AN INNOVATIVE APPROACH TO WEAPONS USABLE NUCLEAR MATERIALS MINIMIZATION

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Abstract

The U.S. Department of Energy's National Nuclear Security Administration (DOE/NNSA) Office of Material Management and Minimization (M^3) works to minimize civilian stocks of highly enriched uranium (HEU) and separated plutonium globally through the conversion of research reactors from HEU to low-enriched uranium (LEU) fuel and, when possible, removing or confirming the disposition of excess weapons-usable nuclear material (WUNM). The majority of uranium-based materials removed by M^3 and its predecessor program, the Global Threat Reduction Initiative, have been unirradiated (fresh) uranium or irradiated (spent) uranium based on U-Al or U-ZrH fuel systems. As of 30 September 2019,[1] DOE/NNSA has removed or confirmed the disposition of approximately 3,520 kilograms (kg) of fresh HEU and 3,200 kg of irradiated HEU.

Although significant progress has been made on HEU minimization, M^3 estimates that large quantities of WUNM are still in civil commerce worldwide, much of which is excess to actual needs and is suitable for elimination. However, a large portion of these inventories is difficult to remove or otherwise disposition due to a number of constraints, including:

— Political: sending additional material to various receipt locations—whether in the United States or abroad—can conflict with U.S. or foreign partner priorities or policies;
— Technical: globally, there is limited, or in some cases no, infrastructure capability and/or capacity to eliminate certain types of WUNM; and
— Economic: given current capabilities and capacity, it can be more expensive to disposition certain materials than to pursue long-term storage options which do not result in permanent threat reduction.

To overcome these obstacles, M^3 is developing a novel approach to work with foreign partners to eliminate difficult tranches of WUNM in an economic manner where they are located. M^3 is developing a mobile platform for stabilizing excess WUNM and converting it into a stable, more proliferation resistant, low-attractiveness waste-form that can be readily disposed

[1] All M^3 metrics cited in this paper are as of this date, which was the last day of the United States Government's 2019 Fiscal Year.

in a solid waste disposal facility. The process being developed by M[3] builds on U.S. DOE's advances in the melt-dilute process, originally developed for the treatment aluminum spent fuel materials, to produce repository-acceptable waste forms. M[3] has further adapted this process to cover wide ranging fuel and clad materials and is currently working to stage this process on a mobile platform. The prototype Mobile Melt-Consolidate test system (MMC) being developed leverages the melt processing technology and our understanding of metallurgical phase stability to develop customizable, stable waste forms to meet foreign partners' solid waste disposal facility performance envelopes. MMC aims to provide a new capability to eliminate small quantities of legacy WUNM in-country or in-region, rather than commercial transport over long distances. M[3] estimates that MMC will potentially be able to address approximately 20-50% of the known excess foreign tranches of WUNM.

This paper reviews the issues and challenges associated with the elimination of diverse types of remaining, legacy WUNM and describes, in detail, the MMC concept and principles. The paper also highlights the planned capabilities of MMC, which M[3] is currently developing, and the associated R&D validation and optimization studies. Finally, it will describe the framework for its design and operation.

1. INTRODUCTION

Acquiring a sufficient quantity of WUNM is the most difficult step in the creation of a nuclear weapon: it is expensive to produce, and the production process is challenging and readily detectible. These facts make existing inventories of WUNM attractive targets for terrorist groups, criminal organizations, or aspiring nuclear states. While it is possible to utilize and store these materials in a secure manner, it requires funding, commitment, and constant vigilance to do so. A more sustainable approach involves identifying new ways to minimize the need for these materials—whether by converting research reactors from HEU to LEU fuel or producing LEU-based versus HEU-based medical isotopes—and subsequently eliminating the excess WUNM. This achieves permanent threat reduction, ensuring that these materials will never be diverted for illicit ends.

