Remote Surveys of the BN-350 Fast Breeder Reactor Refueling Pathway (Aktau, Kazakhstan) - 11061

Anatoliy Ivanov*, Igor Yakovlev*, Sergey Pustobayev*, Yevgeniy Tur**, Alexander Klepikov***, Andrew Herrick[†], David Wells[†], Ian Adsley[†], Collin Knight[‡]
* MAEC Kazatomprom, Aktau, Mangistau region 130000, Kazakhstan
** National Nuclear Center of the Republic of Kazakhstan, Kurchatov, Kazakhstan
*** Nuclear Technology Safety Center, Almaty 050020, Kazakhstan
[†] Nuvia Limited, Dorchester, Dorset, DT2 8DH, United Kingdom
[‡] Idaho National Laboratory, Idaho Falls, Idaho 83415

ABSTRACT

Remote visual and radiation surveys have been undertaken throughout the spent fuel discharge route (the refueling pathway) of the BN-350 fast reactor located in Aktau, Kazakhstan. The objective was to confirm the absence of significant amounts of nuclear material remaining from past operations, following the consignment of the spent nuclear fuel to secure storage away from the reactor. For BN-350 there was a particular area of concern – the hot cell which was used for fuel cutting, inspection and packaging and the vault underneath the cell, designed for storage of beta/gamma-active irradiated off-cuts produced during fuel sub-assembly handling/dismantling. These areas were not easily accessible, especially the vault which was not equipped with any visual or radiation monitoring systems. The results of surveys of the hot cell vault, the spent fuel handling and washing boxes and initial examination of the fuel storage ponds have allowed estimates to be made of the amount of residual fuel contamination from past operations. It has been confirmed that no significant holdings of nuclear material remain.

INTRODUCTION

During decommissioning of nuclear power plants the presence of spent fuel residues in different parts of the refueling pathway may have a grave impact on subsequent deactivation, dismantling and waste management. Fuel failures or handling incidents during reactor operation may have resulted in such fissile material remaining undetected in the reactor vessel and loops, fuel reloading and washing areas and spent fuel cooling ponds even after defueling. The potential for diversion of nuclear materials should these remain undetected and unprotected by safeguards is therefore of concern.

For BN-350, Project K-1583 was set up under the auspices of the International Science and Technology Center (ISTC) to allow surveys of the refueling pathway to be undertaken. Funding for the project was provided by the UK Government Department of Energy and Climate Change (DECC), as part of the UK's Global Threat Reduction Programme.

DESCRIPTION OF BN-350 SPENT FUEL HANDLING SYSTEM

BN-350 was a loop-type sodium-cooled fast neutron reactor with a design power output of 1,000 MW thermal. Its core fuel loading was enriched uranium oxide. Plutonium-fueled sub-assemblies were also included in the experimental irradiation program and plutonium was bred both in the core and in blanket sub-assemblies. The reactor operated successfully from 1973 to 1999, when it was shut down for decommissioning. A large amount of the reactor's inventory of spent fuel (approximately 3,000 sub-assemblies) remained on site at the cessation of power operations and a significant program of work was initiated [1] to package and eventually transfer the fuel away from the reactor. This program was completed in November 2010. Background on BN-350 decommissioning is given in [2].

The BN-350 fuel handling system was designed for removal of spent fuel sub-assemblies from the reactor, loading of fresh core fuel sub-assemblies, radial blanket fuel sub-assemblies, control system rods, cartridges and neutron sources into the reactor, as well as for relocation of fuel sub-assemblies within the reactor to level the neutron flux and burn-up.

