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Concept Study for a Passively Cooled ISO Container for the Transport of Materials from Dounreay

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ABSTRACT

Over the next few years the engineering support required to meet the UK Nuclear Decommissioning Authority's strategic targets for redistribution of materials will ramp up significantly. To carry out these activities efficiently requires innovative solutions to be applied. This paper describes an approach for the transport of certain categories of heat-generating materials which offers operational and payload benefits.

For the transport of certain materials, the use of a relatively small package is required for handling purposes, carrying internal product cans of material containing fissile product. It is proposed that 'INS3578' packages could be used. The packages are to be contained within an ISO container. Due to the heat-generating nature of some of the material to be transported, consideration must be given to the evacuation of heat from the container.

A passively cooled container has the advantage of not requiring the complication of a forced ventilation system and refrigeration plant. This has operational, licensing and security benefits.

The paper describes a concept study undertaken to investigate a passively cooled container. The paper describes options that have been considered and the results from calculations undertaken to determine the package temperature.

The results from the concept study suggest that with further work and further consideration of the heat load to be placed inside the container, the concept of a passively cooled ISO container for the transport of material might be a viable option.

INTRODUCTION

Dounreay is located in Caithness, on the North coast of Scotland, and was established as a research reactor site with fuel production and reprocessing facilities [1]. At the time of selecting a site, consideration of a potential explosion was one of the reasons for choosing the Dounreay site because in the 1950's, the site was at least 5 miles away from a population of just 2500 [1]. The chosen site was also selected due to convenient access to sea water for cooling purposes.

An experimental fast breeder reactor was constructed at the site in the 1950's. This type of reactor could produce new fuel as well as generate electricity [1]. This was seen as a solution to the UK's energy crisis following the Second World War. The characteristic 'Sphere' on the Dounreay site was chosen in which to locate the experimental fast breeder reactor, as a sphere was considered to be the strongest means of containing explosive forces that breached the primary containment around the reactor. The reactor vessel was located within the lower half of the sphere within a biological shield of concrete [1].

Between 1967 and 1972, 30 tonnes of breeder material was removed from the Fast Reactor and reprocessed to produce new fuel. The success of the experimental reactor led to the construction of a second Prototype Fast Reactor (PFR) between 1968 and 1974. The PFR was the final step towards bringing fast reactors in to use as conventional power stations. However, in the 1980s it was decided that there was no need for such development and the PFR was closed in 1994 [1].

The facilities constructed at Dounreay, which also include a materials test reactor, experimental criticality reactor and fuel cycle area are no longer required. The Dounreay site is undergoing decommissioning with a target to complete site closure by 2022 to 2025 [1].

There are a range of materials currently in storage at Dounreay. However, in 10 to 15 years many of the storage facilities would need to be replaced with new facilities [2]. Rather than undertake the process of design, build and commission new stores, the transport of these materials to Sellafield would reduce the security risk at Dounreay and is expected to save "hundreds of millions of pounds" in security and infrastructure costs [2]. Transport to Sellafield is currently the preferred option.

The UK Nuclear Decommissioning Authority's (NDA) strategic goal of legacy site decommissioning will require redistribution of materials resulting in an increase in the engineering support over the next few years. To carry out these activities efficiently requires innovative solutions to be applied.

For the transport of certain materials, the use of a relatively small package is required for handling purposes, carrying internal product cans of material containing fissile product. International Nuclear Services (INS) is currently developing a new package, the 'INS3578' which could be used for this purpose across the NDA estate. The packages would be contained within an ISO container. Due to the heat-generating nature of some of the material to be transported, consideration must be given to the evacuation of heat from the container.

A passively cooled container has the advantage of not requiring the complication of a forced ventilation system and refrigeration plant. This has operational, licensing and security benefits.

This paper describes a concept study to investigate the feasibility of passive cooling for transport of materials within the UK.

INS3578 Package

The INS3578 Package is being developed and licensed to carry Category One materials contained within various product can types.

