# New Save Confinement as a Barrier Between Destroyed Reactor of the Chernobyl NPP and Environment (design, purpose, modeling)

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*Abstract:* This paper describes the purpose and the design of the New Safe Confinement (NSC), which was raised and slid over the destroyed Reactor Unit 4 and "Object Shelter" (SO) of the Chernobyl nuclear power plant and shows the examples of CFD modeling of these objects. Paper shows important physical processes, such as heat, air, humidity and radioactive aerosols (RA) transfer, taking place in the SO and NSC and the necessity of their analysis and forecasting, which eventually determine the safety of people and the 100-year lifetime of the NSC. Paper shows how developed 3D CFD model allows analyzing the thermal and humidity state to check the design of the NSC ventilation system and estimate present and future levels of RA concentrations.

*Key-Words:* Chernobyl NPP, New Safe Confinement, destroyed reactor, radioactive aerosols, environment, modelling

## 1 Introduction

The melt down of the Reactor Unit 4 of Chernobyl Nuclear Power Plant (ChNPP) that happened on 26 April 1986 is the worst accident in history in terms of resulting deaths, health issues, environment and costs. It is one of only two accidents classified as a level 7 event (the other being the Fukushima Daiichi nuclear disaster in 2011).

The sarcophagus or Object Shelter (SO) (Fig.1) was designed and built in November 1986 to limit radioactive contamination of the environment, by encasing the most dangerous area and protecting it from climate expos [1]-[3]. It is located within a large restricted area known as the Chernobyl Exclusion Zone.

Fig.1. The Shelter Object.

Inside the OS there still remains about 95% of the fuel, which was in the reactor at the moment of the accident (Fig.2,3).

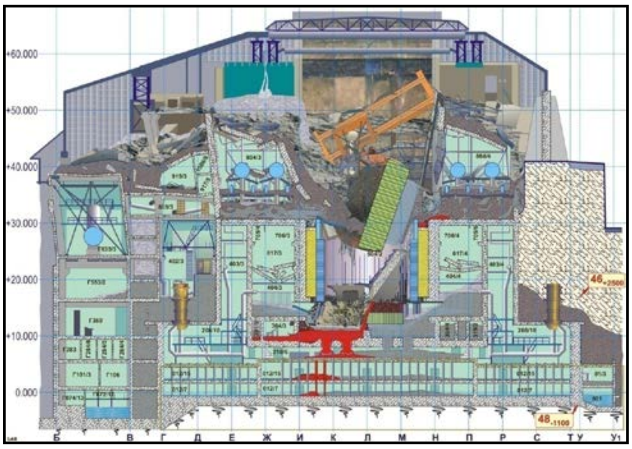



Fig.2. Destroyed reactor and Shelter Object

During the last 30 years some of SO bearing constructions became unstable and were strengthened and repaired. Metal light roof of the SO was sealed but for today there still remain about 120-150 $m^2$ of cracks and holes, through which a large amount of radioactive aerosols can get to the environment.

Fig.3. Highly radioactive melted fuel masses under destroyed reactor in the Shelter Object (Fig. 2, red zones).

A decision to enclose the SO by a so called **New Safe Confinement (NSC)** was taken, and a project to reconstruct the enclosure has since been completed.

It is a complex of engineering solutions, designed in the form of the Arch, covering the SO (Fig.4,5). Main purpose of the NSC is the protection of the environment from radiation and radioactive aerosols (RA) during the SO dismantling and the 100 years operation of the NSC. It also contains the equipment for extracting the nuclear fuel remains from the destroyed unit, to transform it to an environmentally safe system ensuring the safety of personnel and environment.

The NSC has been built for 5 years near the SO (Fig.4,6) and was slid to its design position over the SO NSC in November 2016 (Fig. 5, 7).

Its height is 110 m, width - 250 m, length - 160 m (Fig. 4,5) and weight of about 36,000 tones. Its frame is a h uge lattice construction consisting of tubes, supported by two longitudinal concrete beams (Fig.5).