Fresh fuel, delivered to the central reactor hall by an overhead runway, was loaded into one of the slots of the rotating fresh fuel drum through a socket in the biological shielding. The fuel sub-assembly was moved from the fresh fuel drum into the fuel transfer box, from where it was installed into the necessary position in the reactor core/blanket by means of fuel transfer mechanisms and the large and small rotating plugs. The same fuel transfer mechanisms were used to unload sub-assemblies from the reactor and to place them into the slot of the spent fuel drum in the fuel transfer box. After rotation of the spent fuel drum, the sub-assembly could be retrieved from its slot in the separate fuel washing box. It was then washed in one of three available washing pits and transferred via an inclined transporter into the cooling pond area for inspection and long-term storage. From the cooling ponds sub-assemblies could be delivered for additional inspection and cutting into the hot cell.

OBJECTIVES OF THE SURVEY PROGRAM

The objectives set for the K-1583 survey program were:

- To quantify or bound the amount of any nuclear material remaining in the Hot Cell waste vault.
- To confirm the absence of any significant nuclear material-containing items within the remainder of the refueling and fuel discharge pathway.
- To agree with IAEA the appropriate safeguards regime for any residual nuclear material.

SURVEY OF HOT CELL WASTE VAULT

The initial phase of work began in 2008 with the preparation of a work plan for the vault survey, requiring an initial review of historical data on plant operations, an intrusive survey within the vault and the associated analysis of the radiation measurements. The vault, a 10m x 5m x 3m high steel lined concrete enclosure, is not equipped with any radiation or visual monitoring or control systems and had not been thoroughly inspected since the beginning of hot cell operations. This included the time of its upgrade in 1984-1986, when a waste collection drum was installed under the passages from the hot cell to the vault. At least one instance of flooding of the vault was known to have occurred during cell operations, when water had risen into the hot cell from the flooded vault. No information about waste distribution, water level and radiation dose rate was available before the survey. Details of the survey work are given below:

Historical data review

Investigation of the reactor operation logs represented a significant part of the efforts to prepare for the survey. The vault inventory logs included only information about irradiated parts of fuel sub-assemblies, such as ducts, tails and lower ends, as well as other metal pieces and spent radioactive sources. No fissile material inventory was indicated and it was therefore necessary to analyse the logs and to investigate all handling accidents and incidents, which may have resulted in contamination of the vault with nuclear materials.

Five handling accidents, which may have resulted in potential loss of fissile material to the vault, were identified. Three of them involved drops of fuel pins inside the hot cell, which were then recovered according to the logs; one involved a non-irradiated blanket pin for which there are no records about the recovery, and one involved the failed spent fuel sub-assembly C-105, an event which happened early in 1980 and is considered now as the main potential source of fissile material inventory in the vault.

The C-105 accident analysis, which included reviews of all the operation logs and questioning of operators, revealed that the sub-assembly was completely fractured during the examination in the hot cell. An attempt to collect all the fragments from the hot cell floor was made, but it was recognised that some could get into the vault through the open passages. This leaves the C-105 event as the key unknown, because the limited information given in the report on C-105 (“major portion of the fuel pins were crushed – fragments were collected”) and the apparent length of time to recover from the event (7 months) suggest the possibility of numbers of pin-equivalents being at risk.

Remote video and radiation survey

It proved impossible to perform the survey from the hot cell, because one of the connecting passages goes directly into the internal volume of the waste collection drum and another one is angled, creating problems with deployment of any video or illumination equipment. In addition, the hot cell is heavily contaminated and requires special precautions to be taken for operations which would require man entry. Therefore it was decided to perform the survey through the area of the truck entrance inside the BN-350 reactor building. The vault is located underneath this area and there is a large square plug in the entrance floor, providing access to the vault and originally designed for waste retrieval but never used during operation. It was decided to drill three penetrations for video, illumination and radiation control systems, which could be easily sealed in case of water ingress into the area and for physical protection purposes.

Visual inspection of the vault (see Fig. 1 and 2), carried out with a Puffin RTC 46 radiation-tolerant waterproofed camera, demonstrated that the bottom of the repository is covered by a layer of sediment of a few mm thickness. There were traces of pitting corrosion on the wall liner and cracking was observed in one place. This indicated that in the past the repository had been repeatedly filled with water up to different levels. There are components of spent fuel sub-assemblies (lower ends, tails, duct sections), control rods and other items on the floor of the vault, as expected. Most of the components were located to the right of the drum.

