THE INTERNATIONAL PROJECTS TO DEVELOP AND SUPPORT SHORT AND LONG TERM MEASURES AT CHNPP UNIT 4 SITE

Based on a “Memorandum of Understanding between the Governments of the G7-countries, the European Commission and the Government of Ukraine on the Closure of the Chornobyl Nuclear Power Plant”, signed in 1995, joint international efforts were initiated to develop “a cost effective and environmentally sound approach to the shelter for Chernobyl Unit 4” and the Study “Chernobyl Unit 4: Short and Long Term Measures” was prepared in 1996 with a recommended course of actions. Based on the recommendations of the study the “Shelter Implementation Plan (SIP)” was prepared and its implementation started in 1998. After its soon expected successful completion, the options for the next steps need to be analysed and decided.

Keywords: nuclear accident, fuel containing materials, remedial measures, decision processes, option analysis.

1. Background and Introduction

During the Chornobyl Unit 4 accident of April 26th 1986 the reactor and reactor building of Unit 4 of Chornobyl Nuclear Power Plant (ChNPP) were completely destroyed and radioactive material was spread over the site and released to the environment. Immediate emergency and accident liquidation measures were undertaken to combat the consequences of the accident including, among others, the creation of the Chornobyl Exclusion Zone (ChEZ), and erection of the Shelter building, so called “Sarcophagus” (also called “Ukr-ritiye”), to re-establish new barriers for the reactor remains which is still containing the major part of the former Unit 4 fuel. Decontamination of territory, roads and premises was part of the accident liquidation measures performed to reduce radiation levels at the contaminated territory as well as at the plant site: it was a prerequisite for workers to restart the 3 adjacent reactor units one after another till the end of 1987.

In 1991 Ukraine became independent after the breakdown of Soviet Union, and consequences of Chornobyl accident became a solely nuclear legacy of Ukraine which sought for international support. In 1992 the G7 and EU initiated a support programme to increase nuclear safety within the transition countries in which Ukraine was part of. Based on a “Memorandum of Understanding between the Governments of the G7-countries, the European Commission and the Government of Ukraine on the Closure of the Chornobyl Nuclear Power Plant”, signed in December 1995, joint international efforts were undertaken to develop “a cost effective and environmentally sound approach to the shelter for Chernobyl Unit 4”.

A project “Chernobyl Unit 4: Short and Long Term Measures” was initiated in early 1996, to analyse options and provide recommendations. Together with Ukrainian experts, an international expert team was formed to analyse needs and possible approaches. A final report summarizing the findings was issued on 29 November 1996. It included a recommended course of action as a main result of the joint effort.

Based on this report findings Ukraine, G7 countries and European Commission instructed the international expert team to prepare a “Shelter Implementation Plan (SIP)”. The SIP was drafted in June 1997, approved at the G7-Denver Summit in 1997 and implementation preparation initiated in 1998 - including establishing of funding mechanisms with the “Chernobyl Shelter Fund (CSF)”, administered by the European Bank of Reconstruction and Development in London. The effective implementation of the SIP started in 1998 and is currently in its final implementation phase.

2. Situation at Chornobyl NPP Unit 4 Site in 1996

The “Sarcophagus” has been erected in less than 6 months under exceptionally difficult conditions as part of the immediate accident response actions to create new barriers around the remains of the reactor. After its erection, one of the controversially discussed options was the further approach necessary to establish a longer term safe structure. Initially, the aim was entombment. For reasons highlighted below, this project was deemed unrealistic and was therefore never realized. The following diagram illustrates some key challenges encountered in 1996.

