An Investigation into the Transportation of Irradiated Uranium/Aluminum Targets from a Foreign Nuclear Reactor to the Chalk River Laboratories Site in Ontario, Canada – 12249

Malcolm Clough and Austin Jackson
Atomic Energy of Canada Limited (Canada)

ABSTRACT

This investigation required the selection of a suitable cask and development of a device to hold and transport irradiated targets from a foreign nuclear reactor to the Chalk River Laboratories in Ontario, Canada. The main challenge was to design and validate a target holder to protect the irradiated HEU-Al target pencils during transit. Each of the targets was estimated to have an initial decay heat of 118 W prior to transit. As the targets have little thermal mass the potential for high temperature damage and possibly melting was high. Thus, the primary design objective was to conceive a target holder to dissipate heat from the targets. Other design requirements included securing the targets during transportation and providing a simple means to load and unload the targets while submerged five metres under water. A unique target holder (patent pending) was designed and manufactured together with special purpose experimental apparatus including a representative cask. Aluminum dummy targets were fabricated to accept cartridge heaters, to simulate decay heat. Thermocouples were used to measure the temperature of the test targets and selected areas within the target holder and test cask.

After obtaining test results, calculations were performed to compensate for differences between experimental and real life conditions. Taking compensation into consideration the maximum target temperature reached was 231°C which was below the designated maximum of 250°C.

The design of the aluminum target holder also allowed generous clearance to insert and unload the targets. This clearance was designed to close up as the target holder is placed into the cavity of the transport cask. Springs served to retain and restrain the targets from movement during transportation as well as to facilitate conductive heat transfer.

The target holder met the design requirements and as such provided data supporting the feasibility of transporting targets over a relatively long period of time.

INTRODUCTION

There was a requirement to investigate the feasibility of shipping irradiated HEU-Al target pencils from a foreign nuclear reactor to the facilities at Chalk River Laboratories (CRL) in Ontario, Canada for subsequent processing. The key challenge was to select a system to protect each irradiated target from mechanical degradation, to minimize impact and fretting damage, and to protect against overheating during transportation. Additional considerations were to ensure the targets could be loaded under water into the transport cask without difficulty.

The known inputs at the start of this study were the contents and construction of the targets as well as knowledge relating to the irradiation and subsequent processing of the targets. To determine the type of transport system (cask and target holder) to be used there were a number of requirements to be established. A brief and non-exhaustive list of these considerations is given below.

Project Inputs

- Number of targets to be transported.
- Decay heat power for each target.
- Expected transportation time.
- Maximum allowable temperature of the targets.
- Selection of a suitable cask.

The total number of targets that could be transported in the same cask was determined by the requirement for a radioactive shipment to be below 15 g to become “fissile excepted” as per paragraph 672 of reference [1] to avoid the need for criticality analysis to be conducted. This meant that a maximum number of six targets could be transported in the same container since the accumulated fissile material was just under the 15 g limit. Therefore, the number of targets was established at six.

The decay heat values for each target were supplied by CRL Nuclear Physicists. The decay heat curves produced involved the calculation of the total decay heat and the spectrum of gamma and beta particles from the targets based on irradiation conditions. The value of decay heat at the start of transporting the targets was determined by how long it would take to unload the targets from the reactor into the fuel bay, provide initial cooling of the targets and load the targets into the cask. The total time was estimated to be 10 hours, which corresponded to a peak decay heat of 118 W at the start of transportation.

For the fissile material being transported time was an important factor since the processing yield of the material, within the targets, is based on its 66 hour halflife. This information together with the need to cool the targets for 10 hours underwater initially, dictated that air transit would be needed. It was determined that an estimated 10 hour period would be required for transportation.

Figure 1 shows the calculated values of decay heat from the time the targets were ready to be transported. It can be determined the decay heat would drop to 82 W/target over the 10 hour transit period.