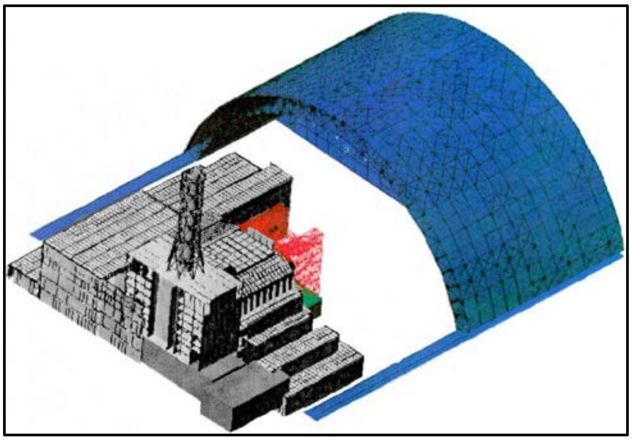


Fig. 4. The scheme of the SO and the NSC relative position.

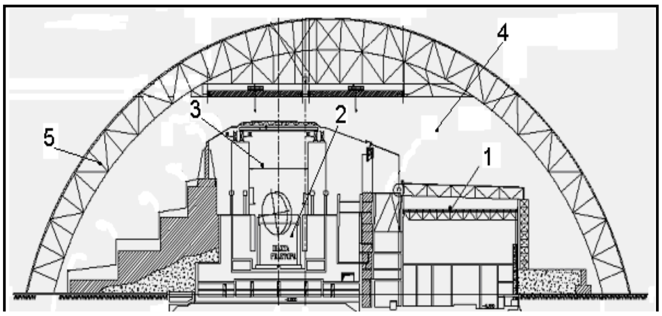



Fig. 5. The scheme of the SO and the NSC cross-section. 1- turbine hall, 2 – destroyed reactor, 3 – central hall, 4 – main volume and 5 – annular space of the NSC.

Fig. 6. T he photo of NSC during construction (2014)

The comparative sizes of the New Save Confinement are shown in Fig. 8. This figure illustrates such a huge size of the NSC that it could cover the Statue of Liberty in USA (height 93 m) and a Colosseum in Rome, Italy (length 188 m).

Fig. 7. The photo of NSC and SO after NSC sliding over the SO (2017)

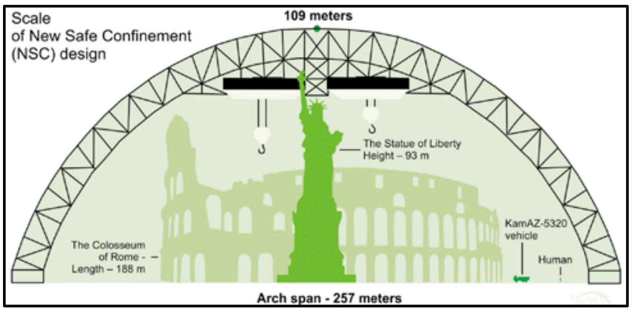



Fig. 8. Comparative sizes of the New Save Confinement

The NSC as a barrier between destroyed reactor and environment was designed with several design goals:

1. Transform the destroyed ChNPP Unit 4 into an environmentally safe system (i.e. contain the radioactive materials at the site to prevent further environmental contamination).

2. Reduce corrosion and weathering of the existing shelter and the Unit 4 reactor building.

3. Mitigate the consequences of a potential collapse of either the existing shelter or the Unit 4 reactor building, particularly in terms of containing the radioactive dust that would be produced by such a collapse.

4. Enable safe dismantling of unstable structures (such as the roof of the existing shelter) by providing remotely operated equipment.

## 2 Problem Formulation

To ensure the 100-year lifetime of the NSC its bearing steel constructions are enclosed into the outer and inner claddings (annular space in fig.6), between which the relative humidity is maintained below 40% under different weather conditions. Special ventilation system was designed for this purpose, which heats up, recirculate and dry the air of the annular space between the NSC claddings.

***Purpose of the ventilation system:***

1. Maintenance of humidity in the annular space of the Arch below 40% and pressure about 50 Pa
2. Maintaining the underpressure in the main volume of the NSC at about -5 Pa.

Such requirements should be fulfilled in following range of climatic conditions: temperature -22 to +31 ° C, relative humidity 0 to 100% and wind speed 0 to 25 m/s.

To verify the ventilation system operability engineering and construction company VINCI Construction Grands Projects/Bouygues Travaux Publics NOVARKA ordered the work on the 3D CFD (Computation Fluid Dynamic) modelling of thermalgasdynamic and humidity state of the NSC-SO which was completed.