© N. Molitor, Z. Drace, I. Stange-Wiehr, 2019
The main challenges encountered in 1996 can be summarised as follows:

*The unreliable and unstable conditions of the Chornobyl Unit 4-Shelter structure*
- The construction was built under extreme radiation conditions: prefabricated steel elements were simply stacked on overstressed building ruins which could only be partially reinforced with the cast concrete (such as the cascade wall made of concrete or the ventilation shafts poured with concrete). As a result, the structural reliability of supporting elements could not be proved. Furthermore, the steel elements piled on these supporting elements with doubtful stability were not connected properly, between each other (most elements are merely stacked and most of the joints were not welded, bolted or fixed in any way together), with the result, that the overall stiffness, stability and consistency of the roof structure was unsatisfactory.
- Moreover, the construction was built on a destroyed building without the support of deep foundations, such that settlements as well as a tilting of the “Sarcophagus” structure were observed. One of the main concerns was therefore the on-going weakening of the structure stability.
In December 22, 1988, Soviet scientists announced that the sarcophagus could not be performed and the environment, many
- Corrosion and weathering deteriorated the existing structure further, which was never meant to be a
  sufficient long term solution (e.g. on December 22, 1988, Soviet scientists announced that the sarcophagus
  would only last 20–30 years before requiring restorative maintenance work).
- The “Sarcophagus” was not airtight, nor watertight, and although a complex dust suppression system
  was operated, the release of radioactive dust through openings to the environment and ingress of waters
  was not fully preventable.
- The ventilation stack on the joint service building between Unit 4 and Unit 3 was severely damaged
  and unstable. A potential collapse of this ventilation stack with falling on the “Sarcophagus” could have
  led to severe damage or even collapse of the “Sarcophagus” itself.

Radioactive inventory of the Unit-4-Shelter
- The inventory contained enormous amounts of radioactivity (estimated to about 20 MCi – Mega-Curie)
  with a high proportion of gamma emitters and transuranics (estimates indicated that the sarcophagus
  may have locked in some 200 tons of radioactive corium, some 30 tons of highly contaminated dust, several
  tons of uranium and plutonium and substantial amounts of radioactive reactor core graphite).
- The inventory contained substantial amounts of fissile materials under unacceptable conditions
  (damaged fuel elements, various types of fuel containing materials (FCM), such as lava-like materials, unde-
  fined admixtures of concrete and fissile materials, and dispersed fissile materials). Furthermore, localisation
  of a substantial part of the original fuel could not be performed because of limited physical access and very
  high radiation levels and the conditions of remaining fuel and fuel containing materials could not be suffi-
  ciently controlled.
- The few existing and operational monitoring and control equipment registered fluctuating neutron
  flux events, meaning that ‘local critically’ of nuclear materials could not be excluded.
- The lower premises contained water from the immediate response activities, precipitation water
  (snow and rain) could penetrate through opening in the roof and the wet dust suppression system was based
  on aqueous liquid spraying: all of this led to the presence of the major amounts of water in a direct contact
  and interaction with the radioactive and fissile inventory altering and changing the conditions of the latter.

Industrial safety/working conditions
- Access ways and corridors to the different reactor compartments and inventories in them were radi-
  ologically and physically unsafe and inadequate or even not existing: ensuring safety of works inside the
  “Sarcophagus” under these conditions was practically not possible.
- The immediate neighbourhood of the “Sarcophagus” was highly contaminated: radiation protection
  was a problem for works not only inside but also outside of sarcophagus.

Interfaces with adjacent nuclear facilities
- The immediately adjacent Unit 3 with a similar 1000 MW RBMK reactor was still operational and
  raised additional safety concerns for situation and possible works at Unit 4.
- Other nuclear facilities were either operated or planned to be constructed at the site (e.g. new in-
  terim spent fuel storage facilities, radioactive waste treatment facilities).

3. Recommended Course of Action

With the overall safety objective being protection of public, workers and the environment, many
heated arguments were exchanged between the experts on how these objectives could be reached by address-
ing the encountered situation and risks. After the discussion, a common understanding was reached: Chorn-
oby Unit 4 could not be converted to a safe final disposal facility for nuclear materials. Consequently, this
implied that the removal of the nuclear inventory is a challenge to be resolved ultimately which has to be
achieved - e.g. in a graded approach step by step - to reduce risks and re-establish and increase safety. This
result was in compliance with the „National Program for Transformation of the Object ‘Ukritiye’ into an
ecologically safe ecological system“.

