NEW SAFE CONFINEMENT BUILDING FOR CHERNOBYL

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ABSTRACT

After the devastating accident at Chernobyl Nuclear Plant, Unit 4, in 1986, short term measures were taken to reduce the release of radioactive particles to the environment. In late 1990’s limited construction was initiated to eliminate the most likely accidental release of radioactivity.

At the same time, strategy to provide adequate confinement of the Object Shelter (OS), which is the building that housed the destroyed nuclear reactor, was worked out in 1997 by a team of Western and Ukrainian experts. A conceptual design was developed to reduce the risk to workers, the general population, and the environment, and transform Chernobyl into an environmentally safe site for the next 100 years. The proposed plans called for construction of a New Safe Confinement (NSC) structure that would cover and enclose the entire Unit 4 reactor and the OS. Detailed design of the NSC has progressed sufficiently to start construction.

This paper summarizes the difficulties encountered in finding a viable method of constructing the NSC, considering the radioactivity issues and the limited working hours for workers during the entire construction period, taking into account the ever present radioactivity inside and around the OS. The criteria developed for the design and construction of the NSC will be outlined, the alternatives considered for the construction methodology for the foundations and the superstructure will be described. Analytical studies for the design of the structures have been carried in several countries; the design is in the review and verification stage and material acquisition over the entire world has already started.

This landmark structure is expected to be completed during this decade, bringing safety to people living nearby and relief to anxiety experienced by the general population and government leaders in the neighboring countries.

BACKGROUND

Within six months of the accident, the “sarcophagus” (now known as the Object Shelter – OS) was constructed, involving a quarter million construction workers and about an additional 150,000 other personnel.

The OS was somewhat effective in meeting the short-term goals of preventing water ingress and confining radioactive contamination releases. However, within a few years of its construction, it became evident that the OS had an unacceptable risk of collapse and it was allowing considerable ingress of rain/snow water and radioactive dust to escape. A long term strategy to provide adequate confinement of the OS was developed in 1997 by a team of Western and Ukrainian experts: the Shelter Implementation Plan (SIP). The SIP outlines a step-by-step approach to stabilize the OS and decrease the risk to workers, the general population, and the environment; it aimed to transform Chernobyl into an environmentally safe site for the next 100 years.
A Project Management Unit (PMU) was formed in 1997 with Bechtel National (BNI) in the lead and including Pacific Northwest National Laboratory (PNNL) and Electricite de France (EDF) to provide program management services for implementing the SIP. Projects have been on-going since 1998 to meet the objectives of the SIP, with the most visible, and by far the largest project, the New Safe Confinement (NSC). The NSC will cover and enclose the entire Unit 4 reactor and the OS. It will prevent ingress of water, prevent release of radioactive dust (even if the OS were to collapse), and provide the means for deconstruction of the OS, the Unit 4 reactor, and for removal of remaining nuclear fuel containing materials.

A design-build contract was signed in 1997 for NSC with NOVARKA, which is a consortium of two major French construction companies: Vinci Construction Grands Projets and Bouygues Travaux Publics. In turn, NOVARKA enlisted support of several international companies and Ukrainian institutes to perform the detailed design. The project completion is scheduled for 2015, at an estimated cost of $1.4 billion.

**DESCRIPTION OF THE STRUCTURE**

The NSC is a steel arch-shaped structure with a span (approximate) of 843-ft (257m), a length of 538-ft (164m), and a height of 361-ft (110m). See Fig. 1. Both ends of the arch are closed by walls, which have “cut-outs” to fit around the existing Unit 4 and OS (it extends outside of the NSC). The arch is comprised of 16 Arch trusses, with spacing of 41-ft (12.5m); at the two ends and in the middle the arch spacing is smaller. Each truss is comprised of inner and outer tubular steel chords, with a spacing of 39-ft (12m). The 16 arches consist of a lattice structure with circular tubes (pipes) interconnected longitudinally by horizontal infill beams and bracings. The inner and outer chord are connected through orthogonal and diagonal bracings. At the two arch ends, both upper and lower chords converge at midpoint to form the arch base together with symmetrically arranged vertical bracings and a horizontal circular hollow beam connecting the arches.

The outer chords are covered by a roofing cladding system and the inner chords are covered on the bottom by a cladding system, forming a ceiling. The space between the exterior and interior cladding systems, the “annular space”, contains main structural members and bracing, and contains a complex HVAC system. The annular space between the upper and lower chords is a confined space with dry conditioned air with less than 40% humidity, in order to protect the steel structure from corrosion.