For this, the model has to consider the following properties and physical processes outside and inside of the NSC and SO (fig.9):

1. 3-D and non-steady state of the NSC and SO
2. The thermal inertia of the NSC and SO in the annual cycle consideration.
3. Consideration of external as well as the movement of internal air flows.
4. Accounting for the work of basic engineering equipment (ventilation, dehumidifying, heating, etc.).
5. Main heat sources in the NSC and the SO.
6. Consideration of non-tightness of NSC claddings
7. The radioactive aerosols spread inside and outside the NSC.

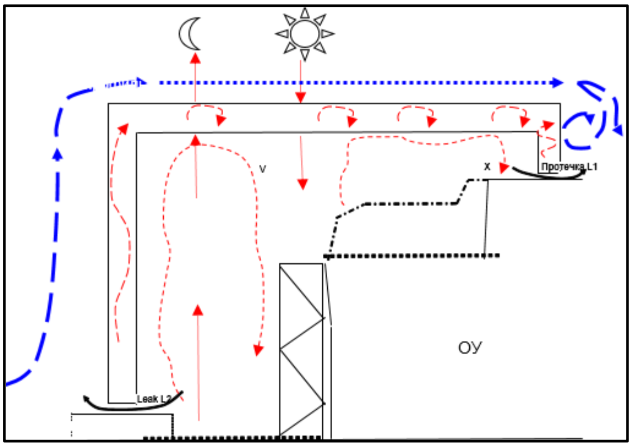



Fig.9. Longitudinal section of NSC and SO. The blue arrows on indicate the outside airflow movement due to wind and pressure difference and the red arrows inside due to thermally induced airflow movement due to temperature differences (thermal convection).

## 3 Methodology

The general idea of the work (Fig. 10) is to go through the following steps: development of separate SO model, then its calibration after which united model of SO and NSC will be developed and applied too.

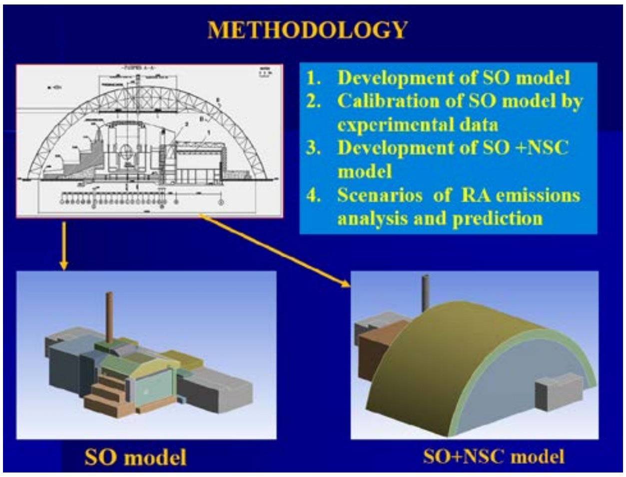



Fig. 10 The general methodology

The SO model calibration is identification (estimation) of its parameters using experimental data. Parameters can be divided into groups: hydraulic resistances of the SO roof and volumes and source terms of radioactive aerosols inside the SO. In model, it is possible to assign properties of porous media to volumes of SO roof and internal volume of chimney. It makes possible adjusting airflows through each opening in the model that is extremely important for aerosol leak rates. Parameters of hydraulic resistances were estimated using the information on a verage airflows through the SO roof and chimney.

## 4 SO and NSC+SO models creation

Numerical models consider all main geometric parts of the SO (Fig.11) and NSC+SO (Fig.12) models and was created in frame of ANSYS FLUENT software [4]. It simulates following steady and unsteady physical phenomena (Fig.9):

• NSC flow-around by wind at different speeds and directions (Fig. 12, b);

• conjugate heat and mass transfer (heat conduction, forced and natural convection, radiative heat transfer between ground, foundation, destroyed reactor, SO and NSC and environment including the solar radiation in the light time and radiation to the sky-space at night (Fig. 13, a);

• humidity distribution in all of the volumes of the SO, NSC and environment (Fig. 13, b, c);

• air and humidity leakages through the small gaps of the NSC claddings and gaps between the vertical NSC walls and existing buildings;

• radioactive aerosols spread, either as a second phase or as particles, moved by the airflows.