Once the objectives and measures with their priorities were identified, a safety-based risk mitigation
decision tree was prepared. By abstraction 3 top decisions were to be taken:
- Short term risks which can be addressed with urgent measures in a short timeline should be funded. This
  led to decision of funding of top priorities (decision no. 1).
- In a next step, a principle decision no.2 had to be taken: could the inventory remain were it is ac-
  cording to common and international standards or not? In case of Chernobyl Unit 4, there was common un-
  derstanding that the site could not be converted into a final repository.
If the site cannot be converted into a repository, the next decision would be about timing of recovery, implying that if an appropriate disposal site would not be available at the time of recovery, there will be the need of interim storage until disposal would be possible.

The corresponding different phases for implementation of measures were defined and described. It was noted by the international expert team that with no decision taken at an early stage, the measures needed to remain flexible with decisions taken at a later stage with limited possibility of optimisation.

These main results were reflected by the international expert team to develop the ‘Recommended Course of Action’, which is illustrated and are summarized in the following diagrams.

Diagram: Graded approach to reestablish safety and eliminate risks at ChNPP Unit 4 site
(source: international expert team 1996)

Diagram: Decision Tree for Recommended Course of Action
(Source: international expert team 1996).
The Phase 3 (from 3.1 to 3.3) was associated with many uncertainties that should be resolved during the tasks from 1.1 to 2.2. Thus, there was consensus to decide and implement first tasks 1.1 to 2.2 which should improve safety considerably and provide a better decision basis for the tasks 2.3 to 3.3. The international expert team was instructed accordingly in 1997 to prepare a “Shelter Implementation Plan (SIP)” covering phase 1, and tasks 2.1 and 2.2.
4. Shelter Implementation Plan (SIP)

The international expert team developed accordingly a detailed decision plan, work breakdown structure, work sequence, provisional time tables and budgets by defining 22 main tasks.

| Task 1 | Stabilization and Shielding Design Integration and Mobilization |
| Task 2 | Stabilization and Shielding of Western Section |
| Task 3 | Stabilization and Shielding of Mammoth Beam and Southern Section |
| Task 4 | Stabilization and Shielding of the Eastern and Northern Sections |
| Task 5 | Stabilization of the Roof, Roof Supports and Covering |
| Task 6 | Structural Investigation and Monitoring |
| Task 7 | Geotechnical Investigation |
| Task 8 | Seismic Characterization and Monitoring |
| Task 9 | Emergency Preparedness |
| Task 10 | Dust Management |
| Task 11 | Emergency Dust Suppression System |
| Task 12 | Criticality and Nuclear Safety |
| Task 13 | Contained Water Management |
| Task 14 | Fuel Containing Material (FCM) Characterization |
| Task 15 | Radiological Protection Program |
| Task 16 | Industrial Safety, Fire Protection, Infrastructure, and Access Control |
| Task 17 | Integrated Monitoring System |
| Task 18 | Integrated Database (Configuration Management) |
| Task 19 | FCM Removal and Waste Management Strategy & Study |
| Task 20 | FCM Removal Technology Development |
| Task 21 | Safe Confinement Strategy |
| Task 22 | Implementation of Safe Confinement to Support Deconstruction and FCM Removal |

Diagram: Main Tasks of SIP (International Expert Team 1997).

The SIP was prepared between February and May 1997 to be completed and available for consideration by the G7 countries. Decision to proceed was formally taken at the Denver 1997 G7 Summit in June 1997 where the creation of a Chernobyl Shelter Fund (CSF) as funding mechanism for the SIP implementation under administration of the European Bank for Reconstruction and Development (EBRD) in London was also agreed upon. The EBRD prepared all necessary rules for the Chernobyl Shelter Fund and arrangements to make the CSF mechanism operational, and a first international pledging conference was organised for November 1997 in New York to feed the CSF.