The United States—in close cooperation with our international partners—has been a leader in WUNM minimization since the establishment of the Off-Site Fuels Policy in 1968. This program ended in 1988 and restarted in 1996—the United States has since removed (to the country of origin) or confirmed the disposition of over 7,166 kilograms of HEU and separated plutonium from 48 countries and Taiwan. This is equivalent to more than 320 nuclear weapons-worth of material. Over these 24 years, the United States has developed a host of new capabilities to enable quicker and safer removals of an ever-expanding gamut of materials. Notable achievements have included the first air shipments of spent nuclear fuel, transport of irradiated uranium liquids, development of Category 1 transport capability for weapons-usable plutonium materials, and support for the development of the first, and to-date only, Type-C shipping package: the TUK-145. Recognizing that circumstances may dictate the rapid removal of WUNM, and building on the lessons learned from Project Sapphire and Operation Auburn Endeavour, DOE/NNSA developed the Mobile Uranium and Plutonium Facilities to enable the expedited removals of large quantities of WUNM from austere, remote, or otherwise challenging locations anywhere in the world.

Despite the wide variety of materials removed from dozens of sites around the world and the different methods taken to eliminate them, at their core, the vast majority of these activities are the same: they involve identifying excess WUNM and sending it back to the country from which it came for disposition. While it has to-date proven quite successful, this approach has some critical requirements that must be satisfied for a removal to take place. Namely, these are willing and able partners, sufficient resources, appropriate legal and regulatory approvals, and existing tools and infrastructure to manage these materials. As more and more materials are eliminated and remaining inventories become more and more diverse, these requirements can turn into major limitations.

Political and legal challenges can occur for any number of reasons and can halt a removal. Whether these challenges exist because of domestic policies, antiquated or poorly drafted legal frameworks, or even personality clashes, they can make it more difficult to secure agreements to remove materials in the first place. Similarly, if there are certain infrastructure requirements to manage or disposition a given type of material, its absence can become an insurmountable obstacle. Many of the remaining WUNM inventories are exotic in nature, thereby making this challenge ever more prevalent. Finally, economic issues often play a decisive role in deciding what to do with a certain material tranche. The low price of uranium, the high cost of new nuclear processing infrastructure (or modification of existing infrastructure), status quo bias, and the intricacies (or inanity) of the budget cycle all conspire against taking decisive action. Because of these challenges, new approaches are needed if the global community is to keep making progress on WUNM minimization.

2. AN INNOVATIVE APPROACH TO WUNM MANAGEMENT

One innovative approach to eliminating these materials is through the development of modular, transportable systems that enable treatment and processing of materials in-country. A versatile, re-usable, mobile system that can be used to treat WUNM can help overcome many of the challenges associated with international transfer of such materials. The MMC concept meets these objectives and provides a platform for the treatment of a wide range of WUNM inventories into a customizable, stable form that is both more proliferation resistant and a lower attractiveness level than the input materials. These products are suitably robust for extended storage and/or final disposition. MMC provides an alternative to the construction and maintenance of expensive treatment facilities within a country, since it is designed to be deployed at a location in proximity of the WUNM to be treated, operated for a short duration, and then dismantled and removed.

3. MELT TREATMENT USING MOBILE MELT-CONSOLIDATION

MMC is an adaptation of the melt-dilute process that was developed for the treatment of spent reactor fuel of U.S. origin. MMC is based on mature science wherein a high-temperature furnace is used to melt dissimilar elements and compounds to create a homogeneous, chemically stable end-product. WUNM tranches include a wide variety of different shapes, sizes, and compositions of materials. MMC utilizes consumable metallic baskets to contain the WUNM to be treated, along with integral master alloys that are selected to take advantage of low-temperature binary and tertiary eutectic compositions. In order to achieve non-proliferation objectives, master alloys may include additives that can be used to provide oxide reduction, isotopic dilution, and maximum fission product retention. MMC will utilize modular shielding and off-gas components to ensure worker safety and meet environmental safety requirements.

