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The Development of Mobile Melt-Dilute Technology for the Treatment of Former Soviet Union Research Reactor Fuel

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Abstract – *On-site application of the MMD process offers an economical method for converting weapons usable Former Soviet Union (FSU) High Enriched Uranium (HEU) research reactor fuel to a safe and secure Low Enriched Uranium (LEU) ingot. The process generates essentially no waste and is performed in a sealed canister that contains all off-gas products, eliminating the need for an off-gas treatment system. The process is modular, reusable, and readily portable to a desired reactor site or storage location. The storage canisters containing the LEU melt could be configured for compatibility with any of the fuel storage technologies currently available or returned to Russia for reprocessing under the Russian Research Reactor Fuel Return Program. The objective of the MMD Project is to develop the mobile melt and dilute technology in preparation for active equipment deployment in the Newly Independent States (NIS) of the FSU*

I. INTRODUCTION

There are 15 research reactors in the Former Soviet Union (FSU), but outside the borders of modern day Russia, that use or store highly enriched uranium (HEU) fuel assemblies. These assemblies pose a weapons proliferation concern and a potential terrorist threat. The quantity of HEU involved is sufficient to make many tens of nuclear weapons. Typically, the uranium is in an aluminum fuel matrix that can be easily processed to separate the HEU.

In addition, these research reactors typically do not have the security infrastructure appropriate for safeguarding such fuel. While the U.S. has taken steps to help improve the security infrastructure at many of these reactors, leaving the untreated HEU fuel at the reactor is not an acceptable long-term solution.

An attractive option is to convert the HEU weapons usable fuel into a non-weapons grade form through the dilution of ^{235}U with depleted uranium to form a low-enriched uranium (LEU) ingot using the Mobile Melt Dilute (MMD) technology. MMD makes the fuel unattractive for diversion or theft while containing the radionuclides for safe, interim-term storage. MMD technology has the potential to provide key benefits to the Department of Energy (DOE).

II. Background

In 1954, President Eisenhower's "Atoms for Peace" program was launched at the first Geneva Conference on the Peaceful Uses of Atomic Energy. This program sought to share the benefits of nuclear technology with all nations that agreed to pursue only peaceful nuclear applications. For that purpose, over the next 15 – 20 years small research test reactors (generally <10 MW) along with U.S. fabricated nuclear fuel were furnished to universities and scientific institutions both within and outside the U.S. However, the U.S. Government maintained ownership of the U.S. manufactured nuclear fuel that was provided under this program to ensure recourse if a country attempted to use that fuel for unauthorized (military) purposes.

During the ensuing years, the U.S. Government became concerned with continuing to fabricate and furnish abroad HEU research reactor fuel. This policy shift was due to the fact that the high enrichment of research test reactor fuels renders them attractive as potential sources of fissile material for paramilitary purposes, the growing terrorist threat worldwide, and the relative simplicity and availability of modern uranium processing technology. To deal with this threat, the U.S. Department of Energy's *Reduced Enrichment Research Test Reactor (RERTR) Program* was initiated in the late 1970's to develop low-enrichment (<20% U-235) fuels and, wherever possible, to use them to replace U.S. supplied HEU fuels in research reactors worldwide.

However, the RERTR program did not address the large quantity of U.S. fabricated HEU spent fuel that was being stored in unsecured locations around the world. Thus in 1996, the U.S. opened a 10-year window for 41 nations to return their U.S. fabricated research reactor fuel to the U.S. for interim storage and final disposition. This *Foreign Research Reactor Spent Nuclear Fuel Acceptance Program* was established with the objective of reducing the HEU stockpile in research reactors globally.