The arch is equipped with a Main Crane System (MCS), consisting of two massive bridges supporting three interchangeable cranes, two of them being 50 mt capacity bridge cranes plus one supporting a robotized arm and tool platform, to provide lifting hook coverage for the entire Unit 4 and the OS. The two massive bridges measuring 315-ft (96 m) long travel on 6 parallel rails measuring 492-ft (150 m) long. In addition to the steel arch structure and MCS, there is an extensive foundation system, support buildings, and many other complex sub-systems: electrical, instrumentation & controls, HVAC, dust suppression, water supply, seismic monitoring, structural steel corrosion monitoring, etc.

Engineering efforts, procurement, and construction of the NSC are on-going. As can be expected on a project involving a huge, unique structure, there are major challenges to be overcome. These challenges are discussed in the following sections, with focus on the NSC.

To minimize radiation exposure to construction workers, the NSC arch will be erected more than 1000-ft (300m) away from its final position. After erection of the arch and installation of the MCS and the main sub-systems in the erection zone, the NSC will be pre-commissioned, then pushed into its final position by riding on a unique sliding system. The foundations are divided into three discrete zones, each having different design requirements:

1. Erection zone – the arch and sub-system construction area, where the foundations will provide support for several years (ground beam/pile cap on steel driven piles).
2. Transfer zone – the arch will slide on the foundations in the transfer zone, with the sliding process expected to be less than one week (monolithic ground beam at grade interlocking with Erection and Service Zone foundations).
3. Service zone – the final resting position of the arch, over the OS, where the foundations will provide support for a 100-year design life (pile caps on Continuous Flight Auger (CFA) piles). The foundations in all three zones consist of heavily reinforced concrete structures, 10 to 11.5 m wide and 4 m thick. The three zones from Erection to Service Zones are approximately 210 m (689 ft), 122 m (400 ft), 175 m (574 ft) long, respectively. Guide rails are anchored to the foundations in all three zones to permit sliding of the Arch structure after its completion.

Figure 2 shows the layout of the zones; the erection zone at the West end, the transfer zone in the middle and the service zone at the East end. The erection platform has been located as far as possible from the OS to minimize radiation exposure to construction workers.

ERECTION SEQUENCE

The arch structure will be built in the Erection Zone, assembling each arch one by one in stages. Connections are made using high strength bolts. Sub-assemblies of arches are partially welded at a fabrication area away from the plant and no welding is performed on site. The eight arches that make up the eastern half of the structure will be completed first and then moved to the East end of the Erection Zone so that the western half can be assembled. Once both halves are completed, the East half will be moved back and the entire arch structure will be connected together at the western end of the Erection Zone.

The assembly process also includes, in parallel to the erection of the arches, installation of the main crane system, roof, ceiling, claddings, heating and ventilation system and other components in the annular space and beneath the ceiling in their entirety in the Erection Zone. It is expected that the completion of the arches will take about two years. The sequence of fabrication and then transfer to the Service Zone is shown in Fig. 3.

The foundations in all three zones will be completed together with a rail system that will be used in moving the NSC to the Service Zone. Each arch support will be fitted with a skid system that is capable of self-adjustment to accommodate relative settlements and horizontal displacements. The skid system will include jacks at each support point to be able to push the assembled arch structure on the rails. A typical skid system is shown in Fig. 4.

ANALYSES OF THE ARCH STRUCTURE

Considering the fact that the length of the foundations of the three zones is about 507 m (1664 ft) long, an early decision was made to use two main models for the analysis of the entire structure:

- A 3D model of the arch structure in the Service Zone, and,
- A 3D model of the entire foundation system in the three zones.

There were numerous other models that were used in analyses with limited objectives and for parametric studies. This paper will be limited to the analyses carried out using the two main models.

*Modeling of the Arch Structure*

The analytical model for the arch structure included the entire superstructure plus the north and south foundations in the Service Zone (SIP-N-TE-22-B102_-CLN-005-00 (2011)). The model is about 175 meters long. The superstructure is modeled as a space truss, using beam or bar elements. All major members of the superstructure were included in the model: upper and lower chords, bracings, longitudinal beams, the main crane system rails, as well as MCS garages and lift cage. The space frame joints are modeled as rigid except those which are designed as hinge joints to facilitate their erection.
Three different options were used in the modeling of the foundations: discrete springs at each arch support point, using impedance matrices, and as rigid. Discrete spring values were obtained from the global foundation model by NOVARKA local subcontractor KIEP (a Ukrainian design institute). A geotechnical subcontractor performed a soil-structure interaction analysis of the foundations in the Service Zone to determine impedances at each arch support point (SIP-N-TG-22-B1010-CLN-001-01 (2011)). The dynamic impedances were used by a third subcontractor to perform seismic analysis and the static impedances were used for analysis under the gravity loads. The third modeling method was the simple assumption that each arch is supported by hinges in three orthogonal directions (i.e., zero displacements at supports). The Arch structure was analyzed using all three boundary conditions and the results were enveloped.