Fig.1. Photograph from video survey showing waste container and debris field (to the right) in the waste vault underneath the BN-350 hot cell.

Fig. 2. Photograph from video survey showing the debris field – sub-assembly duct sections and lower ends

The survey scope of works included measurements of the dose rate in the vault, taking smears from the floor and walls, followed by measurement of the specific activity of smears and their gamma spectrometry, and taking liquid samples from the waste collection drum to determine the specific activity of the liquid and its gamma spectrometry. Dose rates were measured using an installed sensor over a 3D grid to allow subsequent modelling, throughout the volume accessible by the manipulator. The dose rates from these measurements varied between 0.06 and 0.3 Sv/hour. Measurements of smears and liquid activity varied in a wide range, between 60 - 450 MBq/kg for alpha and 33 - 235 MBq/kg for beta nuclides.

Analysis of radiological data

Two different codes were used for the modelling – Microshield 8.02 at the early stages of the survey for preliminary assessments and MCNP 5.1.4.0 for the final modelling. In order to assess the amount of fissile material in the vault an initial source term was created, based on ^{60}Co and ^{137}Cs isotopes; the activity of other isotopes is considered as negligible on the basis of gamma-spectrometry data. A more sophisticated approach of using the measured dose rate data to infer source positions and magnitudes, an approach known as deconvolution, was also considered. However, as the identified beta gamma sources in the vault could be well characterised from reactor data, it was decided that the simpler approach of comparing dose rates estimated from these sources with the measured dose rates should be adopted.

The ^{60}Co source term was the most complex to establish. The waste drum was modelled in the form of a cylinder, which sits above the floor level. The level of metal fragments in the drum is taken as ¾ of the liquid level. By comparing the number of items seen in the visual survey against the known loading of irradiated fuel components consigned to the vault, it was considered that ~60% of the ^{60}Co source is in the drum. Fragments of fuel sub-assemblies outside of the collection drum were modelled in the following way (see Fig. 3):

- Lower layer of elements on the floor to the right of the drum (if we look at the drum from the manipulator side) - as a rectangular parallelepiped,
- A pile to the right of the drum (immediately near the drum) - as one quarter of a cylinder ,
- A pile to the right of the drum near the right wall – as a semicylinder,
- Individual fragments of items scattered on the floor of the vault – as hollow cylinders corresponding to the known fuel sub-assembly duct radius.

The ^{137}Cs source term was modelled in the form of a sediment layer of thickness 3 mm evenly covering the vault floor and in the form of liquid filling the waste collection drum. Specific activity values were taken from the measurements of smears and liquid samples. The density of the sediment was taken to be equal to the density of iron rust – 3 g/cm^3.