The two U.S. interim fuel storage sites selected by the Department of Energy (DOE) are the Savannah River Site (SRS) and the Idaho National Environmental and Engineering Laboratory (INEEL). Because of the moratorium on aqueous reprocessing established under President Carter's administration, the DOE performed engineering option studies to evaluate final disposition technologies for the research reactor fuel in the 1990's. During this period, the Savannah River Technology Center (SRTC) developed the Melt and Dilute research reactor fuel treatment concept, which was the treatment option selected by the DOE. Thus, under DOE authorization, SRTC designed and built a pilot-scale Melt and Dilute treatment facility for aluminum-base spent fuel. [2,3,4]

In parallel to this U.S. history and during the Soviet Union era, Russia similarly provided nuclear technology throughout the region and fabricated fresh fuel for those research reactors at both the Bochvar Institute in Moscow and the Chemical Concentrates Plant in Novosibirsk. The Novosibirsk plant still manufactures nuclear fuel for many research reactors. Since 1973 they have supplied more than 25,000 fuel assemblies of 56 different types to the countries shown in Figure 1. During the 1970's, the Russian government became concerned with the quantity of HEU being provided and used at research reactors throughout the Soviet Union and changes were implemented in the 1980's.

In recognition of the shared danger of nuclear proliferation, the Russian Federation began its own RERTR program in 1992 in close cooperation with the U.S. program. In just the last few years, the U.S. and Russian governments have entered into negotiations regarding the initiation of the *Russian Research Reactor's Fuel Return Program* that would be modeled after the U.S. program. In 2003, an Agreement between the U.S. and Russian Governments was signed concerning cooperation for the return of Soviet/Russian origin research reactor fuel to the Russian Federation for interim storage and aqueous reprocessing at the Mayak PA, near Chelybinsk, Russia.

One of the major implementation difficulties with this program has been the time necessary for political negotiations required between the Former Soviet Union countries that have possession of the fuel and Russia. Because of these difficulties, the DOE has expressed an interest in developing a technology that could provide an alternate disposition path for FSU research reactor fuel if for any reason a research reactor's fuel cannot be shipped back to Russia. Also, this technology could provide an interim disposition path to mitigate proliferation concerns during the long political process that will be required to return the fuel to Russia from some ten different countries. ANL and SRTC proposed the Mobile Melt and Dilute Technology Development Project to fulfill this mission need.

The Mobile Melt Dilute (MMD) technology is an extension of the Melt Dilute process that was developed at the Savannah River Site for treatment of spent reactor fuel of U.S. origin. By incorporating these proven concepts along with a closed system approach, a simplified mobile treatment system is being developed for rapid deployment. As envisioned, the MMD system will be compact and staged on a transportable vehicle, with capability to treat and encapsulate research reactor spent fuel at either the reactor or storage site. The MMD process simply melts the HEU fuel assemblies and dilutes the alloy to less than 20% isotopic content using depleted uranium metal or alloy. After processing, the sealed canister containing the solidified non-weapons grade aluminum-uranium ingot, can be placed in interim storage pending reprocessing or emplacement into long-term storage using any proven storage technology. Thus, weapons usable HEU material can be treated using the MMD process to generate a safe and secure LEU ingot.

II. General System and Work Station Descriptions

The Mobile Melt-Dilute (MMD) system will be built inside transportable cargo shipping containers that meet the International Standards Organization (ISO) specifications. Container movements by rail, truck, barge, or ship are possible worldwide because loading, unloading, and trailering equipment are commonly available.

The control room is built inside a 20-foot-long container, and the treatment cell is built inside a 40-foot-long container. Each container is loaded onto a separate 40-foot long trailer for transportation to reactor storage sites. Another 20-foot container maybe used for housing the forklift and associated cabling. Tractors are separated from the trailers when they are positioned at the site to process fuel, and they are reattached for moving to another site when processing is complete. Proven technology is incorporated as much as possible in the MMD system to assure good performance, enhance reliability, and make repair or replacement less problematic.

The control trailer will house the operator's station and console where system monitoring and some process control operations are performed. A forklift will occupy most of the remainder of the control trailer when the MMD system is moved to different locations. The treatment cell will contain the Direct Electric Heating (DEH) furnace, the welding systems, evacuation and gas filtering system, as well as the diesel generator that supplies all electrical power for the process and safety devices

The general layout of the MMD facility for the control room and forklift storage is shown in Figure 1 and for the MMD treatment cell in Figure 2. The treatment cell layout has three basic stations: (1) fuel canister loading (2) welding, off gassing and inspections and (3) melt and dilute. The furnace is multifunctional and moves along rails to the various stations inside the MMD cell.