The primary superstructure model includes approximately 4000 nodes and 12,000 elements (SIP-N-TU-22-B102_-RPT-054-04 (2011)). Two wide views of the Arch structure model is shown in Fig. 5. Typical arch cross elevation is given in Fig. 6.

**Loads**

The predominant load for the superstructure is the self weight. Live loads, snow loads, wind loads, temperature loads and crane loads were also considered. Wind pressure maps were determined on the basis of Wind Tunnel Tests. In addition, extreme loads including effects of snow and ice avalanche from the Arch Roof, tornados and earthquake shaking were considered. It is worth noting that the NSC is designed for Tornado 3, with a probability of occurrence of $1 \times 10^{-6}$. This is a very severe loading condition and did control the design of some of the space truss members. The tornado loading condition was analyzed 196 times, each case representing a different path and tornado center which were selected to maximize its effects on the structure. The seismic analysis was carried out for a site design response spectrum with 0.13g zero period acceleration and a peak spectral acceleration of 0.30g between 1.0 and 10.8 Hz frequencies (SIP-N-LI-22-A500_-CDS-001-01 (2008), Chapter 2). The fundamental frequencies of the superstructure are 0.34 Hz in the longitudinal, 0.42 Hz in the transverse and 1.33 Hz in the vertical direction (SIP09-2-001 NI 03 RPT 010 01 (2010)).

Design criteria called for consideration of two groups of limit states based on the Ukrainian norms: the 1st group corresponds to Ultimate Limit State (ULS) and the 2nd group to Serviceability Limit State (SLS). SLS loading combinations include dead and live loads, crane loads, snow and ice loads, wind load and thermal loads. ULS loading combinations consist of all loads including tornado, earthquake, and accidental and thermal effects.

**Analysis Results**

Analysis results of the Arch structure in the Service Zone, including member forces, displacements and support reactions are important for the design of the superstructure as well as the foundations. Considering the size of the analytical model and the number of load combinations, a huge amount of output was obtained. Selected results for the design parameters are reported in Table 1. The data given in Table 1 shows (SIP-N-TU-22-B102_-RPT-054-04 (2011)) that support boundary condition modeling does not have much impact on the superstructure forces or support reactions. Difference in Axial Forces in selected members of Arch F does not exceed 10%. At the supports, it slightly exceeds 10%, though reaction loads from Arch F are relatively low compared to the maximum reactions in End Walls (the end wall reactions being greater than twice the arch F reactions), in which maximum difference in most loaded arches remains less than 10%. There are two reasons for this behavior: (1) the superstructure is essentially a determinant structure, thus the support reactions do not
change with support characterization and, (2) the superstructure is flexible relative to the supports and therefore differences in the support stiffnesses do not cause much change in the member forces (Gurbuz 2010a, 2010b). Of course, support stiffness is very important for determining both horizontal and vertical displacements which must be within the allowable limits under all loading conditions.

ANALYSIS OF THE FOUNDATION SYSTEM

For the substantiation of the conceptual design, the entire foundation system was analyzed using a global model. The ground beams were modeled with discrete beam elements both in the longitudinal and transverse directions, the nodes in the transverse direction being located at each pile location. The expansion joints between the three zones were modeled as hinges that could transmit vertical and transverse shear forces but no axial force or moment. Similarly, the expansion joints within the ground beams in the Erection and Service Zones were modeled as hinges. Fig. 7 shows the global foundation model.

The driven steel piles in the Erection Zone and the CFA piles in the Service Zone were also modeled using beam elements; each pile consisting of about 20-25 elements. The soil stiffness was calculated in accordance with the Ukrainian standards and represented by horizontal springs at discrete nodes along the length of the pile. The resistance to vertical displacements due to pile-soil friction was also modeled as springs at each node. Finally, the pile end point resistance was represented by a concentrated spring at the bottom of each pile.

In the Transfer Zone, the ground beam was modeled by multiple beam elements in the longitudinal and transverse directions, without any piles. Again, soil springs in the horizontal and vertical directions were used to model the soil.