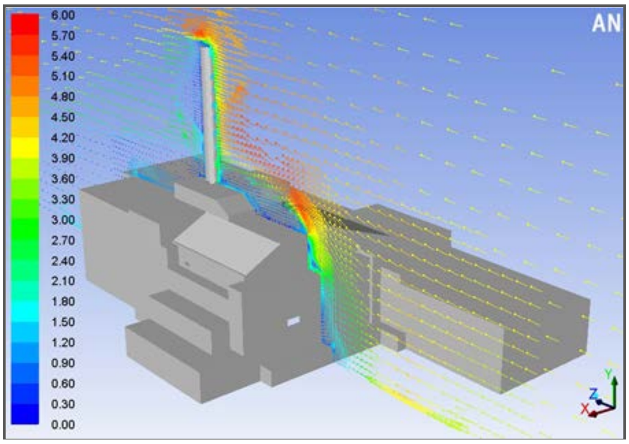
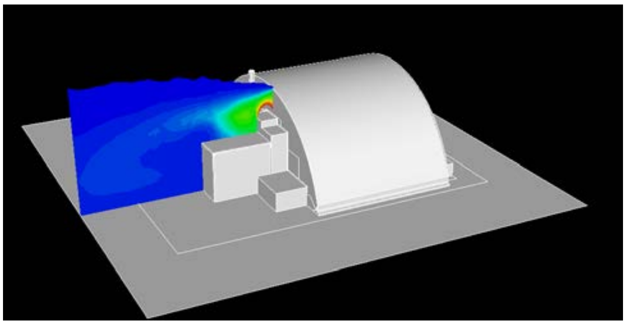



Fig. 11. Geometrical model and velocity vectors for SO

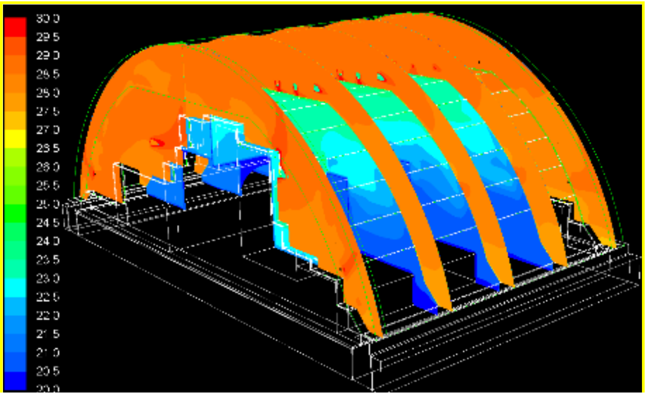
a



b

Fig. 12. Geometrical model, (a) cross-section of the model mesh and (b) velocity field for combine NSC+SO model

Model allowed to check the operability of the ventilation system under various weather conditions and also in cases of different failures of ventilation equipment.



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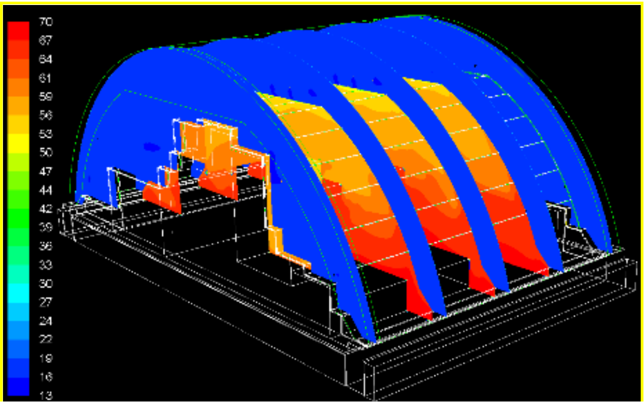

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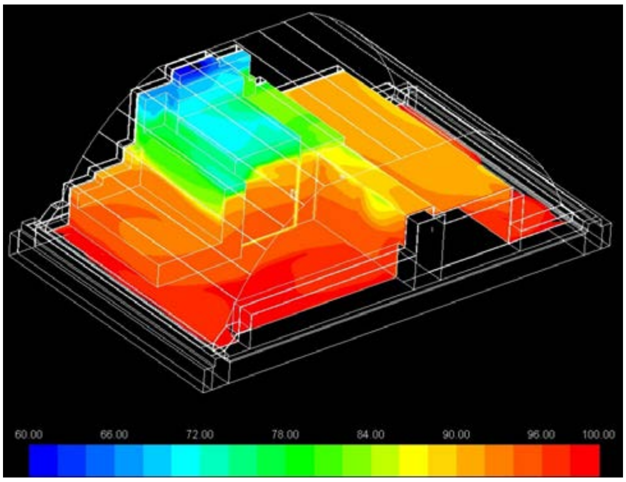



c

Fig. 13. (a) temperature, °C and (b,c) humidity, % distributions in different cross-sections of the (a,b) NSC and SO as well as (c) on the SO outer surfaces and the lend under NSC.