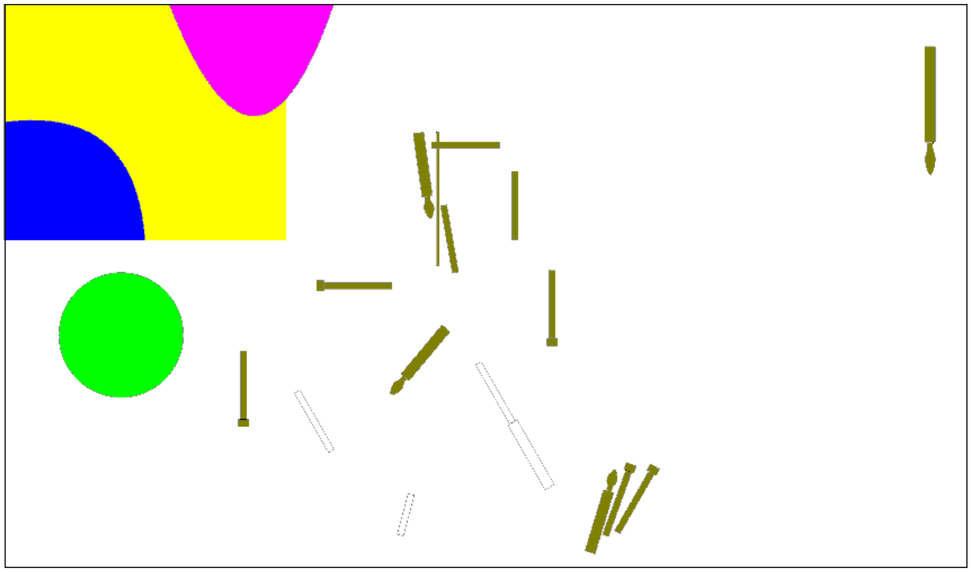

Fig. 3. Layout of Co-60 active radiation sources in the vault – the circular green area is the waste drum, other colors represent the debris field (Fig. 2)

Fig. 4 below shows the calculated map of dose rates inside the vault.

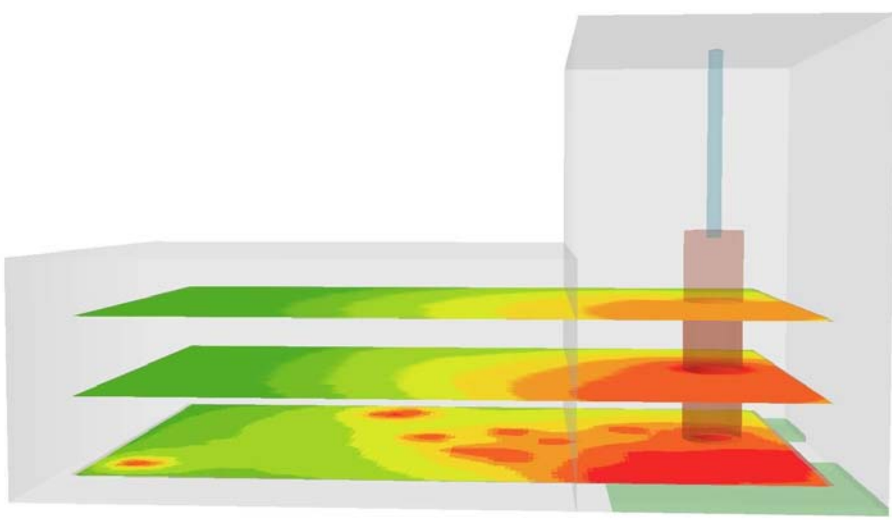

Fig. 4. Map of dose rates in the Hot Cell waste vault

Analysis of the results of the calculations showed that, given the considerable uncertainties in values of the initial parameters of the model, it was impossible to determine the exact contribution of various radiation sources (fissile material, activation isotopes) to the formation of dose rate fields in the vault. Either source could in principle form a dose field (dose rate and distribution) similar to that measured. However, the model based on activation products in the array of all the fuel sub-assembly components matched the reality more completely and qualitatively than the dispersed model of fission products. It should be emphasised that the latter was based on the analysis of only a few discrete samples, each differing considerably, leading to difficulties in applying the values over a large area. Therefore, the possible quantity of fissile material in the vault was estimated assuming that activation products make the major contribution to the radiation dose rate (70-90%), i.e. fission products make a 10 - 30% contribution.

The recorded C-105 sub-assembly specific burn-up value (5.6%) approximately corresponds to the equivalent of 70 MW·day/kg HM (heavy metal). The estimated ratio between ^{137}Cs and ^{235}U activity for BN-350 fuel of this type, just unloaded from the reactor, will be in the range from $1 \cdot 10^6$ to $3 \cdot 10^6$. However, when the actual amount of fuel located on the vault floor is estimated, it is also necessary to take into account the change in this ratio due to cesium decay, cesium release from any fuel pins or pellets and its irretrievable carry-over by repeated water flooding of the vault. The proportion of cesium loss was estimated to range between 10% (escape of cesium into the gas cavity of a fuel pin under normal reactor operational conditions at the given burn-up) and 52% (accident at TMI-2, [3]).