The SIP implementation started in 1998 and most of the tasks including the major stabilization were completed in 2008. The contract for the new safe confinement (NSC) was signed in 2007. The NSC, which is to support partial deconstruction of sarcophagus and FCM removal, is currently constructed and under commissioning which is expected to be completed in 2019. After completion of the NSC, the partial deconstruction of unstable parts of the old sarcophagus shall be commenced and completed within a few years. This sequence is illustrated in the following diagram within the overall framework of graded approach, stipulated by the international expert team in 1996.

Diagram: Implementation of the SIP.
5. Achievements and Next Steps

In summary, the main technical achievements of the SIP are the following:
the unreliable structures of the old ‘Sarcophagus’ are stabilized such to reduce collapse risk;
an integrated monitoring system is put in place to ensure much better control of structures, inventory and impacts on the environment;
a new reliable confinement structure is constructed to allow essential elimination of collapse risk related to old “Sarcophagus” structures by dismantling upper unstable parts;
further, when the upper unstable parts are removed, a much safer and technically more efficient access to the inventory from the top will be allowed.

The SIP is a success reaching an important milestone for safe site management until safe inventory removal will be possible. However, during project implementation it became clear that a major essential boundary condition remained unresolved: the availability of a deep geological disposal was so uncertain that it was decided to postpone the fuel removal strategy and configuration and to conclude that the lifetime of NSC should be 100 years in order to allow sufficient time to resolve the FCM removal strategy - including for inventory disposal.

Therefore, the logical and consistent way forward, is the development of the FCM strategy based on the necessary studies and pilot tests which are part of the ‘Recommended Course of Actions’. To initiate them after the completion of the SIP has the advantage to take into account the improved knowledge on the inventory and further development of technologies available, which have been improved further over the last 20 years since the ‘Recommended Course of Action’ was developed and the SIP initiated.

Over the last two decades, the site conditions and site infrastructure have improved and a lot of valuable experience has been collected at the site and its context, including among others:
stabilization of the old “Sarcophagus” (e.g. organization of the safe work in highly contaminated environment);
clearing and cleaning for new safe confinement construction site (e.g. including removing of wastes and high level wastes from the site);
implementation of the Industrial Complex for Solid Radwaste Management (ICSRM);
implementation of other radioactive waste disposal facilities at VEKTOR complex site;
better understanding of type, distribution and properties of the site inventory.

Further, over the same two decades, substantial technologies have been developed and know-how was acquired during dismantling of highly contaminated facilities in different countries. The occurrence of another large-scale nuclear accident in 2011 in Japan, also contributed to fostering of approaches and technologies for managing highly contaminated sites, including the necessity of damaged fuel and debris removal with the new technologies.

In practical terms, when the upper parts of the sarcophagus including the roof are dismantled below the NSC, there will be a flexible and efficient access to the Unit 4 inventory from the top. NSC equipped

Diagram: Possible approach and elements for retrieval of inventory within NSC after upper part dismantling. Legend: 1 - recover the inventory and load it into a handling container; 2 - optional preliminary sorting of recovered inventory, which may be possibly combined with segregation by fragmentation or cutting processes; 3 - storage of preliminary waste containers within the NSC until it can be locked; 4 - locking out waste containers e.g. with the use of clean over-packs; 5 - transport to the next process step e.g. to treatment/processing and/or interim storage.
with remotely operated cranes that will allow the moving of materials, equipment or containers vertically and horizontally with only few restrictions into and out of the former Sarcophagus compartments which are also available for retrieval.

The inventory will consist of different types requiring different configuration for retrieval, e.g.: bulk type inventory in the upper areas (A) (e.g. dropped materials during immediate accident fighting as well as FCM and moderator graphite from liquidation efforts when cleaning the Unit 3 roof); large or massive inventory which can only be retrieved by using segmentation and/or fragmentation technologies (e.g. reactor bio-shield “Elena” (B), building walls and other building structures) when moving downward during removal; lava type fuel containing materials (C) (e.g. in the lower part of former unit 4 premises).