This new asset has been developed with existing NDA estate Category One materials in mind, but also with a view to potential shipments for other customers. Consequently, the new design has been driven by the international road, rail and sea regulations (respectively the ADR, the RID and the IMDG code) and its interpretation by the UK regulator (ONR RMT) [3].

The new package has been designed to transport solid fissile material, Plutonium Contaminated Material and other types of waste, which are contained in cans. The types of products considered can be summarised as PuO_2 powder, MOX residues and pellets, and other waste forms in different cans and overpacks [3].

The INS3578 package is compatible with different can designs used and transported within the NDA estate. This new package design has been developed to interface with facilities which are already in operation. It was decided to reduce the impact of the package on these existing installations to optimise the design with respect to the existing processes and assets [3].

For onsite operation, the INS3578 package will be individually handled during the loading operation. The storage and transport of empty or loaded packages is performed with a stillage. Three stillages will be available to transport 2, 6 or 9 packages at a time. The stillages are designed to fit to the customers transport requirements, to be compatible within the current facilities and to maximise the packing capacity during any transport.

Figure 1 presents a cross-section through the INS3578 Package. Within the cavity there is room for two cans. The package has been designed with a cavity of 660 mm height and 170 mm diameter, and uses liners and spacers, to adjust the cavity geometry to the contents. The package will accommodate cans with diameters between 115 mm and 170 mm, and heights from 230 mm to 315 mm. The internals also help to customise the package behaviours for specific contents by improving the impact absorption and/or the thermal behaviour of the overall design [3]. The cans are surrounded by an inner and outer containment vessel which are constructed from stainless steel. Above the top can is the inner lid, also made of stainless steel. The outer packaging is CLP-NS (Cross Linked Polyethylene – Neutron Shielding) which provides neutron shielding. Within the central section, fins run through the CLP-NS to enhance heat transfer. Between the CLP-NS and fins there are air gaps.

A seal is located between the lid and the body of the package which in this study is assumed to have an upper temperature limit of 150°C.

From the properties of CLP-NS, at around 100°C there is a change in the material property that might be irreversible. For this concept study a target upper temperature of the CLP-NS of 100°C is assumed.

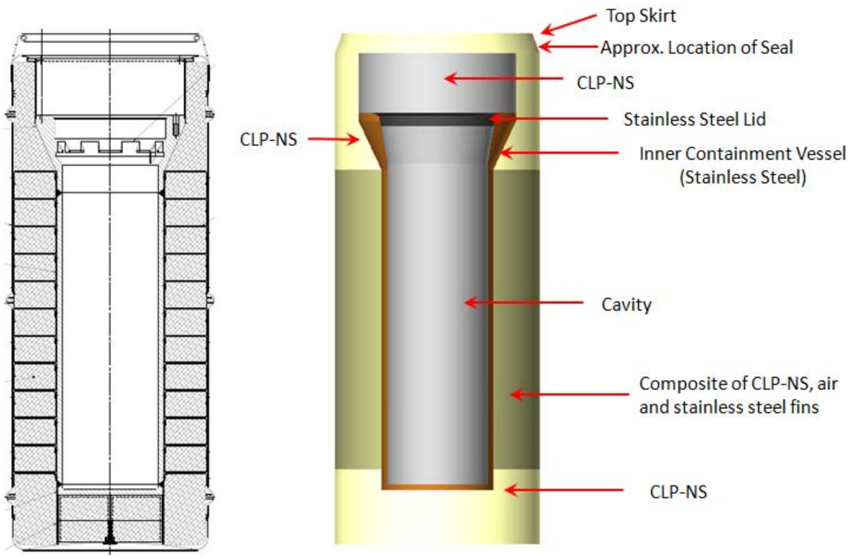

Figure 1. INS3578 flask and the internal components.

ISO-CONTAINER

For modelling purposes, it was assumed that the walls of the security vehicle were perfectly insulating. In all cases the stillages were assumed to be equally spaced within the container.

