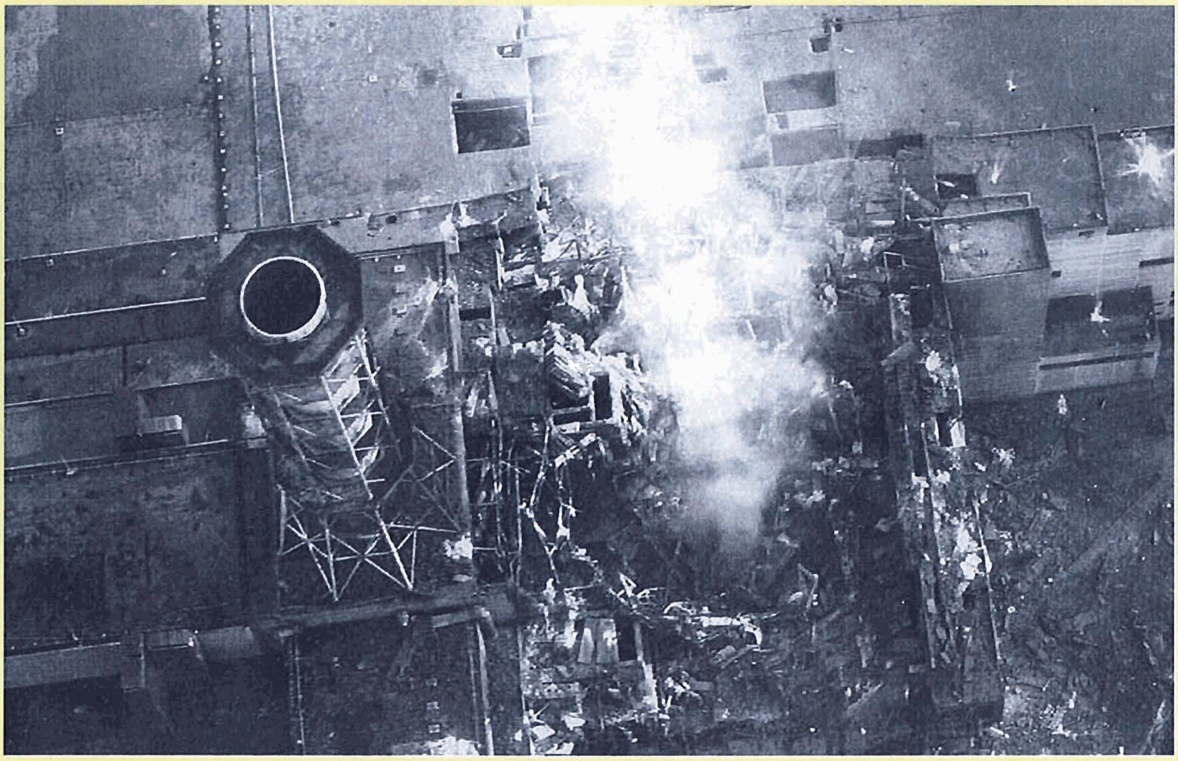
Project № 2916
"Development of the Models for Nuclear Fuel Behavior during Active Phase of Chernobyl Accident"
(Performed under a special Agreement between the International Science and Technology Center and the Russian Research Center "Kurchatov Institute")

THE EFFICIENCY OF MEASURES ON ELIMINATION OF THE CHERNOBYL ACCIDENT CONSEQUENCES (The Active Accident Phase)



Moscow 2007

Project № 2916
"Development of the Models for Nuclear Fuel Behavior during Active Phase of Chernobyl Accident"
(Performed under a special Agreement between the International Science and Technology Center and the Russian Research Center "Kurchatov Institute")

Borovoi, A.A., Pazukhin E.M. and Strizhov V.F.

THE EFFICIENCY OF MEASURES ON ELIMINATION OF THE CHERNOBYL ACCIDENT CONSEQUENCES (the Active Accident Phase)

Project Manager: Borovoi A.A.