## 5 SO model verification

According to methodology (Fig.10) the SO model was calibrated and verified with the data of measurements of Aspiration Units (AU), measuring RA concentration nearby the SO and also with accumulating pads, located on the SO roof (Fig. 14), measuring value of RA emissions through the SO roof.

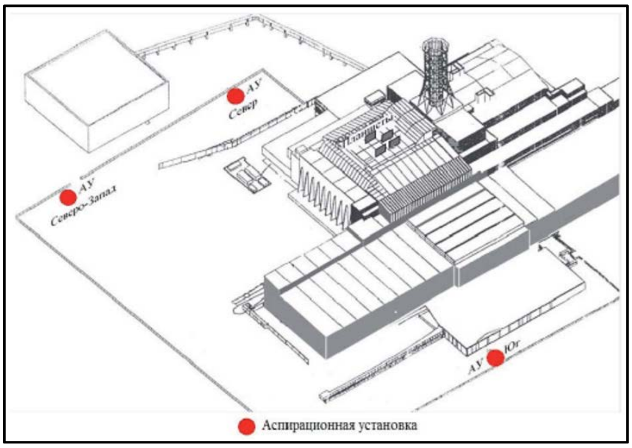



Fig. 14. The Aspiration Units and accumulating pads location scheme nearby the SO and the SO roof.

For example, the table below gives satisfactory results of comparing the experimental measurements (Fig. 14) and the calculated values of the RA emissions through the SO roof, obtained with the help of the model (Fig. 15).

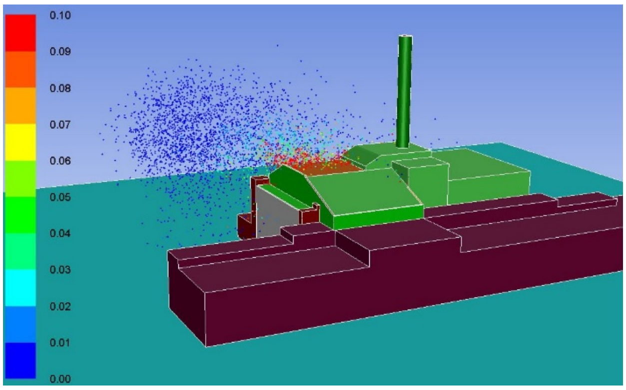



Fig. 15. Visualization of RA emissions through the SO roof of the model in the south wind.

| # | AU name | RA concentration, Bq/m$^3$ | | Average concentration, Bq/m$^3$ | |
|---|---|---|---|---|---|
| | | Measured | Model | Measured | Model |
| 1 | AU1 (north) | 0.0150 | 0.0026 | **0.013** | **0.019** |
| 2 | AU2 (north-west) | 0.0098 | 0.0479 | | |

| | | | | | |
|---|---|---|---|---|---|
| 3 | AU3 (south) | 0.0140 | 0.0057 | | |

Verification of the SO unsteady thermal state model was conducted using the data of temperature measurements inside SO, carried out in 2003 and shown in report **[5].** Calculations were conducted taking into account thermal and gas dynamic state of the SO as well as RA concentration changing inside and nearby of the SO. Weather condition was considered as en vironment temperature changing during the year according to the meteorological data, wind velocity in the model is growing with height (4m/s on the height of 10m). Wind direction was changing with time. To make modelling results closer to experimental data the porosity and hydraulic resistances of SO volumes were assessed. Comparison of modelling results and experimental data is shown in Fig.16. It can be seen that average temperatures of SO inner volumes are reasonably close.