This global model was analyzed with the application of superstructure reactions at each arch support point. The foundation system was analyzed for discrete positioning of the superstructure as it was transferred from the Erection to the Service Zone. Lateral and vertical displacements of both north and south foundations were captured and compared with the allowable values for each position of the superstructure along the travel path. Table 2 shows the maximum horizontal and vertical displacements at the arch support points along the transfer path for several different positioning of the arch structure. Figure 8 shows the horizontal displacement profile in different zones when the superstructure is being moved to its final position.

CONCLUSIONS

The NSC project for the Chernobyl plant has brought together a multi-national team that has performed well, overcoming language barriers. The work performed by the international companies was also a technology transfer project; integrating Ukrainian and European standards as well as input from the USA. Once completed, the NSC will be a unique structure, a monumental symbol to international support and cooperation to mitigate the effects of a disaster. At the same time, the resulting design will serve well to achieve the ultimate goal of the project – removal and disposal of the highly radioactive debris inside the OS.

The most significant results from the analyses and design efforts may be summarized as follows:

- The arch structure will withstand the most severe loading conditions. Review of the design data shows that arch structure design is controlled mostly by the gravity plus tornado load combination. Considering the conservatism associated with the tornado loads and the average stress ratios in the members, there is significant design margin in the arch design.

- Modeling of the Service Zone foundations did not have much impact on the arch stresses but significantly affected horizontal displacements of foundations.
REFERENCES


SIP09-2-001 NI 03 RPT 010 01 (2010). “Checking Calculations of NSC Arch Spatial Model in Common with Arch Base”, Prepared by NIISK, Client Engineer for the NSC Project for Chernobyl, Kiev, Ukraine.


### Table 1. Member Forces and Reactions with Different Foundation Modeling Gravity Loads

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Support Model</th>
<th>Maximum Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Impedances (E1)</td>
<td>Springs (E2)</td>
</tr>
<tr>
<td>Arch F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. axial force in Element 438, top chord, kN</td>
<td>834</td>
<td>886</td>
</tr>
<tr>
<td>Max. axial force in Element 1568, bottom chord, kN</td>
<td>1476</td>
<td>1561</td>
</tr>
<tr>
<td>Max. axial force in element 1546, near support, kN</td>
<td>3737</td>
<td>3961</td>
</tr>
<tr>
<td>Max reaction at support, South, kN</td>
<td>6676</td>
<td>5845</td>
</tr>
<tr>
<td>Max reaction at support, North, kN</td>
<td>6808</td>
<td>6891</td>
</tr>
</tbody>
</table>

Notes:  
1) Element numbers are shown in Fig. 6.  

### Table 2. Displacements at Selected Arch Support Points as the Arch is Moved to Service Zone

<table>
<thead>
<tr>
<th>Superstructure Position</th>
<th>Point where Maximum Displacement is Measured</th>
<th>Direction</th>
<th>Maximum Displacement, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>In Erection Zonea</td>
<td>Arch A – South</td>
<td>Horizontal</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Arch A - North</td>
<td>Vertical</td>
<td>47</td>
</tr>
<tr>
<td>Straddling Over Erection and Transfer Zonesb</td>
<td>Arch H</td>
<td>Horizontal</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Arch H</td>
<td>Vertical</td>
<td>27</td>
</tr>
<tr>
<td>Straddling Over Transfer and Service Zonesb</td>
<td>Arch F</td>
<td>Horizontal</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Arch G</td>
<td>Vertical</td>
<td>67</td>
</tr>
<tr>
<td>Service Zonec</td>
<td>Arch N0 – North</td>
<td>Horizontal</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Arch N0 - North</td>
<td>Vertical</td>
<td>37</td>
</tr>
</tbody>
</table>

Notes:  
a) SIP-N-KP-22-C02-CLN-012-00 (2010)  
b) SIP-N-KP-22-C02-RPT-001-01 (2011) (combined Wind, Snow and Temperature Loads)  
c) SIP-N-KP-22-B1010-CLN-016-02 (2012) (combination G+0,95Q+0,9T+0,9S+0,9W+0,9CL)

![Figure 1. NSC Structure and Dimensions.](image-url)
Figure 2. Foundation Zones: Erection, Transfer and Service

Fig. 3 Sequence of Completion of the Arch Structure
Fig. 4 Arch Support During Transfer

Fig. 5 Two Views of the Arch Structural Model:

Fig. 6 Typical Arch Space Frame, Element numbering for Arch F
Fig. 7 Global Foundation Model including all Three Zones:

(a) South Ground Beam

(b) North Ground Beam

Fig. 8 Horizontal Displacements of the Foundations as the Arch Structure is moved to its final position.