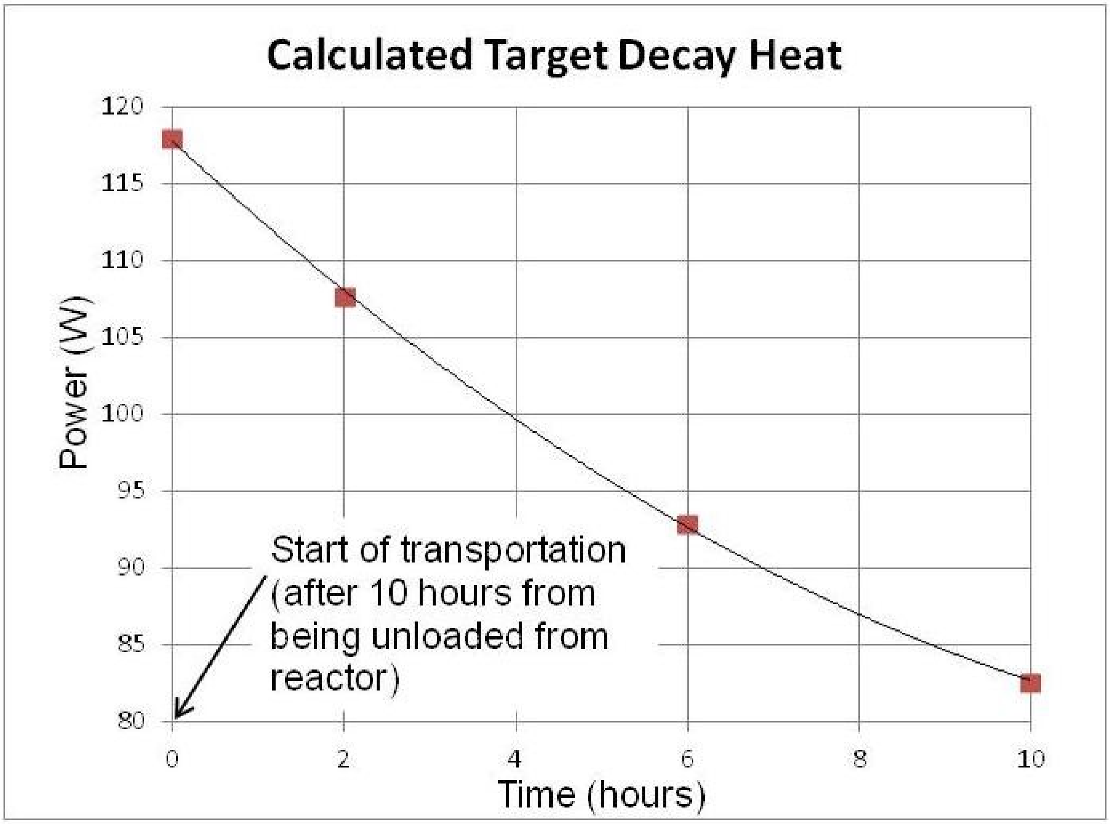

Figure 1 Calculated Target Decay Heat Time History

The temperature of the targets was limited by processing constraints since high temperatures would affect the extraction of products from the targets. A temperature in the order of 350°C was estimated to be the point where processing yield could be affected. Therefore, a conservative value of 250°C was chosen as the maximum allowable temperature of each target pencil during transport.

To transport the targets, a cask was chosen from a number of existing casks that already met certain safety requirements. The most suitable cask chosen was currently used for transporting Co-60. The nominated cask has a mass of 3447 kg, a diameter of 0.8 m, height of 1.24 m, a 254 mm lead radiation shield around the inner chamber, and a steel lining. The cask provided a suitable diameter although it was approximately 150 mm too long. To fill the additional volume an Al spacer was added above the target holder.

Once the above inputs were established, the design of the target holder could commence. The following sections summarize the design and validation of the target holder.

TARGET HOLDER DESIGN

A schematic shown in Figure 2 lists the major components of the transportation system which comprises the cask and its lid, the target holder (labeled Al heat sink) housing the six targets, and an Al spacer to fill the gap inside the cavity of the cask.

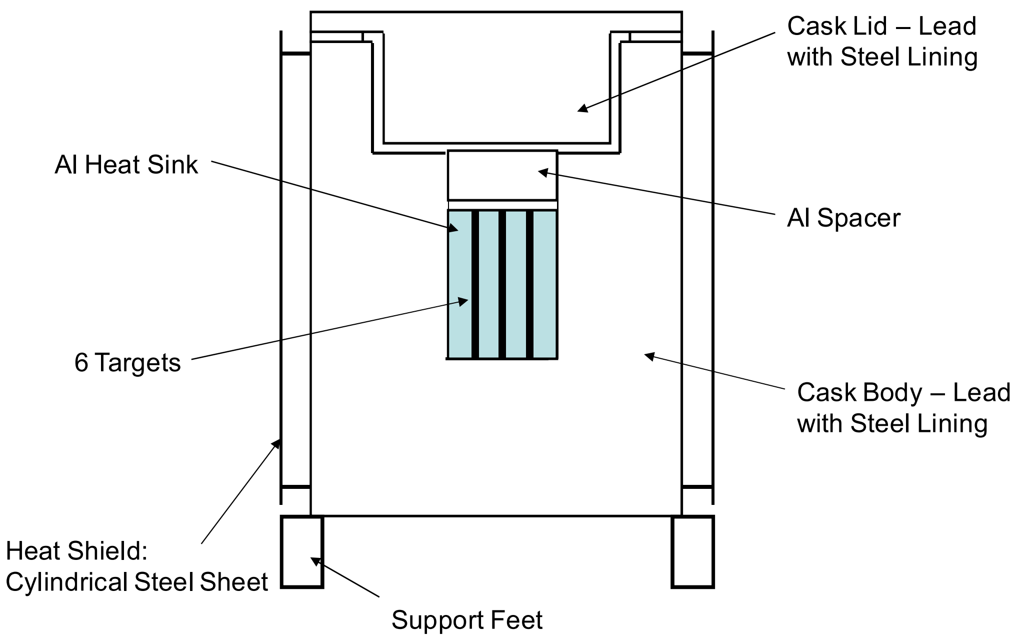

Figure 2 Major Components of Transportation System

A number of specific design requirements were determined based on discussions with operations staff both at the source and receiving ends. This included observing and reviewing current processes and tools used in loading and unloading targets underwater in fuel bays. These considerations together with previously determined inputs are listed below.

Design Requirements

1. Provide a means of transferring heat, representing that induced by decay heat, from the targets to the target holder and also from target holder to cask surfaces such that the maximum target temperature during transportation does not exceed 250°C.

2. Allow for problem-free installation and removal of targets under 4.5 to 6 m of water using simple tools to avoid pinching and crushing of the targets.
3. Provide a means of restraining the targets during transportation to avoid impact and fretting damage to the targets.
4. Accommodate the effects of a bent target to simulate a known incident where a target was observed to be bent by approximately 1 mm after irradiation in the reactor.
5. Accommodate water drainage and drying processes after loading targets.
6. Accommodate the effects of an oxide layer on the surface of the dummy targets as this would be present and would likely hinder heat transfer from actual targets to the target holder.