Ventilation flow through the container is driven by the buoyancy of the air within the container, which will be heated to a higher temperature than the ambient air external to the container. The buoyancy force increases with the separation distance between the inlet and extract points and a larger buoyancy force will drive a higher ventilation flow which is beneficial for cooling. For this reason, openings for ventilation were provided at floor and ceiling level. Openings were provided in the floor directly below the stillages holding the packages. This was so that cool air is able to pass up and between the packages. As this is a concept study, the geometric details of the inlets and outlets are not defined and therefore, it was assumed that these openings would be covered by a grill that is 50% open to the ventilation flow. An appropriate pressure loss coefficient was specified which was augmented by assumed entry and exit loss coefficients.

A number of cases have been investigated to determine the package temperature. The results for three examples are presented in this paper:

Case 1: 36 x INS3578 packages orientated horizontally within 3x3 stillages, with a heat load of 70 W per package, giving a total heat load of 2520 W within the ISO container.

Case 2: 36 x INS3578 packages orientated horizontally within 3x3 stillages, with a heat load of 170 W per package, giving a total heat load of 6120 W within the ISO container.

Case 3: 36 x INS3578 packages orientated horizontally within 3x3 stillages. Only the top two rows of packages contained heat generating material, with a heat load of 170 W per package, giving a total heat load of 4080 W within the ISO container.

METHODOLOGY

For this assessment, calculations have been undertaken using the general purpose Computational Fluid Dynamics code Ansys CFX v14.

For the concept study, a quarter of the ISO container was assessed as it was assumed that the temperature profile would be reasonably symmetrical about the centreline of the container.

Within the flask arrangement, a single 'detailed' package was incorporated for the purpose of resolving the distribution of heat through the flask and hence a more accurate calculation of the external temperature profile. Resolving the conduction of heat through a package also allows the temperature of the CLP-NS to be calculated. Figure 1 presents the resolution of the 'detailed' INS3578 flask. The cans containing heat generating material were not resolved and instead, an appropriate heat flux was defined on the inner surface of the inner containment vessel. For the remaining packages, a heat flux was specified at the external surface.

The top skirt is represented to include the obstruction to the air flow, but does not include conduction of heat from the external skin. The seal is not resolved explicitly and the temperature of the seal is inferred from the surface temperature of the top of the flask which is closest to the seal location.

Only the major features of the stillages were resolved and as the base of the stillages are 68% open, these were represented as being porous via the specification of an appropriate pressure loss coefficient.

For this concept study, the internal fins within the CLP-NS of the INS3578 package were not resolved explicitly and instead, average material properties were defined for the central region comprising CLP-NS, air and fins. The thermal conductivity was determined by a calculation based on a series of resistances in parallel, where each resistance was specified for thermal conduction through a hollow cylinder. Convection and radiation within the air gap was assumed to be negligible. Figure 2 presents the arrangement of the resistances using an electrical network analogy.

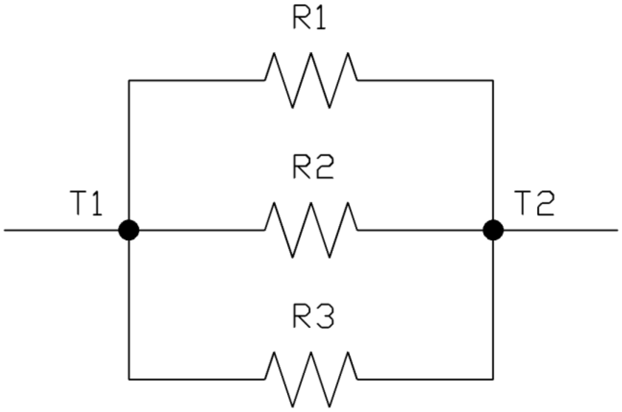

Figure 2. Electrical resistance analogy for approximating the thermal conductivity of the region of the package comprising CLP-NS, fins and air in parallel where R_1, R_2 and R_3 are the thermal resistances of the CLP-NS, fins and air gap respectively [4].

The external ambient temperature was assumed to be a constant 38°C. As the container is assumed to be perfectly insulated, there was no need to define boundary conditions relating to solar insolation on the external surfaces of the container.