Estimating the total sediment activity as ~10^{13} Bq of ^{137}Cs (based on the specific activity of a smear from the vault floor, assuming that the density of the sediment is 3 g/cm^3 and its volume is distributed evenly on the floor of storage with thickness 3 mm – to give a total of about 500 kg of sediment), the calculated and measured dose rate values coincide adequately. Taking into account the cesium decay for the period since discharge from the reactor, as well as the assumption that fission products make a 10% - 30% contribution to dose formation and 10% - 52% of cesium loss because of water wash-out, the maximum estimated ^{235}U amount in the sediment is up to 126 g and in the waste drum liquid up to 155 g. Experimental data on the $^{235}U/^{239}Pu$ ratio for BN-350 spent fuel also allows calculation of the potential plutonium content: up to 30 g in the sediment and up to 39 g in the waste drum liquid.

At the request of IAEA, conservative estimations were made of the magnitude of a hypothetical “hidden source” – an unrecognized amount of fissile material, which may potentially reside in the bottom area of the waste drum, shielded by metal fragments and drum liquid. For this assessment it was assumed that is the source was concentrated in a layer 10 cm deep at the bottom of the drum. Calculations demonstrated that if the ^{137}Cs activity of this layer was taken as $4 \cdot 10^{14}$ Bq, the average ratio of calculated and measured dose rates was equal to 1. Taking into account such an activity of ^{137}Cs and assumptions similar to those stated above (ratio of activities of cesium and uranium, decay of cesium, contribution of fissile products in activity and cesium release), the estimated maximum mass of a ^{235}U “hidden source” located at the bottom of the drum could be up to 5.15 kg.

Additional measurements

Such a relatively high value of the “hidden source” prompted the taking of additional measurements to justify or to deny this estimated value. In the original survey equipment configuration it had been impossible to reach the area close to the drum from the manipulator location (8m - 10 m away). As a result, an additional dose rate sensor was procured to perform the additional measurements through the existing inclined passage from the hot cell into the vault. The new sensor was ordered because of the risk of its loss or damage in the process of its deployment/removal from the vault. Additional measurements were duly performed along a line parallel and close to the waste drum wall. These gave measured dose rate values up to 0.97

Sv/hour in the bottom area. This updated data allowed a re-estimation of the "hidden source" term as a maximum of 0.4 Kg of ^{235}U – a better than tenfold reduction in the upper bound value.

Conclusions regarding the Hot Cell vault

The survey and analysis resulted in a final estimated amount of fissile materials in the vault of up to 281 g ^{235}U in the floor sediment and waste drum water plus 69 g of plutonium (calculated from fuel specific isotope ratio). The revised "hidden source" term of the amount of fissile material, which might reside in the bottom area of the waste drum shielded by other vault waste, is estimated at up to 400 g. These values are in reasonable agreement with estimates of potential losses of fuel into the vault arising from incidents and accidents during the hot cell operational period.

The video and radiation survey of the BN-350 hot cell area allowed clarification of the status of the waste vault and estimation of the amounts of fissile materials which may need recovery and handling later in the decommissioning of the facility. This information, as well as the recorded configuration of individual irradiated items, will assist in the development of vault waste retrieval and handling methods.

EXTENSION OF SURVEYS TO OTHER PARTS OF THE REFUELING PATHWAY

Fuel discharge and washing area

After the completion of the hot cell vault survey it was decided to extend the survey to the BN-350 refueling and washing area to ensure no significant amounts of fissile material remained. This work was performed in the framework of the first prolongation of the ISTC K-1583 project. The scope of work of this project stage included visual inspections and radiation measurements within the following areas:

- Fuel transfer box with all the internal mechanisms and the fresh fuel drum;
- Fuel washing box with all the internal mechanisms and washing pits;
- Inclined transporter for delivery of spent washed fuel into the cooling pond area;
- Interim/transfer pool #018.

