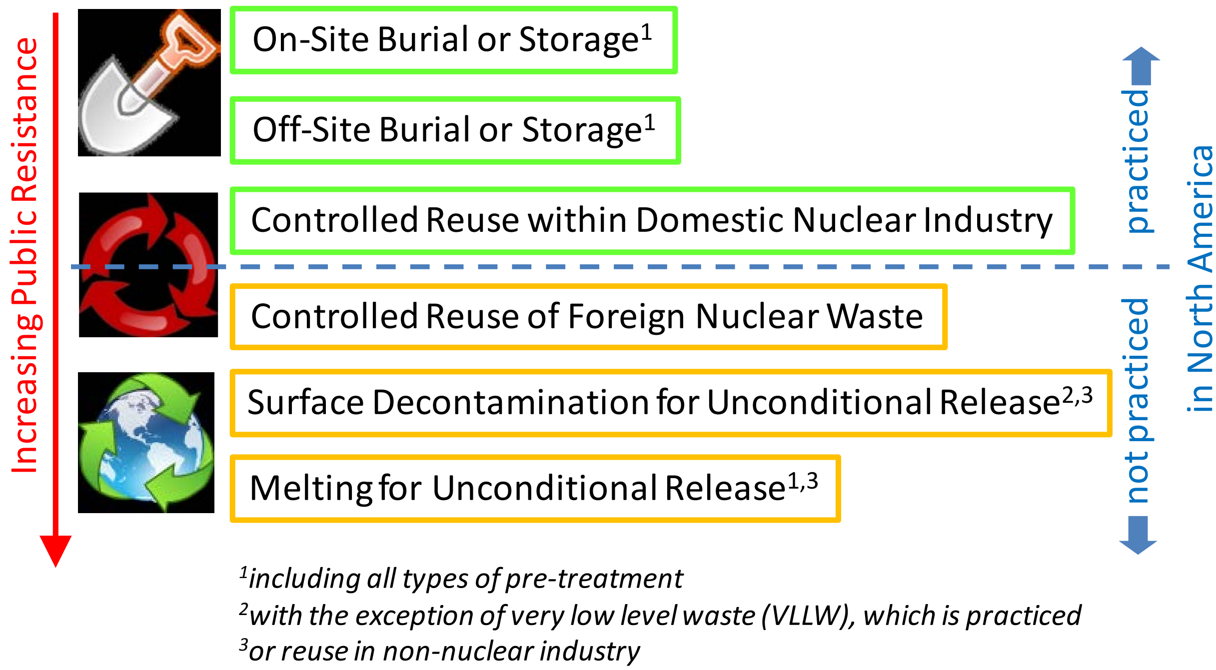

Figure 4: Strategies for dealing with radioactive metallic waste

The Figure 4 categories have been graphically sorted from the perspective of 'public acceptance' in North American, with a dividing line separating categories that 'are' and 'are not' widely practiced on the continent. Some important clarifications/notes:

- Burial has been sub-categorized as either 'on-site' or 'off-site' to capture the fact that off-site storage requires transportation of nuclear waste across public land.
- As described in Section 2.1, buried waste can be pre-treated by one or more processes, including melting for volume reduction.
- Controlled reuse of nuclear waste involves the repurposing of metallic constituents in any capacity at a site already handling radioactive material, either with or without prior pre-treatment.

- A distinction is made depending on whether the nuclear waste is generated within the country or originates outside its borders.

- Melting for unconditional release is typically limited to LLW, as the degree of decontamination with most separation processes is fairly limited.

Upon close examination, two prevailing themes emerge. Firstly the “not in my backyard” mentality of waste management appears to be a dominant factor in determining what is normally practiced. For example, treatment and reuse of nuclear material for an application within the nuclear industry is apparently deemed acceptable not due to an overriding confidence in the effectiveness of the treatment/monitoring methods (as this material is strictly prohibited from release for any non-nuclear application), but primarily because it will only expose those inside the nuclear industry, to the perceived risks.