The computational model therefore resolved conduction of heat through one package, convection of heat from all heat generating packages as well as thermal radiation within the container.

The heat load within a single INS3578 package was considered at 70 W and 170 W. A 170 W heat load is considered to be an upper bound.

RESULTS

Case 1: 36 x INS3578 packages orientated horizontally within 3x3 stillages, with a heat load of 70 W per package, giving a total heat load of 2520 W within the ISO container.

The air temperature distribution through the centre of the container is presented in Figure 3. This shows stratification of the temperature field as cool air flows from the bottom to the top of the ISO container and is heated by each row of packages. The average temperature of air at the outlet vents is 49°C which reflects a temperature increase of 11°C.

The temperature distribution at the centre of the 'detailed' package is also presented in Figure 3. The maximum CLP-NS temperature is 71°C and in the region comprising fins, CLP-NS and air, the maximum temperature is 70°C and therefore within the upper temperature. The seal temperatures are approximately 50 to 63°C, which are within the upper temperature.

Hence, for this heat load, the various components of the packages are within the upper temperatures assumed in this study.

Case 2: 36 x INS3578 packages orientated horizontally within 3x3 stillages, with a heat load of 170 W per package, giving a total heat load of 6120 W within the ISO container.

This case examines a heat load that is almost 2.5 times higher than Case 1. The air temperature distribution through the centre of the container is presented in Figure 4. This again shows stratification of the temperature field as cool air flows from the bottom to the top of the ISO container and is heated by each row of packages. The average temperature of air at the outlet vents is 61°C which reflects a temperature increase of 23°C.

The temperature distribution at the centre of the 'detailed' package is also presented in Figure 4. The maximum CLP-NS temperature is 111°C and in the region comprising fins, CLP-NS and air, the maximum temperature is 108°C and therefore above the upper temperature. The seal temperatures are approximately 62 to 89°C, which is within the upper temperature.

Hence, for this heat load, the CLP-NS is slightly above the upper temperature assumed for this study.

Case 3: 36 x INS3578 packages orientated horizontally within 3x3 stillages. Only the top two rows of packages contain heat generating material, with a heat load of 170 W per package, giving a total heat load of 4080 W within the ISO container.

This case examines the transport of 36 packages, but with only the top two rows i.e. 24 packages containing heat generating material.

The air temperature distribution through the centre of the container is presented in Figure 4. The average temperature of air at the outlet vents is 57°C which reflects a temperature increase of 19°C.

The temperature distribution at the centre of the 'detailed' package is also presented in Figure 4. The maximum CLP-NS temperature is 107°C and in the region comprising fins, CLP-NS and air, the maximum temperature is 103°C and therefore slightly above the target temperature. The seal temperatures are approximately 44 to 81°C, which is within the upper temperature.

Hence, for this heat load, the CLP-NS is slightly above the upper temperature assumed for this study.