Besides retrieval, the processing of FCM with conditioning and/or packaging in the final disposal ready form is one of the most important challenges for a long term sustainable safety. Although the final form/package for that waste stream will be dependent on geological and engineering barriers of the geological disposal site (Waste Acceptance Criteria), it is more than prudent to start technology development work for conditioning (including packaging) of such waste in parallel with removal and segregation of the inventory of the Shelter. The pilot tests for detailed characterization, chemical processes for extraction and separation of different elements and investigation of appropriate stable matrices and processes to develop industrial scale facilities, should be a logical way forward. Experiences collected in research and testing of real FCM samples over the last 30 years by the scientific organisations located and working in Chornobyl context, are a valuable asset for this task and should be used further. This would require configuration and implementation of an appropriate test and development facility, able to handle high radiation fields. Since the problem of conditioning fuel debris is not unique only to Chornobyl, an international cooperation effort should be considered for resolution of the challenges related to FCM and fuel debris processing and conditioning at Chornobyl and elsewhere.

Configuration of the inventory management and retrieval process steps will be a challenge and should follow Key Performance Indicators (KPI) to be set in line with desired safety objectives (in terms of nuclear safety, industrial safety, and/or radiation protection), such as: safe access and exit corridors and locks (e.g. for remote equipment, occasional staff or materials); dose uptake (in terms of ALARA-principles); waste volumes generated (in terms of waste reduction); path forward for FCM conditioning/packaging for long term storage or disposal; releases and environmental impacts (in terms of impact reduction); effectiveness (in terms of overall safety levels achieved); efficiency (in terms of efforts – including costs – and times vested to achieve effectiveness).

Configuration and implementation of the inventory recovery measures, supported by the KPI, might lead to the conclusion that it only makes sense to recover parts of the inventory in the nearer term future (e.g. the easily accessible inventory in the upper part) and that the remaining part of the inventory may be better removed later after long in-situ control time.

Shall that be the case, the NSC would be instrumental for further improvement of the conditions of the residual inventory prior to removal (e.g. shrink size, optimize geometry, install long term monitoring and control means) and for eventual implementation of a further optimized confinement which would last longer, would be easier and cheaper to be maintained and operated than the NSC.
The challenge is more than developing a technical solution: Besides the availability of a technical solution with appropriate technologies and disposal option, the availability of an appropriate funding will be a crucial boundary condition for optimised technically and financially feasible solutions within the overall decision process requiring a coordinated interaction with interested and involved stakeholders.

![Diagram: Possible development and decision map for a technically and financially feasible solution.](image)

### 6. Summary

In summary, the SIP including the NSC is a major milestone in the very challenging site remediation works that is still to be done at ChNPP Unit 4: it has to start with deconstruction of upper unstable parts, provision of safe access corridors for the daunting task of safely managing the inventory including FCM contained since 30 years in the ruins of the reactor hall until it can be safely retrieved, conditioned and disposed. In an optimised approach, there will be the option to proceed with retrieval for the accessible and retrievable parts of the inventory and to create a sufficiently safe, cost-effective smaller in-situ storage for the parts of inventory which are difficult to retrieve under the current boundary conditions. For the latter parts of inventory the retrieval may postponed until boundary conditions can and will be changed favourably.

Such approach will require a sequence of detailed studies, pilot tests and a project framework which needs to be developed step by step addressing the technical and financial aspects such to ensure an overall consistent, safe, technically and financially feasible process for the conversion of the unit 4 site into sustainably environmentally safe conditions.