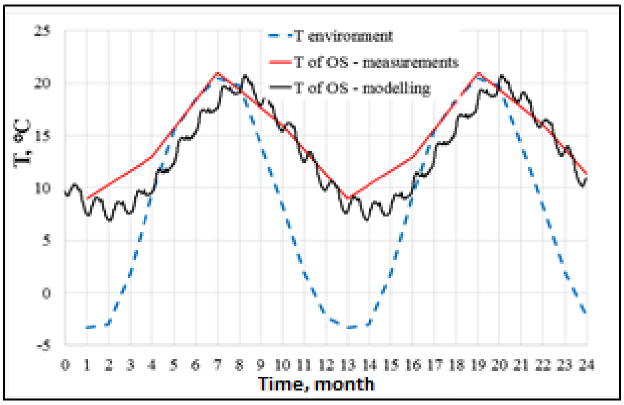


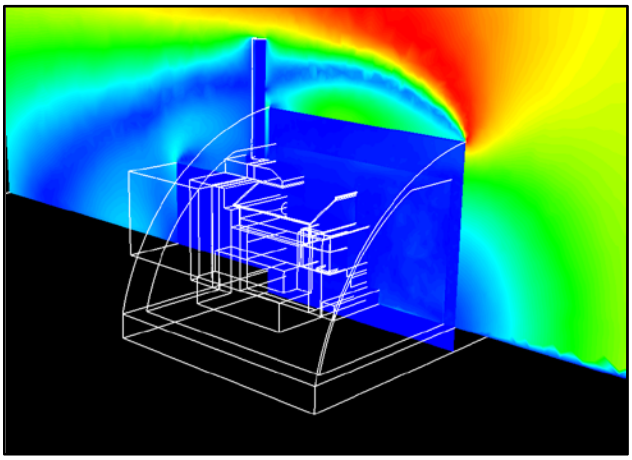

Fig. 16. Dynamic changes of average temperatures (T) of SO inner volumes and environment during two years

## 6 NSC+SO model analysis

Since developed NSC+SO model can simulate the 3D flows of the air, it also can simulate the radioactive aerosols emission from the destroyed heat-generating reactor, either as second phase or as discrete particles, transferred by the airflows (Fig. 17- 19) for different scenarios. The mass transfer is simulated in the units of $kg/m^3$, and concentration distributions are recalculated through the weight activity Bq/kg for 1 kilogram of RA.

Since not so much time passed since NSC sliding to its design position, the experimental data on t he distribution of aerosol concentrations inside and nearby the NSC are not available. Therefore, the results presented below are preliminary and estimated.

Simulation of the RA concentration is very important for the radioactive state analysis of the inner air space of the NSC, where personnel works (Fig. 19, c).



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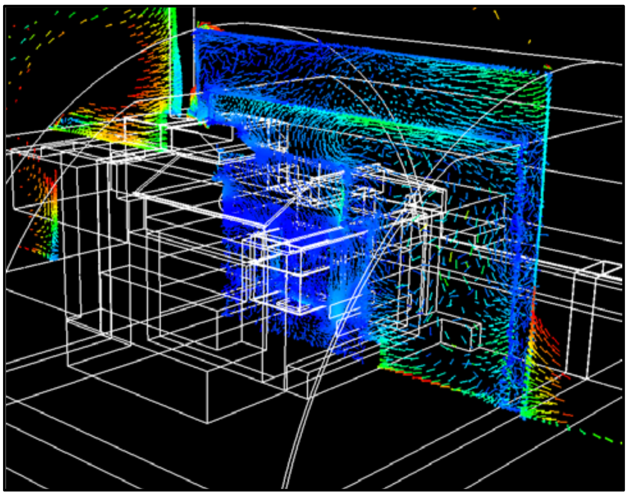


b

Fig 17. Velocity (a) field and (b) vectors distribution in longitudinal cross section of NSC+SO model and surrounding area