4. TREATMENT PROCESS

MMC is targeted to treat a variety of different materials, including enriched-uranium oxide/thorium oxide fuels and uranium metal and uranium alloy materials. These materials will vary in form, from various-sized pieces/parts to full-size fuel elements (Figure 1). For clad fuel, the envelope of cladding materials may include aluminum, magnesium, stainless-steel, and zirconium metals and alloys. The MMC treatment process will typically yield a customized and robust, more proliferation-resistant and reduced attractiveness metallic or cermet ingot. However, additional WUNM tranches with different constituents may be investigated as the system matures.

FIG. 1 Research Reactor nuclear fuel elements.

To begin the MMC treatment cycle, WUNM will be placed into a metallic basket, specifically engineered with master alloys customized for those fuel materials. The basket will be designed to loosely contain its contents while being placed in a transfer cask. Any bulk water within the transfer cask and contents will be drained, prior to moving to the receipt area of MMC. Upon receipt of the loaded transfer cask at MMC, the cask will be moved into MMC's transfer module, via forklift, and the transfer module door will be closed. The transfer cask's contents will be remotely moved into a one-time use crucible liner and reusable crucible sleeve within the shielded trolley. The loaded trolley will then move along its track to a position beneath the furnace. The fuel, basket, crucible liner, and crucible sleeve will be raised into the furnace, and the treatment process will commence (Figures 2 and 3).

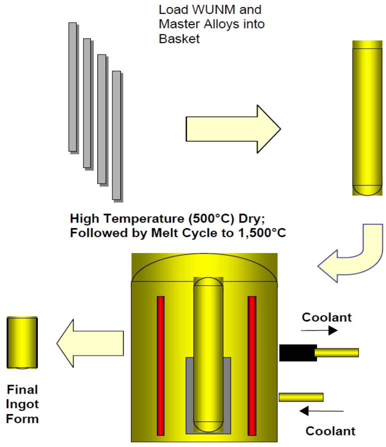

FIG. 2 MMC process overview.

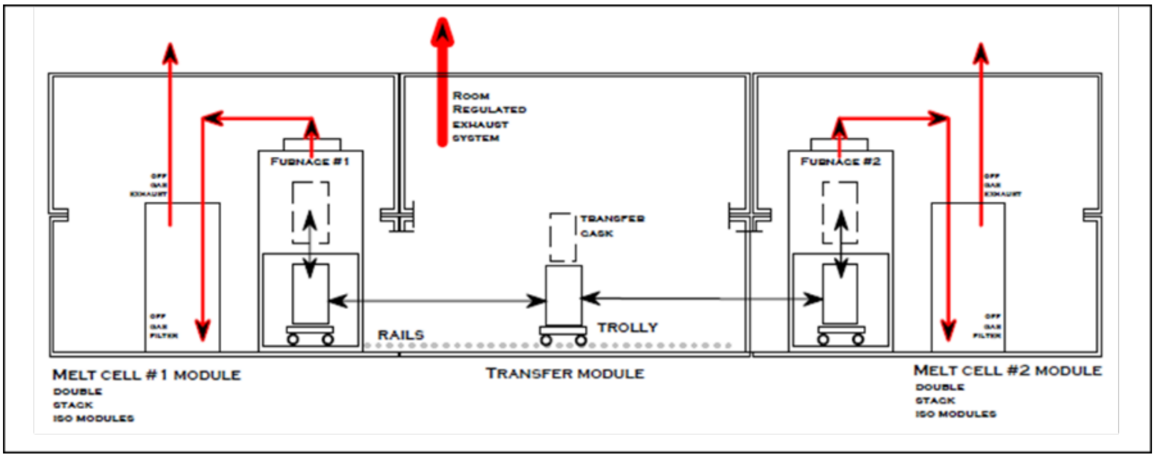

FIG. 3 Conceptual elevation view of MMC treatment modules.