A unique target holder (patent pending) was designed that consists of three main components; a central pillar connected to a base, and two pairs of segments (designated inner and outer petals) shown schematically in Figure 3. The inner petal is allowed to slide radially along fasteners connected to the central tower. Springs acting in parallel with the fasteners force the petal in the outward radial direction. The outer petal has the same set-up, except it is connected to its respective inner petal.

The left hand iso-view in Figure 3 shows the targets located between the outer petals (blue) and the inner petals (yellow) with the central post (orange) connected to the base (grey) together with springs and fasteners. The side view is shown in the upper right hand view of Figure 3.

Figure 3 also shows a plan view of the target holder in its open position (out of the cask) as shown in the lower left view, and when it is inserted inside the cask, as shown in the lower right view. These views show the petals close up when the target holder is inside the cask. A photograph of the actual target holder that was manufactured for testing is provided in Figure 4. In the open position, the targets can easily be loaded into the target holder due to the clearance when the inner and outer petals are expanded radially by the springs.

The target holder components were manufactured from Al due to its relatively high thermal conductivity and its resistance to degradation in radioactive fields. From the side view in Figure 3 it can be seen that a taper is present on the lower edge of each outer petal. This assists in closing up the target holder assembly when it is inserted into the cask cavity, shown by Figure 5. In Figure 5, the target holder is lowered into the cylinder representing the cask cavity and the inner and outer petals close up such that the springs compress the petals onto the targets. The spring load enhances heat transfer to both the target-to-target-holder and target-holder-to-cask interfaces as well as provides a means of restraining the targets during transportation. The spring stiffness was chosen to balance ease of assembly into the cask, to provide sufficient restraint of the targets by avoiding excessive movement and to provide thermal contact to encourage heat to flow from the targets to the cask walls. To avoid overstressing or crushing of the targets, it was important to have sufficient remaining compression within the springs.

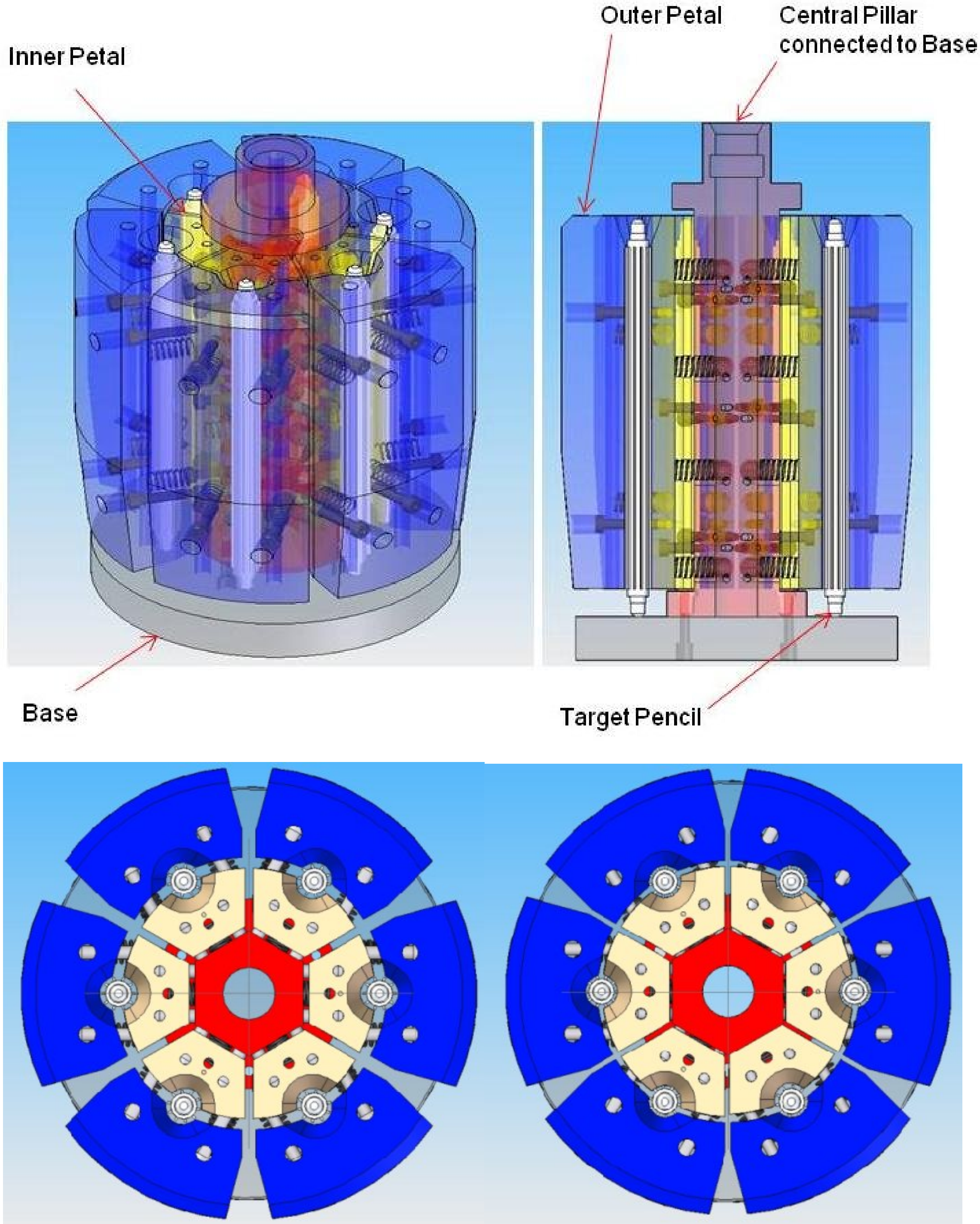

Figure 3 Target Holder Design Concept and its Key Components (above) and Views Showing the Target Holder in its Free State (lower left view) and in its Closed State, when Fitted Inside the Cask (lower right view)

A commercially available lifting tool with a ball lock pin that is actuated from the tool's handle was used to lift the target holder. The ball lock pin engaged into the upper internal feature of the center post shown in Figure 3 and then locked into position. The tool's frame is made from a light weight Al tube with drainage holes, shown in Figure 5.