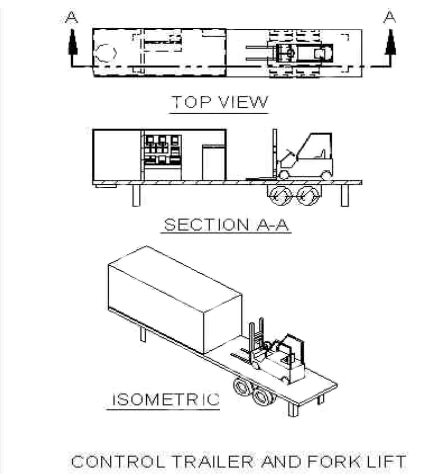

Figure 1. .Mobile Melt-Dilute Control Room and Forklift Truck Located on 40ft. Flat Bed Trailer

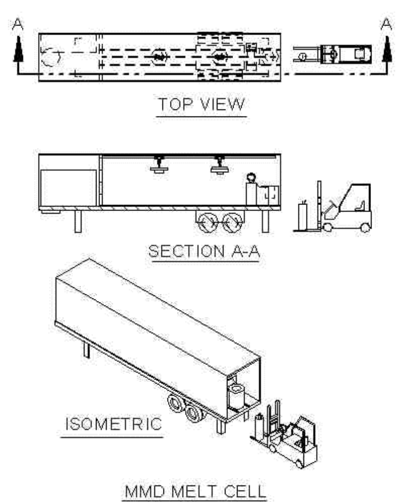

Figure 2. Mobile Melt-Dilute Treatment Cell

Spent fuel is loaded into baskets under water in the reactor storage pool, and the basket is loaded into a bottom loading fuel transfer cask. The transfer cask is taken to the MMD treatment facility staging area. The forklift truck is then used to lift the transfer cask to the furnace top, so the fuel basket can be unloaded directly into the canister inside the furnace. Loading the furnace using the transfer cask reduces radiation exposure to personnel and to the surroundings. Once the spent fuel is within the shielded furnace, the area inside the MMD treatment facility becomes safe for hands-on work by technicians. Bottom loading casks are sometimes used in FSU countries to remove spent fuel from the basin and are not foreign to reactor operators.

IIA.Cargo Container Description

The MMD systems are built in standard corrugated steel shipping containers that are commonly used worldwide. Their dimensions, materials, strengths, handling, stability, and other aspects of their construction are covered by ISO standards. The control module is housed in a 20 foot ISO container, and its equipment secured to the structure with minimum alterations. During melting operations, remote control functions and process monitoring are performed from the control room.

The DEH furnace will travel along floor-mounted rails to various positions within the treatment cell . Additional structure, to position the bottom-loading fuel transfer cask is located near the rear opening of the treatment cell. Supports for the furnace lid, welding and evacuation equipment are added as needed above the furnace track. Allowances are possible for additional height, if required, at the furnace loading station in the treatment cell, but any container modifications may have to be done after delivery of the system to Europe/Russia. A partition will divide the container, so the melt-dilute treatment cell can be separated from the diesel generator.

IIB. Fuel Transfer Cask

Spent fuel assemblies are transferred to the treatment facility in a shielded transfer cask. The transfer cask is first positioned over the storage basin at the reactor site, and the fuel basket containing spent fuel assemblies drawn inside the shielded cask. The cask and contents are then drip dried over the basin before attaching the bottom shield. Once the shield is attached, the transfer cask moves the spent fuel to the pickup point or staging area outside the treatment cell. The forklift truck picks up the cask and places it over the furnace. The bottom shield is designed so the fuel basket can be lowered through a sliding door into the canister located in the furnace. After loading the furnace, the bottom shield plug is detached from the transfer cask and left on the furnace top for shielding. The top part of the transfer cask is removed using the forklift, but prior to removal, the opening in the bottom shield plug is closed to eliminate radiation streaming from the furnace. Preliminary calculations indicate that 7 inches of lead shielding is needed for the cask. With 7 inches of lead shielding, the transfer cask is expected to weigh about 6.5 tons.

IIC. Forklift Truck

A diesel powered hydraulic forklift is used to transport the fuel transfer cask. The forklift will pick up the fuel transfer cask containing the loaded spent fuel basket at the reactor staging area and transport it to the MMD processing cell. Following spent fuel processing, the forklift will again transport the fuel transfer cask back to the reactor staging area. Reactor personnel will receive the transfer cask at the staging area and position the canister in the appropriate storage area.