During treatment, the fuel basket, including its master alloys, will begin to melt, initiating the desired reaction with the target materials in order to reduce and/or melt the fuel cladding and contained fuel (Figure 4). Upon completion of the treatment process and subsequent ingot cooling to room temperature, the material will be lowered out of the furnace and back into the trolley and the process reversed. The final product will be a homogenized ingot containing the basket, diluents and master alloys, the WUNM and its cladding (if applicable) all solidified within the crucible liner. The ingot/crucible liner combination is expected to have a weight of less than 300 kg and a diameter and height of approximately 30 cm.

FIG. 4 Melting fuel element and final fuel form.

5. MOBILE MELT-CONSOLIDATE SYSTEM DESCRIPTION

MMC is designed as a versatile, modular, and rapidly deployable mobile system for the purpose of converting WUNM into a robust and more proliferation-resistant form. MMC will be assembled inside universally transportable shipping containers that meet International Standards Organization (ISO) specifications, referred to hereafter as cargo containers. MMC's treatment modules will include one or two melt-cell modules, depending on mission needs, that are adjacent to a transfer module within the integrated system. Additional modules for managing utilities, process control, and services provide the requisite support for these treatment modules. Upon receipt of WUNM at MMC for treatment, the material is contained within the customized fuel basket that would have been previously loaded into the transfer cask at the host-site, fuel storage location. The cask is introduced into the MMC treatment modules through the transfer module.

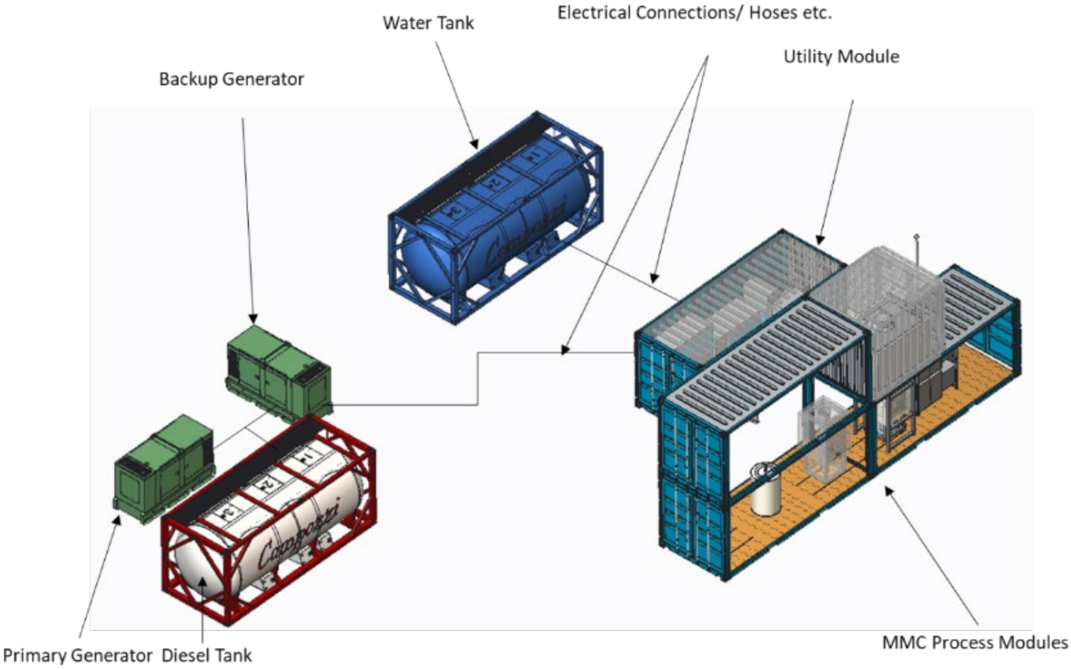

FIG. 5 The MMC system components.