From Figure 4, it can be seen that the radial clearance between the targets and the holes in the target holder are generous and greater than 2 mm to accommodate a bent target. In addition to this clearance, a lead-in taper was added to improve the ease of target loading into the target holder.

Holes machined to house the springs in the target holder initially resulted in pockets that could potentially trap water during the drainage process. Any residual water left in the cask has the potential to boil and pressurize the inside of the cask threatening the integrity of its sealing system. To assist in the draining of these pockets, additional vertical drainage holes were added that connected with holes for the spring allowing water to drain out the bottom of the target holder and out through the cask drainage hole.

The above descriptions of the design have met the design requirements 2, 3 and 5.

Figure 4 Target Holder in Free State with Receiving Holes Providing Clearance for the Targets

Figure 5 Target Holder Inserted into a Representative Cask Cavity

VALIDATION

A specific Test Plan was prepared for the validation phase which required special purpose test equipment to be designed as well as special preparation of the test targets prior to testing.

Test Apparatus

The role of an actual cask, for transporting the targets, is to retain the target holder during shipping, act as a radiation shield and function as a thermal heat sink for the targets. The plug (or lid) of the actual cask provides additional shielding and a heat sink as well as preventing excessive longitudinal movement of the target holder during shipping. The test cask was required to replicate the internal dimensions of the actual cask, to provide representative surfaces and geometry of the actual cask, and was also required to have representative interfaces to replicate heat transfer. Since a full size cask was not available for testing, a new surrogate design was required and consisted of the parts shown in Figure 6. In the case of the test cask the lid included an Al heat sink and components to manage the instrumentation and provide sealing to allow for drainage and drying processes.

The test cask was made from a stainless steel frame filled with lead with an internal chamber with the same dimensions as the designated cask. For testing and practical purposes, the external geometry of the test cask was significantly reduced. The design and manufacture of the test cask was completed on site at CRL.

It was considered important to ensure the lead-to-steel liner contact surface would be similar for both the actual cask and the test cask. These interfaces can affect the resistance to heat transfer and therefore could affect the validity of the temperature measurements. Therefore, the manufacturing method employed for the actual cask was retained for the test cask which involved manufacturing the shell and then pouring in molten lead. Thermocouples were installed inside the cask to provide a measure of the leads' internal temperature during testing.

The lid of the test cask was designed to cover the access into the internal cavity and allow the instrument leads to pass through. The structure of the test lid consisted of instrumentation flanges and gaskets to provide a seal to enable drainage and drying processes to be tested. Inside the test lid was a heat sink, to represent the thermal mass of the actual casks' lid, and also to insulate the instrument connections from high temperature.

The target holder and Al spacer were modified to accept thermocouples for temperature measurements.

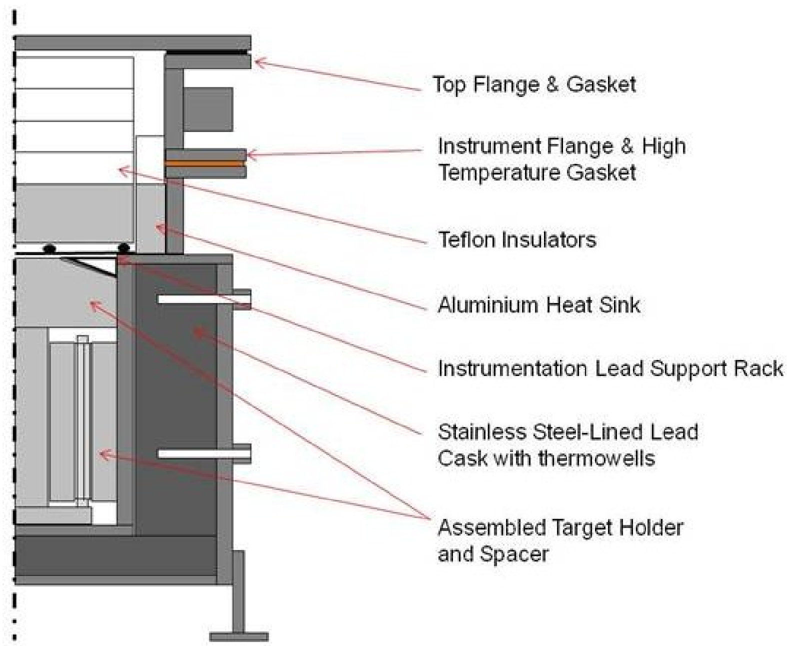

Figure 6 Test Transportation System Comprising Target Holder, Test Cask, Heat Sink and Instrumentation Management Components

Target Preparation

The test targets were modified using non-radioactive target housing material containing 6061 grade Al instead of HEU-Al alloy of the actual target. All the modifications to the test targets were intended to simulate the post-irradiated conditions of the production targets and provide access for instrumentation. As such, two radial holes were added to the test targets to house the thermocouples. The depth of the holes was slightly past halfway into the target to ensure the thermocouples were in close proximity to the core of the target. Thermal cement was placed inside the holes to secure the thermocouples in place and to provide a thermal conduction path between the thermocouple and the target heat source.