### REFERENCES

1. Molitor N., Drace Z., Javelle C. Achievements and Remaining Challenges for the Conversion of Chornobyl NPP Unit 4 into Ecologically Safe Conditions.
2. Molitor N. Chernobyl Challenges, Presentation, Berg- und Hüttenmännischer Tag, Freiberg/Germany, 18 June 2015.
3. Molitor N., Javelle C. Chernobyl Experience – International Projects: Conversion of Chernobyl Unit 4 into Environmentally Safe Conditions, Presentation, RANDEC Decommissioning Seminar, Tokyo/Japan 27 October 2011.
4. Molitor N., Javelle C. Conversion into Environmental Conditions, Article, RANDEC Decommissioning Journal Nr.44, Japan, September 2011.
5. Molitor; N., Javelle C. International Projects at Chernobyl Unit 4, Presentation, 7th Annual conference on decommissioning and waste management, Prague/Czech Republic 7 - 8 September 2011.
6. Molitor N. et al. Mutual Benefits During Decommissioning Projects in CEE, Presentation, CEE Decommissioning & Waste Corporation, Berlin/Germany, 18 - 19 June 2008.
7. Molitor N. Sicherung des Havarie-Reaktors Tschernobyl – Entwicklung und Stand der Projekte – Presentation at the 6th Darmstädter Kolloquium/Germany, 11 March 1999.

8. International Expert Team led by N. Molitor; Chernobyl Unit 4 Shelter Implementation Plan, Final Report, 31 May 1997, Tacis Services, DG 1A, European Commission, Brussels/Belgium, US Department of Energy, Washington/US.

9. International Expert Team led by N. Molitor; Chernobyl Unit 4: Short and Long-Term Measures, Final report, 29 November 1996, Tacis Services, DG 1A, European Commission, Brussels/Belgium.

N. Molitor, Z. Drace, I. Stange-Wiehr

Плеяди GmbH – Международные эксперты, Feldstr., 5, DE 64347, Грейсбейм, Германия

МЕЖДУНАРОДНЫЕ ПРОЕКТЫ ПО РАЗРАБОТКЕ И ПОДДЕРЖКЕ КРУГТО- И ДОЛГОСТРОЧНЫХ МЕРОПРИЯТИЙ НА ПЛОЩАДКЕ ЧЕТВЕРТОГО БЛОКА ЧАЭС

На основании «Меморандума о взаимопонимании между правительствами стран “Большой семерки”, Европейской комиссии и правительством Украины о закрытии Чернобыльской АЭС», подписанного в 1995 г., были предприняты совместные международные усилия для разработки «экономически эффективного и экологически обоснованного подхода для создания укрытия Чернобыльского блока № 4», а в 1996 г. было подготовлено исследование «Чернобыльский блок № 4: краткосрочные и долгосрочные мероприятия» с рекомендуемым планом действий. На основе предложений исследования был подготовлен «План осуществления мероприятий (ПОМ - SIP)», его реализация началась в 1998 г. Вскоре ожидается его успешное завершение, после чего необходимо проанализировать и определить варианты следующих шагов.

Ключевые слова: ядерная авария, топливосодержащие материалы, мероприятия по восстановлению, процесс принятия решения, анализ альтернатив.

N. Молитор, З. Дрейс, И. Станже-Вие

Плеяди GmbH - Международные эксперты, Feldstr., 5, DE 64347, Грейсбейм, Германия

МІЖНАРОДНІ ПРОЕКТИ З РОЗРОБКИ ТА ПІДТРИМКИ КОРТОКО- І ДОВГОСТРОКОВИХ ЗАХОДІВ НА МАЙДАНЧИКУ ЧЕТВЕРТОГО БЛОКА ЧАЕС

На підставі «Меморандуму про взаєморозуміння між урядами країн “Великої сімки”, Європейської комісії та уряду України про закриття Чорнобильської АЕС», підписаного в 1995 р., були зроблені спільні міжнародні зусилля для розробки “економічно ефективного та екологічно обґрунтованого підходу для створення укриття Чорнобильського енергоблока № 4”, а в 1996 р. було підготовлено дослідження “Чорнобильський блок № 4: краткосрочні і довгострокові заходи” з рекомендованим планом дій. На основі рекомендацій дослідження був підготовлений «План здійснення заходів (ПЗЗ - SIP)», його реалізація почалась в 1998 р. Незабаром очікується його успішне завершення, після чого необхідно проаналізувати й визначити варіанти наступних кроків.

Ключові слова: ядерна аварія, паливовмісні матеріали, заходи по відновленню, процес прийняття рішення, аналіз альтернатив.

Надійшла 13.02.2019
Received 13.02.2019