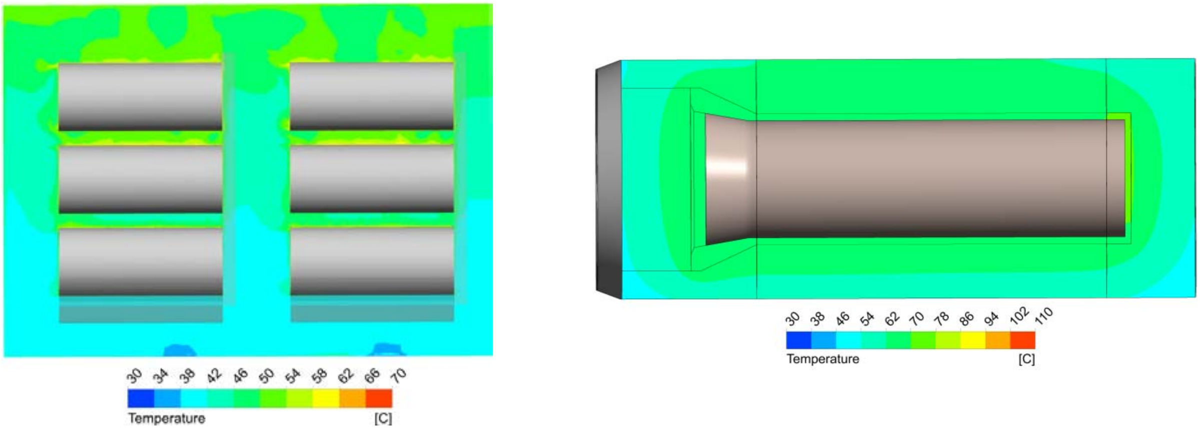

Figure 3. The temperature distribution through the centre of the container and at the centre of the 'detailed' package for Case 1.

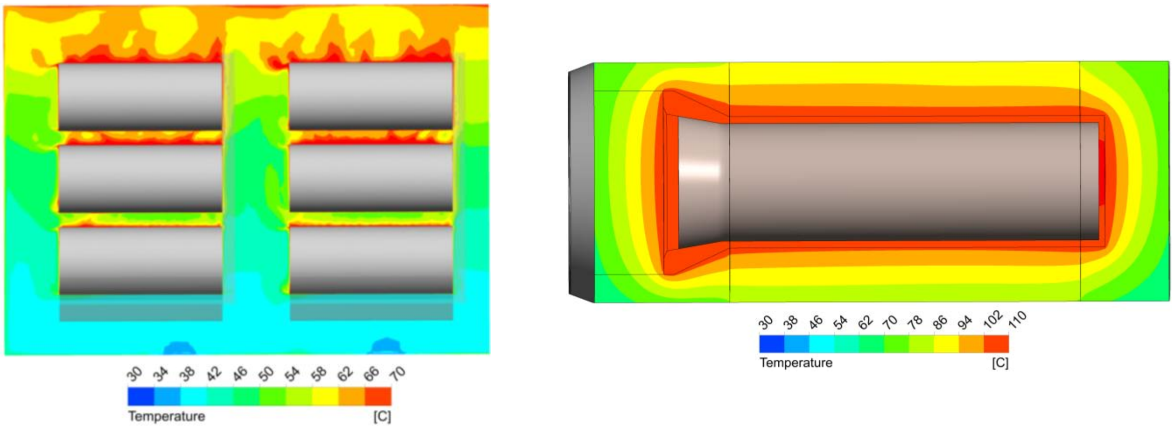

Figure 4. The temperature distribution through the centre of the container and at the centre of the 'detailed' package for Case 2.

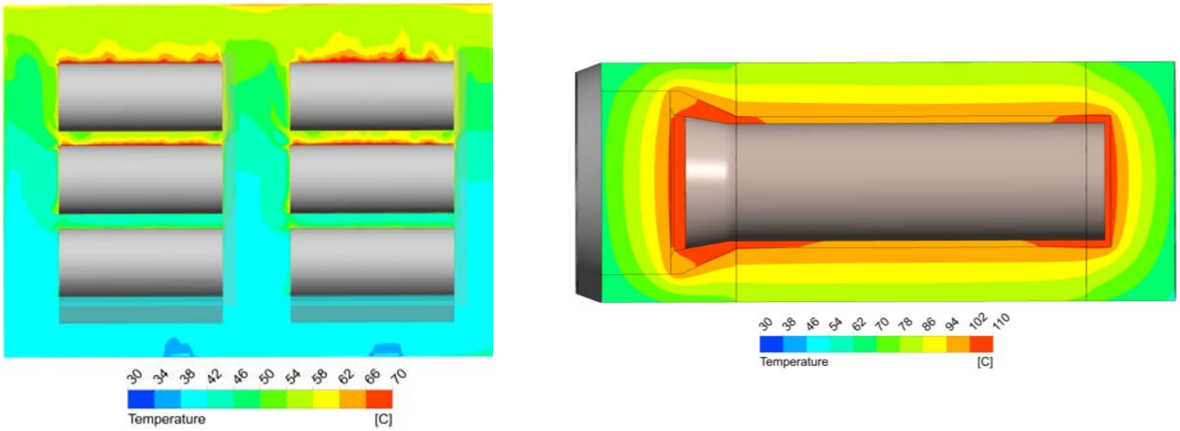

Figure 5. The temperature distribution through the centre of the container and at the centre of the 'detailed' package for Case 3.