Cartridge heaters were used to provide power representing decay heat produced by the actual irradiated targets. To receive the cartridge heaters, longitudinal holes were machined into the targets. The clearance between the cartridge heater and the test targets was relatively tight to ensure heat was adequately transferred to the test target body.

A number of test targets were also bent to represent the condition once found during post irradiation. Any bending defect would reduce thermal contact between the target and the target holder and as such it was decided this needed to be validated. A 1 mm of axial distortion was found in the field, thus a bend of 1.4 mm was applied to the targets for conservatism.

An oxidation layer has been observed on actual targets after being removed from the reactor with estimated thicknesses ranging from 1 to 20 µm. This oxidation layer would hinder conductive heat transfer. To account for this in the tests, a representative oxide layer was added to the targets by soaking them in an autoclave. To remove residual oils from manufacturing, the targets were first exposed for 10 minutes to acetone, and then 10 minutes to methanol. The autoclave was cleaned and then exposed to water within the autoclave at 163°C with a pH of 5 for 22 hours. To measure the oxide layer, a 2.5 mm slice was removed from one of the test targets using wire electrical discharge machining. The oxide layer thickness was measured using an optical microscope after the cut surfaces were polished. Oxide layer thicknesses were measured at 111 locations and the average oxide layer thickness was established at 2.7 ± 0.6 µm. These values were less than expected, but were considered acceptable for the testing since they were within the range of the production targets.

Validation testing was performed with targets that had an oxide layer and also with a bend of 1.4 mm to meet design requirements 4 and 6.

Instrumentation and Data Acquisition System

The Data Acquisition and Control system (DAQ) used for testing was developed and built on site and is shown in Figure 7. The system logged thermocouple data and allowed for the operator to control the power to the heating cartridges.

The thermocouple data cards (8-channel input temperature loggers) were connected to a computer via a USB port for calibration, recording settings and downloading data. During logging, the USB port was connected to the power supply. The cards were set up for K-type thermocouples that were logged once every second for each channel. There were 32 thermocouples used to measure the target, target holder, test cask and various interface temperatures. Figure 8 shows the position of the thermocouples within the target holder, the targets, the upper heat sink and the test cask. The left hand view in Figure 9 shows the target holder with wires protruding that were connected to the six cartridge heaters and various thermocouples.