The forklift adds additional versatility to the MMD system. The forklift can assist in maintenance activities on the MMD equipment including the generator set, MMD furnace and shielding, and the fuel transfer cask. In case of a failure of the main MMD system generator, the forklift's generator/alternator may be used to provide operational backup power to various MMD systems.

The MMD forklift is positioned for transportation behind the control module on the 40-foot control trailer. Both chassis and flatbed trailers are available commercially to haul ISO containers. However, the control module and forklift combination will probably require a reduced-height trailer with ramps or hydraulically operated trailer lift system for loading and unloading the forklift. A trailer with a reduced height maybe necessary to allow adequate clearance for overhead obstacles.

IID. Fuel Basket and Canister

The MMD canister design is modular. [9] The primary canister in this system is fabricated from carbon steel and is used during the MMD processing of the spent fuel assemblies. After processing, the primary canister may be stored at the reactor site until further processing is required. Storage in a dry environment requires no additional containment. If stored in a wet environment (e.g. reactor storage pool), then the carbon steel primary canister is loaded into an aluminum over-pack and seal welded. The aluminum over-pack will avoid galvanic corrosion with the aluminum-lined reactor storage pool. This system provides the maximum flexibility while maintaining a simple and economical design. Figure 3 shows the conceptual canister design along with the aluminum over-pack.

The primary MMD canister is fabricated from carbon steel with a "blued" or oxidized surface. Carbon steel was chosen because it is not significantly corroded by molten aluminum below approximately 1000 ºC. Carbon steel is also economically available in FSU countries. The canister outside diameter is approximately 260 mm (10.2 in) and has an internal height of approximately 890-mm (35 in). A lid will be installed on the canister once it is loaded with the basket containing the fuel assemblies. The lid will be welded using an automatic welding unit.

The aluminum basket is used to transfer fuel assemblies using the transfer cask from the research reactor's storage pool to the canisters located in the MMD furnace. The basket is designed so that the pool water can drain from it back into the storage pool once it is loaded into the fuel transfer cask. The basket is capable of holding four assemblies. It will be fabricated from aluminum, which will add to the dilution materials.

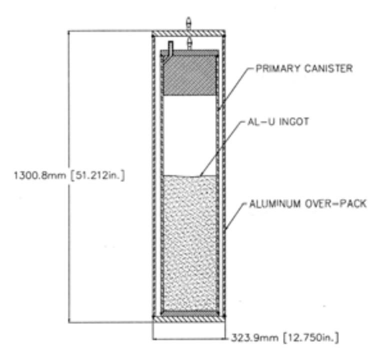

Figure 3. Canister with Melted Fuel Assemblies Inside an Aluminum Over-pack

IIE. Canister Lid Welder

An automatic welding unit is used to weld the lid to the canister. An overhead material-handling unit is used to position the automatic welding unit on the canister lid. The canister lid is welded to the fuel canister while it is inside the furnace in a vertical position. A full penetration exterior weld is used to join the canister lid to the fuel canister. The automatic welding unit will index off the canister and rotate during the welding operation. Controls to monitor the automatic welding equipment are placed inside the adjacent cargo container containing the control room. A video camera is used to monitor the welding operation and to perform a visual inspection of the completed weld joint.

IIF. Canister Moisture and Gas Removal

A drying station is used for leak testing, drying and evacuating the MMD canisters. The drying operation is performed while heating the canister loaded with HEU fuel assemblies to a temperature of approximately 450°C. A vacuum is applied to the system using a vacuum pump to approximately full vacuum to remove adsorbed and hydrated water from the canister and its contents. The water vapor is removed from the gas stream by molecular sieve traps filled with zeolite. This system is used in conjunction with the MMD furnace, which is used to heat the canister during the drying process. The system also includes equipment to backfill the canister with helium gas to leak check weld joint between the canister lid and canister. The drying system is shown in Figure 4.