The transfer module is comprised of 20-foot-long containers and is designed to support either single melt-cell or two melt-cell operation. The transfer module will contain tracks on which one or two trolley systems will maneuver, by remote control, into and out of the melt-cell module(s). It will also contain lifting equipment to maneuver the transfer cask for loading/unloading. WUNM and the fuel basket will be moved from the transfer module to the melt-cell utilizing a shielded trolley container.

The melt-cell module(s) is constructed within two cargo containers. A single melt-cell module will contain a bottom-load induction furnace, with continuous shielding, as appropriate for the WUNM being treated, and effluent off-gas system components. The effluent off-gas system components will be comprised of redundant trains that are contained primarily within the melt-cell.

The utilities module will house treatment module support equipment, including the furnace power supply, stirring unit, and a chiller unit. It will also provide power to all MMC functional components.

The control room will contain an operator's station and console, where system-monitoring and some process control operations are performed. MMC will be equipped with cameras to facilitate remote operation of all the system's functions. Data and video feeds from MMC to the control module allow for remote operation and monitoring of MMC treatment processes and parameters. Figure 5 shows the conceptual layout of MMC's various subsystems.

6. DESIGN STRATEGY AND CONSIDERATIONS

In developing conceptual designs for MMC, the focus was maintained on developing a treatment platform that provides the optimum balance of safety, versatility, modularity, and durability. These key project focus areas resulted in a design that maximizes its potential for addressing a wide variety of treatment challenges.

6.1. Safety

The primary design consideration for MMC is ensuring safe operations through the duration of an operational campaign. The design of the furnace, air handling, and shielded/remote operations are the most critical design features for achieving this.

To ensure confinement of radioactive materials being treated by MMC, the melt-cell utilizes a bottom-load, water-cooled, induction furnace design that includes induction stirring capability. A bottom-load furnace design allows improved confinement characteristics over a top-load furnace, because the off-gas head will be affixed to the top of the furnace housing throughout a campaign, eliminating the potential for contamination that would result from removing the off-gas head for loading/unloading operations in a top-load design.

Air flow within MMC will be tightly controlled and air infiltration restricted. Air handling equipment and design features of the integrated furnace, furnace enclosure, and effluent off-gas filtration system will ensure a slightly negative pressure, relative to the rest of the melt-cell module, and that this air is directed through the off-gas filtration system before it is exhausted.

Shielding provided by the furnace enclosure will serve multiple purposes. The enclosure will provide a confinement barrier for radioactive material, as described above. It will also provide radiation shielding for the furnace contents and for the primary effluent off-gas stages. To ensure the system's compliance with environmental safety requirements, the melt-cell module room air (external to the furnace enclosure) will be filtered through HEPA filtration units prior to exhaust. This design will ensure optimum system performance while maintaining confinement of radioactive effluent.

6.2. Versatility

MMC will be used to treat a range of irradiated and/or unirradiated WUNM (e.g. uranium, uranium-alloy, uranium-based, or uranium-thorium materials). These could take many forms, including fuel, targets, activated materials, or bulk materials. Within these broad forms, there is a diverse array of potential sub-forms, which for fuel, for example, could include uranium metal fuel; uranium-based aluminide, silicide, or oxide fuel; and uranium-thorium oxides fuel, any of which could be either unclad or clad with aluminum, magnesium alloys, stainless steel, or zirconium.

The system will accept WUNM in a variety of shapes, sizes, and compositions. The nuclear materials to be treated will not exceed 91 cm in length nor 25 cm in maximum cross-sectional dimension. WUNM tranches containing exceedingly long pieces may be cropped prior to treatment. The customizable basket will allow for the inclusion of master alloys, including diluents, which will be selected to optimize the treatment process for minimization of treatment temperatures, retention of radioactive constituents, reduction of oxide fuels, as necessary, as well as the dilution of enriched fuels.