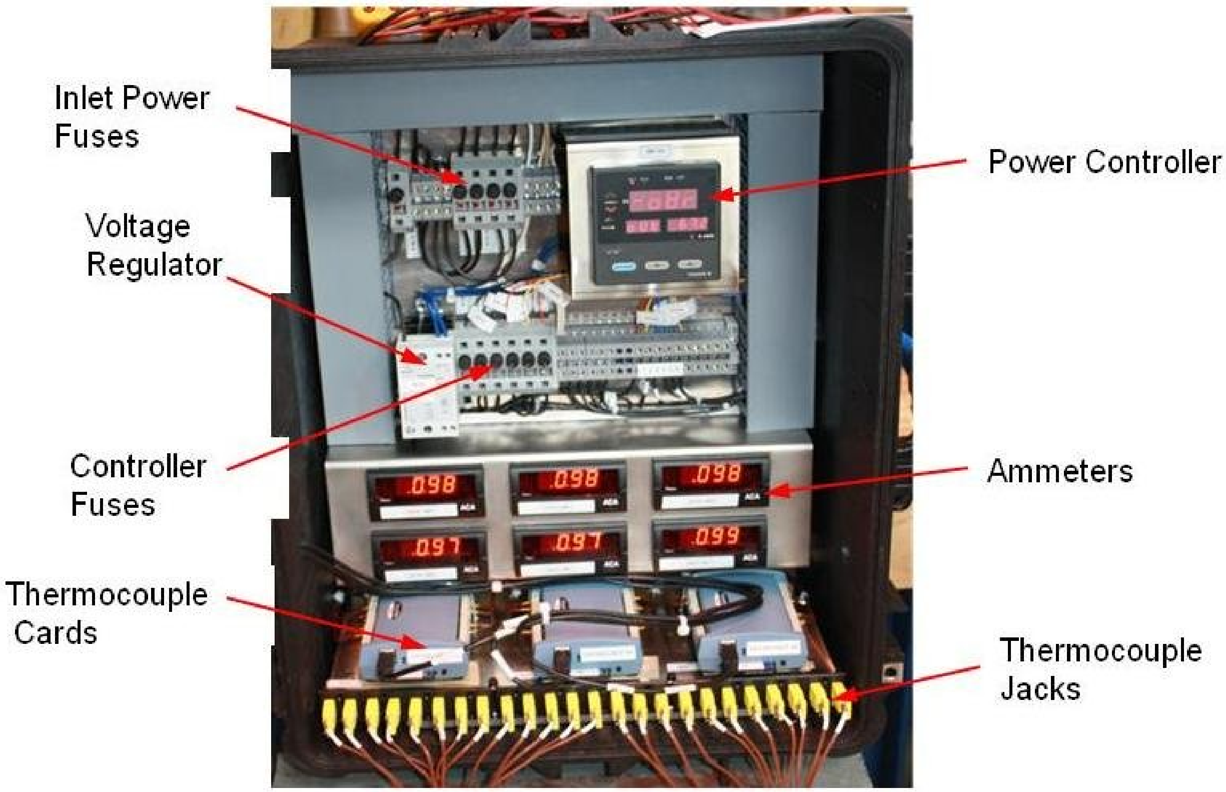

Figure 7 Data Acquisition System Used for Validation Testing

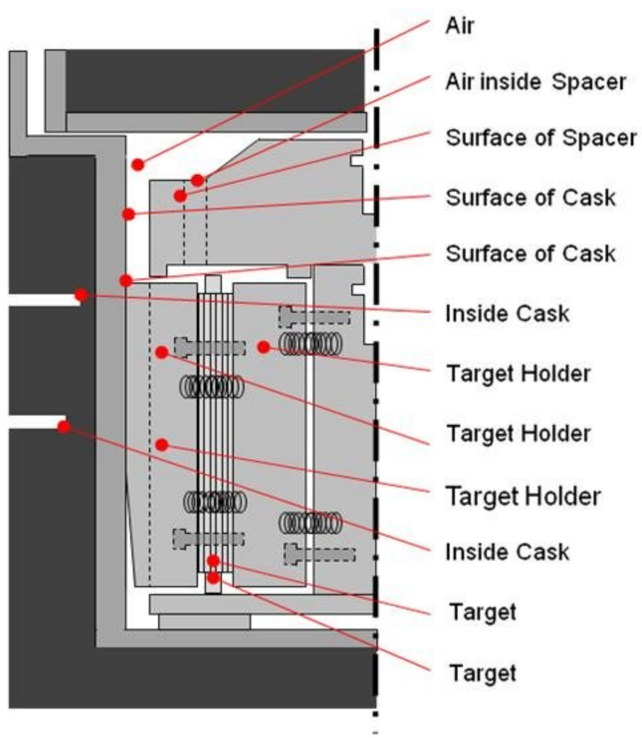

Figure 8 Schematic Showing Locations of Thermocouples

Thermocouples with 30 gauge wire were used to provide a small exposed bead diameter to respond quickly to changes in test target temperature. The thermocouple's lead lines were routed through the test cask and plug assembly to the top of the instrument flange. They were connected to "quick connections" and were routed to the outside via feedthroughs, shown in the right hand view of Figure 10. Connections outside of the test apparatus were connected to the DAQ system.

A voltage regulator was used to set the voltage to the heaters (in parallel), and six current meters displayed the current to each heater. The decay heat was controlled and logged manually by the operator.

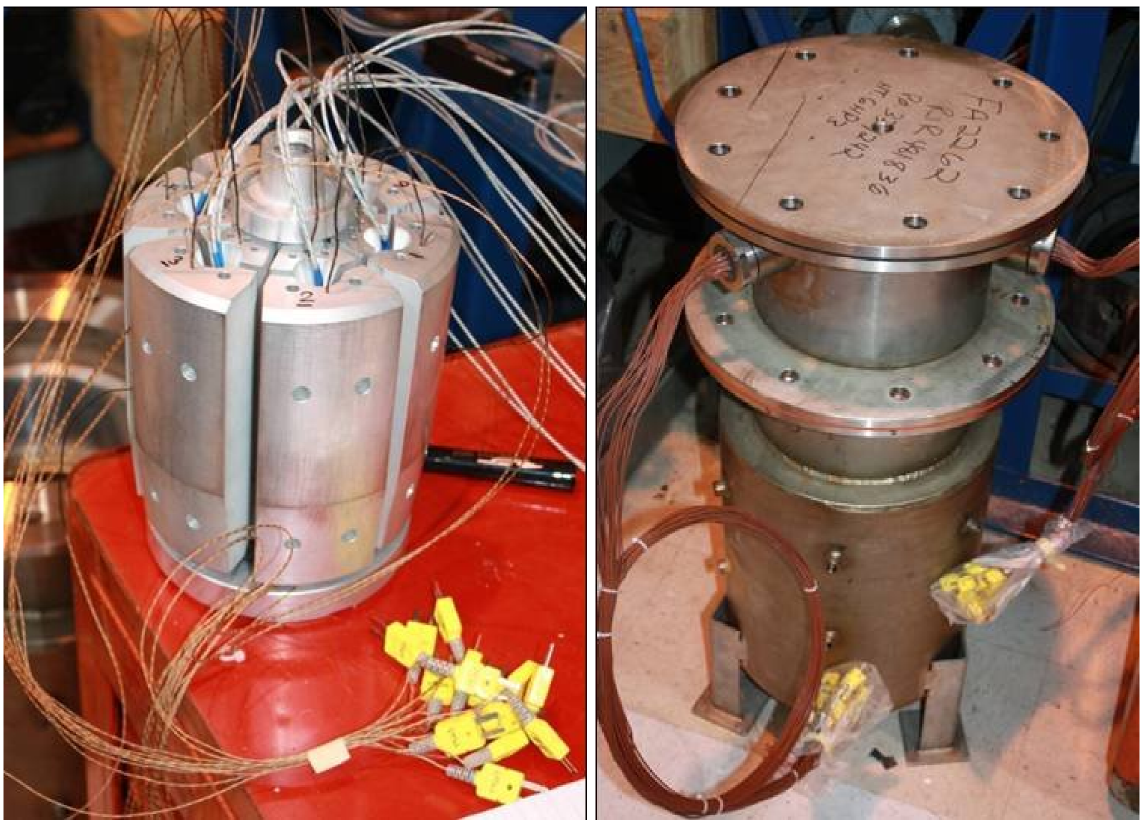

Figure 9 Left View: Instrumented Target Holder. Right View: Test Assembly with Feedthroughs (shown under the top flange).