The visual survey was undertaken by inspection of hard to access areas using the Puffin RTC346 camera and visual inspection and recording of still images by regular compact digital camera. The Puffin camera was used mainly for the surveys of the fuel drum, washing pits and inclined transporter. Part of the area could be surveyed through the designed man access doors in the biological shielding provided for surveilance and maintenance. Dose rates in the man-accessed areas varied from a few mSv/hour up to 100 mSv/hour at a height of ~1 m above floor level. Visual inspection of all the listed areas did not discover any noticeable pieces of fuel.

The scope of work for radiation measurements of the areas included the following:

- Measurement of dose rates using a portable dosimeter-radiometer;
- Measurement of dose rates at various depths for the fuel reloading slots and the fuel washing chambers using an ionization chamber;

- Taking of swabs/smears from the floor and walls of the areas, from the fuel reloading slots, the washing pits and all the mechanisms;
- Measurement of specific activity of swabs and their gamma-spectrometry.

The radiation survey, as well as the visual inspection, did not discover any significant amount of fissile material in the surveyed premises. Some identified areas with elevated dose rates were attributed to the presence of radiologically contaminated sodium oxide deposits, mainly in the fuel transfer box (see Fig. 5), or fragments of control rod cartridge, which had cracked in the process of washing. Nevertheless, fissile material and fission product activity was measured at a low level in all the swabs taken. A few areas of the wash water discharge pipelines, adjacent to the steam-nitrogen collectors, require additional analysis to determine whether they may contain dispersed fissile material in amounts higher than in the floor/wall sediments.

Fig. 5. Photograph of access point into spent fuel drum, taken during man entry into the fuel transfer box, showing oxidised deposits of sodium

Spent Fuel Storage ponds

This stage of the project is being realised in the framework of the same K-1583 project. The scope of work includes visual and radiation surveys of all the spent fuel ponds to verify the absence of any major amounts of remaining fissile materials. This activity is ongoing. Up to October 2010 only one irradiated item from a fuel sub-assembly had been found in the pool #08, which was used for inspection and cutting of fuel sub-assemblies. This pin was retrieved and no fissile material other than trace amounts was found.

OVERALL CONCLUSIONS

The survey performed at the BN-350 reactor with the objective of identifying or bounding the amount of any remaining nuclear material has been very important for the planning of final handling and deactivation of the area, as well as for material accounting and control and safeguard purposes.

Facilities similar to the BN-350 hot cell vault exist in many other nuclear plants and represent a significant problem for the decommissioning of these facilities. Such areas are usually very difficult to access and require special consideration and planning to perform any survey activity and subsequent handling procedures. As demonstrated in the BN-350 case, it is not necessarily possible to create a comprehensive plan at the very beginning, which would cover the whole scope of work for the survey, and it is therefore necessary to make iterations in the course of the survey activity to respond to situations as they develop. These considerations relate to any contaminated area with an unknown inventory but in the case of the presence of fissile materials they are of special concern.

REFERENCES

1. E. HOWDEN, R. SNIPES, and D J. BALLOWE, “Design and application of SNF casks for the Kazakhstan BN-350 program”, paper to Institute of Nuclear Materials Management Conference, Santa Fe NM, 2009.
2. I. TAZHIBAYEVA, G. PUGACHEV, and A. R. HERRICK, “Decommissioning of Kazakhstan’s BN-350 fast reactor”, Nuclear Future, Vol.04 No.5, 281 – 286 (2008).
3. A. HIDAKA, T. KUDO, T. ISHIGAMI, J. ISHIKAWA and T. FUKETA, “Proposal of Simplified Model of Radionuclide Release from Fuel under Severe Accident Conditions Considering Pressure Effect”, Journal of Nuclear Science and Technology, Vol. 41, No. 12, p. 1192–1203, 2004.

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