When treating corroded fuel where the cladding has been breached, there is a potential for release of radioactive fission gases such as iodine, xenon and krypton during evacuation drying and melting processes. Also, fuel clad blistering, which occurs at about 550 ºC, will release fission gases and products from aluminum clad fuels. [10] Additionally, contaminated and/or tritiated water inside the canister from the reactor storage pool will be evaporated during the canister drying step. Containment of these species may require development of special in-line traps or ducting these products back into the reactor building's exhaust system.

The drying station system is equipped with some filtering capability. A pre-filter is used to remove any large particles from the off gas during drying. A HEPA filter is also used to remove any remaining small radioactive particles. A system to capture volatile gases in the event there is a breach in the canister during drying or melting will also be evaluated.

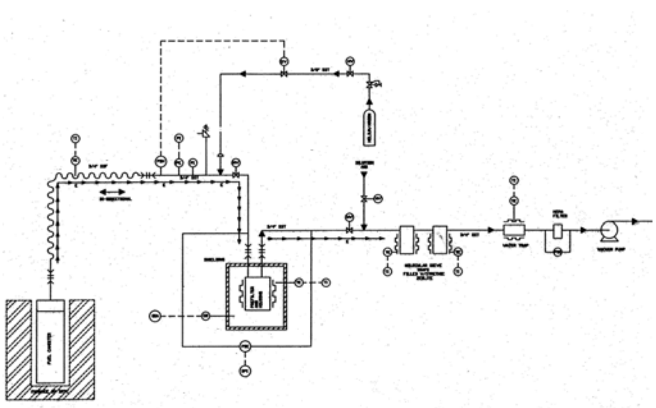

Figure 4. Canister Drying System

IIG. Sealing and Inspection

The sealing station will be used in conjunction with the drying station to hermetically seal the evacuation port on the MMD canister lid following leak testing, drying and evacuating operations. A vacuum inside the canister is necessary prior to commencing fuel assembly melting operations to minimize the pressure buildup inside the canister from volatile fission products and residual gases. At 850 ºC, the yield strength of carbon steel is approximately 3 ksi.

The sealing station consists of a tube crimper/welder and tube cutter. The crimper/welder performs the dual function of crimping the canister evacuation port and seal welding the crimped tube using resistance welding. While still connected to the drying station equipment, the canister evacuation port seal weld is checked to verify its integrity. The tube cutter is then used to disconnect the drying station from the canister.

IIH. Melt-Dilute Furnace

The primary candidate for this application is an air-cooled induction heating system called Direct Electric Heating (DEH) developed by Inductotherm, Corporation in about 1998. [11,12] Induction heating offers the advantage of rapid heating by coupling directly to the carbon steel canister. The canister acts as the heating element in this case. Heat to melt the spent fuel assemblies is transferred by radiation and conduction to the fuel assembly that is inside the canister. The typical furnace footprint is about 53 inches wide, 64 inches long and 38 inches high with a 17-inch diameter opening in the crucible for the canister.

DEH technology offers advantages for the MMD facility. The technology was developed for the aluminum industry to make available an efficient, reliable and a highly productive controllable system with improved safety. The furnace was designed for rugged use and is very efficient. The technology applies induction-heating experience combined with air-cooling. Induction heating reduces the total heat input required by minimizing heating time and heat loss to the surroundings. Molten aluminum tends to dissolve iron very slowly below 1000 ºC; thus, decreasing exposure time at high temperature is desirable.

The DEH furnace utilizes the best qualities of an electric furnace with almost none of its drawbacks. It provides a compact and simplistic design and eliminates the need for traditional water-cooling in typical induction systems. The elimination of water near molten metal removes the possibility of a steam explosion, which improves operational safety. Additionally, without water cooling, the system is not restricted to low temperatures and freezing conditions when operating in cold climates. Airflow through the DEH system is about 2000 cfm, which keeps the furnace shielding and coil temperatures at about 35-40 ºC during normal furnace operations. The cooling air is filtered at the inlet, passes around the outside of the coil/crucible and typically exhausts clean air at the front of the furnace.

Shielding around the crucible in the DEH furnace will be provided to reduce the radiation field from the fuel in the canister. Sufficient airflow between the radiation shielding and the coils can be maintained without effecting furnace operations.