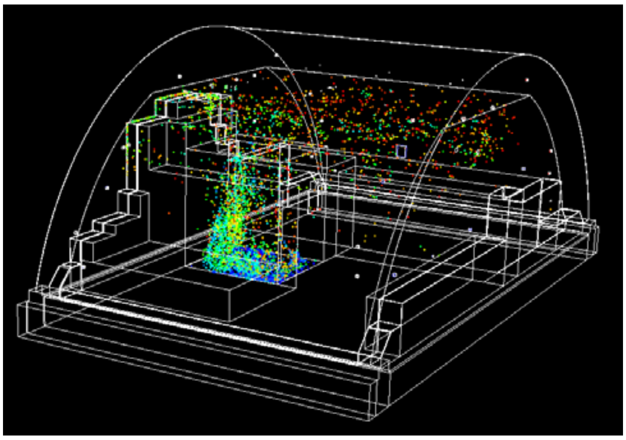
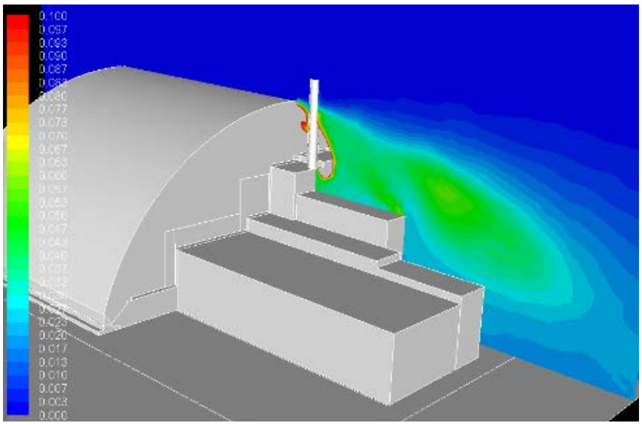


Fig 18. The process of radioactive aerosol particles distribution from SO to main volume of NSC modelling.



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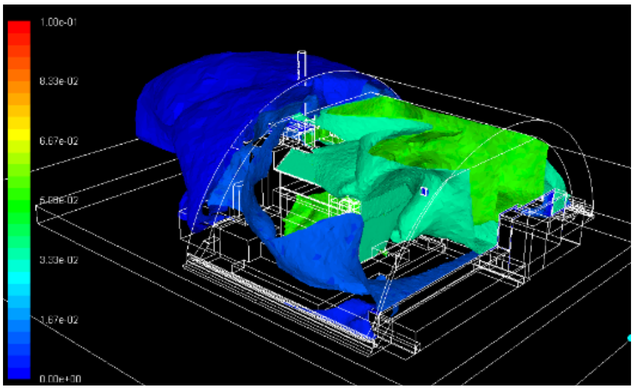

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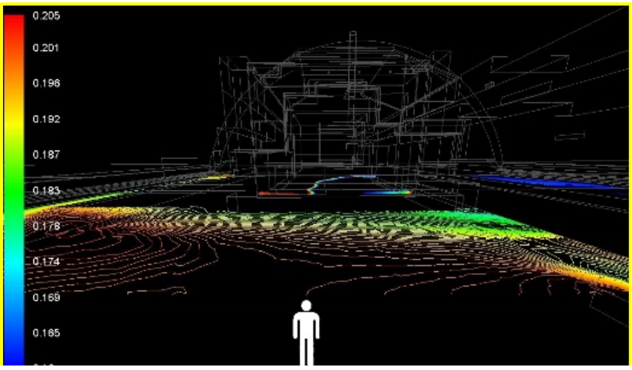


c

Fig. 19. RA concentration distribution, Bq/m$^3$, (a) outgoing from NSC to the environment, (b) isosurfaces of RA concentrations inside and outside the NSC, and also (c) isolines of RA concentrations inside the NSC at the height of 1.5m from the ground at the area of possible personnel activity.

- The analysis shows that the NSC is not an absolute barrier for radioactive aerosols between the destroyed reactor and the environment. Small amount of RA can penetrate to the environment along with air flow (Fig. 17 and 19,a,b) through the outer cladding and gaps between the western and eastern walls of the NSC walls and building structures (Fig. 19,a,b). To take into account such phenomena specific features were implemented and built into the model, part of which are not included into the software used. Among such features is considering the heat and mass transfer through the inner and outer non-hermetic claddings of the NSC under small pressure gradients and large hydraulic resistances. It must also be emphasized the importance of the natural thermal convection in the SO and NSC under the influence of the weak driving forces (small temperature differences and air-speeds) as it determines air, heat, humidity and RA transfer in the studied objects.

## 7 Conclusion

This paper discussed the purpose and design of the New Safe Confinement (NSC), which was built and slid over Object "Shelter" (SO) and Destroyed Reactor of the Chernobyl nuclear power plant. The necessity of analysis and forecasting of the conjugate thermal, gas dynamic and humidity transfer processes in the SO and NSC, which determine the 100-year lifespan of the NSC, was justified. For this a 3D CFD-computer model was developed, which allows to analyze the abovementioned phenomena as well as the radioactive aerosols spread in the SO and NSC volumes and their leaks to the environment.

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