Figure 10 shows the profile of the power required plotted together with the actual power that was supplied to the cartridge heaters during one of the tests. It can be seen there was deviation from the desired profile due to the stepped nature associated with the manual operation and the temperature-dependant resistance of the cartridge heaters. However, in general the actual power supplied into the targets was considered to be acceptable and was generally conservative.

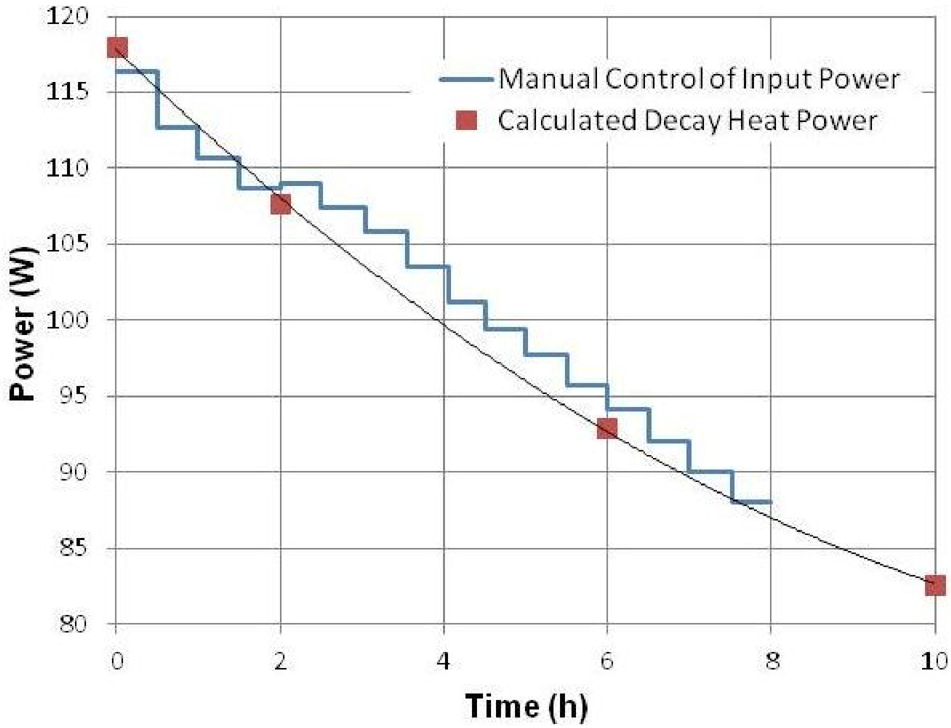

Figure 10 Manual Control of Power to Cartridge Heaters v Power Desired

TEST RESULTS

Figure 11 shows the temperature profiles recorded from the thermocouples fitted closest to the core of each test target. It can be seen the targets' temperatures initially rose relatively rapidly at approximately 3°C/s after power was applied. This rapid heating phase was likely due to the low thermal mass of the dummy targets, the time delay of any natural convective cooling, and the thermal inertia of transferring heat into the transportation system.

After the initial rise, the targets' rate of temperature increase dropped and gradually matched that of the petals (<0.03°C/s). After 5.5 hours of testing the maximum temperature recorded was 300°C after which it decreased to 294°C after 8 hours.

It was observed, that although each target had a similar temperature profile, there was a spread of 75°C in the temperature measurements for the targets tested. This spread in temperature was likely due to the orientation of the targets within the target holder. Theoretically there would only be a minimum of three effective points of contact between the targets and the target holder due to the bend in the targets. The location of these contact points would influence the direction and magnitude of lateral heat flow.

As already stated, the peak temperature reached by the test target during testing was 300°C and the goal was not to exceed 250°C. However, there are a number of compensations to take into account between testing and real conditions. The key differences between the test equipment and conditions versus the actual case are listed as follows:

- The test cask was significantly smaller.
- There was no compensation for dispersing gamma decay heat to the transportation system. The assumption for testing was all the decay heat would be directly produced by the test targets via the cartridge heaters.