Assessment of Inlet/Outlet Arrangement

In order to improve the transfer of heat from the ISO container, further consideration has been given to the potential of increasing the inlet and outlet vent area in order to enhance the ventilation flow. This was undertaken for 36 packages each generating 170 W, which is representative of Case 2.

Spreadsheet calculations were undertaken to calculate the average surface temperature of the packages. This required that the ventilation flow and hence the air temperature within the ISO container were calculated assuming that all the heat from the packages would ultimately be transferred to the ventilation flow.

The ventilation flow was calculated for steady state conditions such that the sum of the pressure losses across the inlet and outlet vents was equal to the buoyancy of the warm air within the container.

Once the air temperature within the container was calculated, a subsequent calculation for the surface temperature of the package was undertaken by solving a heat balance which included convective and radiative heat transfer. A simplification was made whereby it was assumed that there is complete mixing within the container. A constant value for the convective heat transfer coefficient was assumed and a radiation view factor was determined such that the average surface temperature compared well to the range of average package surface temperatures in the CFD calculation.

Repeating the calculation for a range of inlet and outlet vent areas, where it was assumed that the inlet and outlet area was the same, allowed the change in package surface temperature with vent area to be determined. The results which are presented in Figure 6 suggest that there would only be marginal gains by increasing the vent area from the size used in the CFD model. For example, doubling the inlet and outlet vent area compared to the area used in the CFD calculation would be expected to give approximately a 7°C temperature reduction. The reduction in package surface temperature for a lower heat load would be smaller.

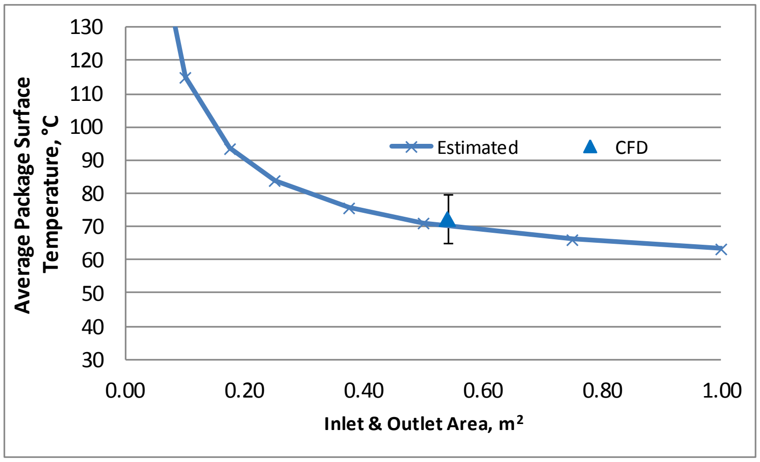

Figure 6. Variation in average package surface temperature with inlet/outlet vent area based on spreadsheet calculations.

FUTURE WORK & CONCLUSIONS

As this is a concept study, there are a number of areas that may require refinement in a detailed assessment. These are:

1. As the cans containing heat generating material were not resolved in the model, it is possible that there is an unequal distribution of heat conducted through the package. This may give rise to a slightly higher package temperature. A detailed assessment would take this in to consideration.
2. The assumption that the container is perfectly insulating would be assessed based on the resistance of the security materials that line the container.
3. The resistance of the openings for ventilation flow would be reassessed as more resistive ventilation ducts would reduce the ventilation flow.

However, noting that a 170 W heat load is considered to be an upper bound, the conclusion from the concept study is that with further work and further consideration of the heat load to be placed inside the container, the concept of a passively cooled ISO container for the transport of material may be a viable option.

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