The second theme is curiously nationalistic in nature, implying that it is acceptable to treat domestic waste for reuse, but somehow the exporting or importing of foreign waste for reuse crosses an important line. This perception persists even when ‘best in class’ facilities for treatment are not available within the country. Perhaps the uninitiated would simply deem this an extension to the first theme, appropriately qualified as: “not through my back yard” (i.e., the waste shall not be transported). However this simplification does not survive scrutiny, since shipping domestic nuclear waste between domestic facilities is not similarly prohibited: “More than a million packages containing radioactive material are transported safely in Canada each year”[4].

Further, it is interesting to note that the three strategies highlighted in Figure 4 not generally practiced in North America are quite common in many regions of the world that otherwise have ‘best in class’ environmental regulations, including Europe and Japan. Thus, the argument that North America is simply favouring approaches that are in the best interest of public health and the environment does not have substantial credibility.

It has been speculated that much of the confusion behind public sentiment stems from a general lack of knowledge of what constitutes a safe level of exposure to radioactivity. A popular public belief is that there is no safe level of exposure, which, to the layman, can appear to be a reasonable conclusion – until of course one realizes that everyone experiences some exposure to radiation virtually on a continuous basis. The two leading authorities that determine safe exposure limits, the National Council on Radiation Protection (NCRP) and the International Commission on Radiological Protection (ICRP) both concur that for all intents and purposes a material is considered ‘non-radioactive’ if it cannot reasonably cause a total effective dose more than 0.01 mSv per year, which has recently been proposed by the US Department of Energy (DOE) as the proposed standard for allowing reuse of metals. The average North American absorbs over 6.2 mSv per year[5], from a variety of sources including food, so it would appear that the DOE standard is extremely safe.

However, the fervour of public opposition to the reuse and/or transport of material at any measurable level of radioactivity has led to the cancellation of many projects in North America over the last decade including the following precedent-setting examples:

- **Bruce Power (Canada)** in 2010 cancelled its plans to ship low-level radioactive steam generators to Sweden for melting and unconditional release to the marketplace due to public opposition against transporting the waste through the Great Lakes/St. Lawrence Seaway. The generators are presently in passive storage at the Bruce nuclear power complex on Lake Huron.

- **Energy Solutions Bear Creek (Utah/Tennessee)**, the only major radioactive metallic waste melting facility in the US was also forced in 2010 to abandon plans to import, treat and recycle metal from Italy for ultimate reuse as shielding blocks. The company is now helping Italy design domestic facilities for the same purpose.

- **The US Department of Energy's** proposed action in 2013 to allow for the recycle of 14,000 tons of scrap metal that meets the requirements of DOE Order 458.1 (Radiation Protection of the Public and the Environment) remains under review, primarily due to intense resistance from numerous environmental groups, the Steel Manufacturers Association and the general public.

At the same time, metallic waste melting facilities in Europe have been unconditionally releasing metal for decades without incident, including Capenhurst, UK (over 7,000 t since 1994), Carla Siempelkamp, Germany (over 1,000 t since 1989), Ecomet-S, Russia (over 8,000 t since 1990), and Studsvik, Sweden, (over 10,000 t since 1987)[6]. Furthermore, numerous greenfield facilities to deal with the large quantity of metallic waste from the 2011 Tōhoku earthquake and tsunami are currently being built at Fukushima and other sites.

While the technical barriers associated with metal melting for unconditional release have proven to be surmountable, the socio-political constraints have thus far been more difficult to overcome. Whether this originates from the aforementioned North American public lack of understanding or an absence of trust in industry/governing authorities remains open to debate. What is certain is there needs to be a fundamental shift in public perception before more effective long term strategies for handling metallic scrap can be implemented in North America.

4. Conclusions & future investigations

The global inventory of metallic LLW and ILW is expected to increase dramatically over the next decade as nuclear facilities are progressively decommissioned. Burial of metallic scrap, long the staple method for waste management in North America, may no longer represent the best approach from a combined social, environmental and economic basis.

Despite recent setbacks in initiating new projects, as burial costs continue to escalate and sustainability issues increasingly gain importance, the drivers favouring metal melting will eventually lead to policy change and greater public acceptance of the practice.

Fortunately, the significant progress being made in the design and optimization of metal melting facilities around the globe, including the development of next generation plasma furnace technologies, will ensure the eventual transition in North America will be a low-risk endeavour based on well proven techniques.

5. References

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