The water-cooled induction furnace is capable of operating continuously at a temperature of up to 1,500°C. This high-temperature capability provides a foundation for the development of a portable system that is capable of reaching the temperatures required to treat high melting-point alloys and oxide fuel. The structure installed around the furnace, the furnace enclosure, will be designed to hold shielding panels of up to 3-inches to accommodate materials with high dose rates.

6.3. Modularity

The modular design of MMC provides the flexibility to optimize the system to the materials being treated. The design of the transfer module of MMC allows the handling of receipts and discharges to support two independent melt-cells. This option provides added operational efficiency to reduce campaign duration.

The design of furnace and furnace enclosure will allow for the installation of panels of variable thickness and density to accommodate nuclear materials over a range of dose rates and decay time, from nuclear materials requiring very little shielding, e.g., fresh fuel or activated scrap materials, to those materials requiring significant shielding, e.g., irradiated fuels and other materials with significant high-energy gamma or neutron emissions. For tranches of WUNM that are known to be unirradiated, panels of stainless steel will be utilized, rather than stainless steel-encapsulated lead shield panels. This design will greatly reduce system transport, recovery costs, and complexity.

The design of the effluent off-gas system will incorporate redundant filtration trains in parallel, each with multiple stages that are comprised of multiple ion exchange media canisters in series, with remote switching capabilities. The final stage filtration components are redundant HEPA filtration units. The individual ion exchange canisters will be designed to be interchangeable in size, media, and capacity to address expected effluent for individual campaigns (Figure 6). The ion-exchange canisters will be designed to be removable and replaceable in the field, if required. However, since the media will be selected and the canisters sized to accommodate the expected effluent from an entire campaign, it is expected that changing filtration canisters in the field will not be necessary. In addition, MMC will be designed and constructed with a redundancy in the off-gas system to mitigate potential filter plugging and canister capacity concerns. This customizable, redundant design increases the flexibility of system operation and precludes the release of radioactive materials in the MMC exhaust.

FIG. 6 Effluent off-gas testing apparatus.

6.4. Durability and waste minimization

Where possible, MMC is being designed and constructed utilizing standard, off-the-shelf components, including the furnace. This design strategy will improve the reliability and operability of the system and facilitate repairs, as needed, in the field. In addition, the current design of MMC provides for the minimization of consumable components by utilizing variable speed motors for maintaining optimum air flow throughout the system during operation. This design minimizes the potential material at risk of contamination during system operation. In addition, the interior surfaces of the melt-cell and transfer modules will be conducive to decontamination of these surfaces prior to system disassembly and return shipment.

7. MOBILE MELT-CONSOLIDATE SYSTEM FLEXIBILITY

The modular design of MMC allows for it to be configured to address different nuclear material treatment needs and objectives. This approach ensures the flexibility of the system, while minimizing costs and complexities associated with transport, setup, and component attrition. MMC will operate with a customized treatment process and configuration that can address a particular nuclear material treatment need. Primary variables for the system configuration are shielding and off-gas filtration requirements. Process variables include the time-dependent furnace heating and stirring cycle sequence, as well as, the time-dependent furnace temperature. Additionally, the fuel basket design and master alloy chemistry, including diluents and other treatment-related additives, will depend on the WUNM being treated. These mission-dependent variables will be evaluated for a range of expected nuclear material systems.

A combination of high furnace operating temperature capability, customizable basket, modular shielding design, and robust and modular effluent off-gas system affords MMC the ability to treat a wide variety of WUNM. The furnace will be capable of operating at temperatures up to 1,500°C, providing capacity to treat typical cladding alloys, including aluminum, stainless steel, and zirconium-base alloys. The fuel basket design will allow for the inclusion of customized master alloys. Master alloys used in the fuel basket will be determined based on consideration of the material being treated and the desired characteristics of the final product. The master alloys may include diluents for enrichment reduction, reducing agents for oxide material treatment and/or alloying elements that are included to optimize the treatment process. This flexibility allows for the treatment of various WUNM, including uranium metals and alloys, as well as uranium and uranium-thorium oxides. The modular design of the furnace shielding and off-gas system provides the capability to treat fresh fuel and irradiated materials.