III. Melting Station

At the melting station, spent fuel is heated to about 850 ºC until fully melted and alloyed with depleted uranium. Induction heating allows rapid heating of the carbon steel canister and fuel assembly with some stirring of the melt to expedite the dilution process. The heating cycle is expected to be about 1 hour. Either deleted uranium metal or aluminum depleted-uranium alloy is used to dilute the spent fuel to below the proliferation limit of < 20% ^{235}U. Dilution material is calculated using reactor accountability data and included in the fuel basket before loading the spent fuel into the canister. The amount of extra aluminum and depleted uranium added to the melt gives a final composition of less than 13.2 wt% uranium in the alloy and a liquidus temperature between 646 and 660 ºC.

The primary containment is the carbon steel canister and the secondary containment is the alumina furnace crucible and furnace top installed at the melt station prior to melting. The secondary confinement space is operated at a slight negative pressure to eliminate pressure buildup in the space and to provide air in-leakage. During processing all radioactive products including volatile species are kept inside the evacuated and sealed canister. In the event of primary containment failure, volatile fission gases from the secondary confinement space will be trapped and not released to the environment. The alumina furnace crucible will catch any retain molten metal and will be disposed of along with the furnace induction coil. A spare crucible and coil will be available for quick change-out if needed.

After melting and alloy dilution, the furnace is opened and allowed to cool until the temperature is below the alloy liquidus temperature. The furnace is then moved to either the welding station where the treated fuel canister will be clad with aluminum or stainless steel for basin storage or to the cell door and loaded into the transfer cask for transportation to dry storage.

Temperature of the melt will be determined by monitoring the canister temperature using thermocouples. Video cameras will be placed through out the facility to assist in monitoring the process from the control room and to assist in process operations. Radiation monitors will determine the presence of radioactive products in the furnace traps and will determine the level of radiation in the vicinity of the furnace to protect technicians inside the cell.

IIJ. Process Monitors/Controls

All process parameters and equipment conditions can be remotely monitored and/or controlled from the control trailer . The moveable furnace related parameters could be connected through a flexible, non-conductive, cable ladder harness to a fixed portion of the main trailer. The welder monitoring and/or control parameters would be separately coupled to data modules in that trailer. All other controls and monitors would be similarly connected. Any process monitoring or equipment conditions (e.g. furnace movements, leak detection, etc) that could be monitored would be observed by remotely controlled video cameras, providing either general views or close-up inspections.

All controlled or monitored parameters within the main trailer would be brought together at the bank of data modules, consisting to analog and digital data input and outputs, that are coupled to the control trailer by a rugged data cable (i.e. Ethernet, fibernet, or similar).

All video views would be controlled from the control trailer and could also be viewed, as needed, from locations in the process trailer. Any required computer control, data monitoring, and video recording would be within the control trailer.

Some automatic controls will be required for the furnace, drying station, welding station, and other operations. For simplicity and maintainability, the use of dedicated loop controllers will be preferred over an integrated automation system.

Key process parameters such as canister temperature and soak times will be logged and archived. An industrial data logging system such as Compact Fieldpoint will be used.

III. SUMMARY

The objective of the MMD Project is to develop the mobile Melt-Dilute technology in preparation for active deployment to the Newly Independent States (NIS) of the FSU. Mobile Melt Dilute (MMD) technology has the potential to provide key benefits to the Department of Energy (DOE) including:

- MMD provides an immediate proliferation solution for the disposition of HEU that would otherwise remain at its current location for a period of some years while in the queue for the Russian Research Reactor Fuel Return Program.
- MMD yields a LEU ingot and hence is an alternative solution to the Russian Research Reactor Fuel Return Program that would limit programmatic risk for meeting non-proliferation objectives.
- MMD provides an end product that is a solid metallic ingot in a steel canister, which does not lend itself readily to the developmental needs of a radiological dispersal device (RDD).
- MMD provides an economic and mobile proliferation solution for HEU orphan sources.
- MMD provides an alternative solution to the current HEU blend-down disposition path for fresh fuel.
- MMD technology can be extended for use with research reactor fuel clad in materials other than aluminum.
- MMD provides a rapid deployment disposition option for HEU research reactor spent fuel in at-risk security locations worldwide

ACKNOWLEDGMENTS

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