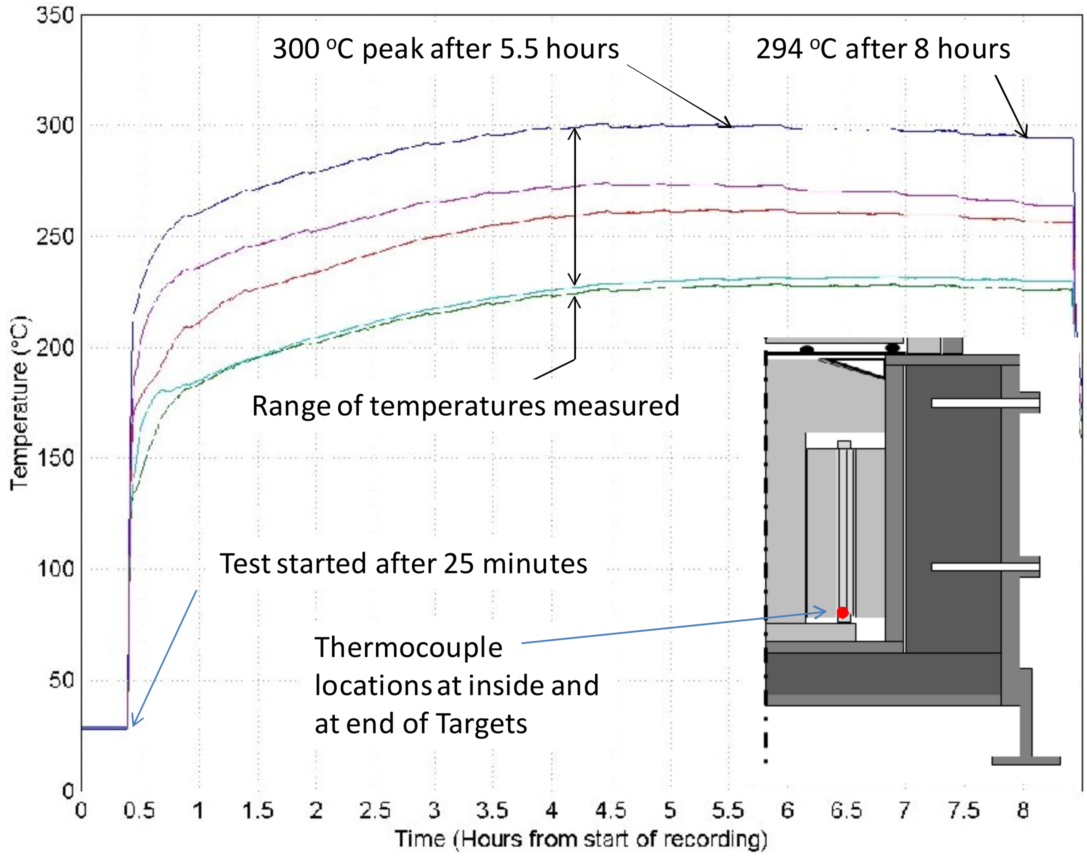

Figure 11 Target Temperature Time History with all Components at 25°C at Start of Test

The impact of having a smaller cask for the experiments meant its thermal capacity, thermal conductance and effective thermal diffusivity would all be more conservative compared the actual cask as verified in Table 1.

The impact of the thermal mass is that after 8 hours the actual cask would have risen to a temperature of approximately 80°C while the test cask would have risen to approximately 575°C (assuming that a value of 118 W/target is induced into the cask with zero heat loss to the surroundings in an ambient temperature of 25°C). Therefore, the thermal mass significantly affects the temperature of the cask which in turn affects the maximum target temperature.

The cask assembly can be considered as a thermal conductor due to the high conductivity of lead and the tight contact between the lead and the stainless steel liner (due to the shrinkage of the lead after it solidified after being poured into the steel liners of both the experimental and actual casks). As a result, the major hindrance in removing heat from the full assembly is the amount of area on the external surface. There is considerable difference between the test and actual cask. The test cask has lower thermal conductance as summarised in Table 1. When taking into account the reduced size of the smaller test cask and its thermal conductance, the steady state temperature difference between the inner wall of the test cask and the actual cask was calculated to be 85°C; this translates to a lower target temperature of approximately 69°C.

Table 1
Thermal Compensation Factors Between Experiment and Real life Conditions

Parameter	Actual Cask	Test Cask	Impact
Thermal Mass (kJ/K)	423	36	Test cask needs only 1/12 of the energy to raise temperature by the same amount as for the actual cask
Thermal Conductance (W/K)	19	6	Test cask conducts only 1/3 as much heat
Effective Thermal Diffusivity ($(Ms)^{-1}$)	46	165	Test flask will move to its equilibrium temperature almost 3 times quicker

Other conservative factors exist that have not been quantitatively considered, such as the impact of the radiation power generation. The 118 W applied at the start of testing originates from the emitted radiation from the fission products within the targets, which is expected to be transmitted 50% through beta particles and 50% through gamma rays. The beta particles are expected to transfer all of their energy into the target, while only about 20% of the gamma energy is transferred directly to the targets. The remainder of the gamma energy would be transferred to the target holder and transfer cask. Thus, the expected thermal power generated in the targets is only 71 W (59 W from beta particles and 12 W from gamma particles while the remaining 47 W would be deposited predominantly into the cask). Calculations, using the experimentally derived interface conduction coefficients, found that this decrease in centralized power would result in a decrease to the maximum target temperature of 31°C.

In summary, the expected maximum target temperature when transporting in the actual cask, based on the above assumption and compensation for conductance, was 231°C (300°C - 69°C), which is less than the design requirement of 250°C meeting design requirement 1. There are other compensation factors that have been mentioned but not taken into consideration which emphasises the peak derived target temperature of 231°C was conservative.

CONCLUSIONS

A suitable transport cask was selected and a device for housing irradiated targets for loading, unloading and transportation has been designed, built and validated. The device was successful in meeting all design requirements for this feasibility study.

Experiments were conducted with a custom test facility to confirm that the design met the maximum temperature requirements during shipping. Results from tests showed that the peak temperature in the apparatus was 300°C. By compensating for experimental considerations, such as reduced thermal conductivity of the test cask versus that of the actual cask the expected maximum target temperature reduces to 231°C. This is below the designated peak value of 250°C.

It can therefore be concluded, based on the content of this paper and from a heat-removal standpoint, the feasibility of transporting targets from a foreign nuclear reactor to Canada is possible, although further testing with irradiated targets and a full size cask would be a recommended next step.

REFERENCES

[1] IAEA Safety Standards Series, "*Regulations for the Safe Transport of Radioactive Material"*, No. TS-R-1 (ST-1, Revised), 1996 Edition (Revised).

ACKNOWLEDGEMENTS

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