Laboratory testing used for optimization of the MMC treatment process for various material systems are being performed to determine optimum process variables for a range of expected configuration/process combinations (Figure 7). Additionally, calculations to determine optimum system configuration variables are being performed. From these efforts, there will be a standard set of configuration/process combinations that will be utilized for expected material treatment campaigns. For materials that are outside of the expected material systems, additional calculations and/or laboratory testing may be performed to determine an optimum combination of system configuration and process variables for MMC treatment.

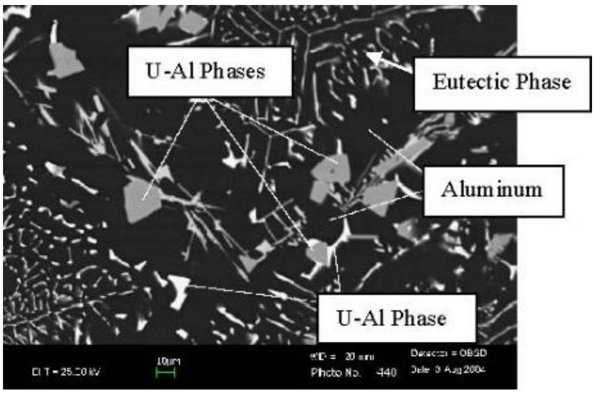

FIG. 7 Microstructure of U-Al ingot.

8. DEPLOYMENT STRATEGY

MMC requires the ability to be rapidly deployed to potential remote locations in order to address many of the world's non-proliferation goals and objectives. The individual containers that make up MMC will be transportable via all modes to remote nuclear material storage sites. For increased mobility and reduced operating and deployment costs, the system is designed to operate with the smallest possible footprint. The cargo containers will be integrated together in proximity to the host-country nuclear material storage site, using standard top-lift or forklift equipment. To optimize the utility of the system, it will be designed to standard utility connections that allow for connection to power and water services from the host country or from MMC's mobile service modules. While the system will be designed to operate as a stand-alone mobile system, MMC is being designed to accept services from host country facilities, reducing the need to transport and operate several support modules, including generators and fuel and water tanks.

The MMC treatment process is being designed to operate in batch mode, with single shift operations per batch. The evolution of the treatment process from receipt of the loaded transfer cask, melt-treatment of the contents, cooling and removal of from the furnace, and the relocation of the final product to its storage location will occur during a single shift. The transfer cask serves the dual purpose of interfacing with the host storage facility for loading of the WUNM and unloading the product ingot to its storage location within the host country storage facility. Utilizing the optional second melt-cell module allows for the preparation of one melt-cell module during operation of the other melt-cell.

When not being utilized, MMC will be maintained in a state of readiness for deployment from a U.S. staging location to the host site. The system is intended to operate at the host site for a period of three to twelve months. Upon completion of its treatment campaign, the non-consumable MMC components will then be returned to the United States.

9. CONCLUSIONS/SUMMARY

This paper highlights the wide array of issues and challenges associated with the elimination the diverse types of remaining, legacy WUNM and discusses the MMC concept and principles as a potential pathway to eliminate these materials. The paper details the principle of the melt-dilute process, which was adapted to develop MMC's capability, and sets out how MMC leverages this technology and our understanding of metallurgical phase stability to develop customizable, stable waste forms to meet foreign partners' solid waste disposal facility performance envelopes. The paper highlights the planned capabilities of MMC and the associated design, safety, R&D validation, and optimization studies underway. It also describes the framework for its design and operation of MMC. In closing, MMC aims to provide a new capability to eliminate small quantities of legacy WUNM in-country or in-region rather than commercial transport over long distances. M^3 estimates that this capability will potentially be able to address approximately 20-50% of the known excess foreign tranches of WUNM.