Preprint of RRC "Kurchatov Institute"
ИАЭ-6471/11

UDK 621.039.51

Borovoi, A.A., Pazukhin, E.M. and Strizhov V.F.
The Efficiency of Measures on Elimination of the Chernobyl Accident Consequences
(the Active Accident Phase)
Preprint of RRC "Kurchatov Institute" ИАЭ-6471/11

Abstract

The paper is based on the outcomes of the Project "Development of the Models for Nuclear Fuel Behavior during Active Phase of Chernobyl Accident" (#2916) implemented under a special agreement between the International Science and Technology Center (ISTC) and the Russian Research Center "Kurchatov Institute" (RRC KI).

Evaluation of the efficiency of countermeasures undertaken during early post-accident days to localize the Chernobyl NPP accident necessitates understanding of the processes that went on within the damaged power unit at that time.
In our opinion, based on the database developed and the results of simulation one may advance on such a way.

The following order of data presentation is accepted in this paper. At first the situation understanding at the event time and measures taken on its basis are described, next these activities are analyzed from the standpoint of the present-day-knowledge.

Fig. 16, Tab. 8, Refs. 29.

CONTENT

ABBREVIATIONS AND DEFINITIONS

BWC	Bottom Water Communications
CH	Central Hall
Chernobyl NPP	Chernobyl Nuclear Power Plant
Component "E"	Upper plate of biological shield
Component "OP"	Reactor basement
EDR	Exposure Dose Rate
FCM	Fuel-Containing Materials
IAEA	International Atomic Energy Agency
IBRAE RAS	Nuclear Safety Institute of the Russian Academy of Sciences
ISTC	Interdisciplinary Scientific and Technical Center
LFCM	Lava-like Fuel-Containing Materials
NPP	Nuclear Power Plant
Project	Project #2916 - Development of the Models for Nuclear Fuel Behavior during Active Phase of Chernobyl Accident (implemented under a special agreement between the International Science and Technology Center and the Russian Research Center "Kurchatov Institute")
PSP-1	Pressure-Suppression Pool First Floor
PSP-2	Pressure-Suppression Pool Second Floor
RBMK	High-power channel-type boiling reactor
RRC KI, KI	Russian Research Center "Kurchatov Institute"
SChR	Self-sustaining Chain Reaction
SDC	Steam-Distribution Corridor
SSE Chernobyl NPP	State Specialized Enterprise Chernobyl Nuclear Power Plant
USSR	Union of Soviet Socialist Republics

INTRODUCTION

The Project **"Development of the Models for Nuclear Fuel Behavior during Active Phase of Chernobyl Accident" (#2916)** implemented presently under a special agreement between the International Science and Technology Center (ISTC) and the Russian Research Center "Kurchatov Institute" (RRC KI) is nearing completion.

Specialists of RRC KI and of the Nuclear Safety Institute of the Russian Academy of Sciences (IBRAE RAS) participate in the Project implementation.

The major goal of the Project consists in the development of a model describing the processes, which underwent nuclear fuel of Chernobyl NPP Unit 4 during the active phase of the Chernobyl accident.

As expected, the results achieved will be used in subsequent "Shelter" transformation activities as well as in solution of a series of nuclear power safety problems.

From our viewpoint, the Project outcomes may be also of the essence for evaluation of the efficiency of countermeasures applied to localize the Chernobyl accident and eliminate its consequences.

Evaluation of the appropriateness and timeliness of scientific, technical and administrative decisions as well as of success of the methods of their implementation necessitates understanding of the processes that went on within the damaged power unit at that time.
Based on the database developed and the results of analysis achieved during the Project implementation one may advance on such a way.
This has become the objective of the study.

It is worthy of note, however, that, while determining the efficiency of some of the decisions taken, we still have to be guided by hypotheses – though most credible ones but not justified in detail.

The following order of data presentation is accepted in this paper. At first the situation understanding at the event time and measures taken on its basis are described, next these activities are analyzed from the standpoint of the present-day-knowledge.
Only the activities of major importance are considered.

For text-integrity purposes several extracts taken from our previous publications and reports on this subject (see the relevant references) have been included into this paper.

1. ACTIVE PHASE OF THE ACCIDENT AND SEVERAL ACTIVE-PHASE MODELS

1.1. Radiation, Nuclear and Heat Hazard

1.1.1. Nuclear Fuel before the Accident

During the accident at Chernobyl NPP Unit 4 all safety barriers between highly radioactive nuclear fuel and the environment were destroyed.
Detailed characteristics of nuclear fuel at Chernobyl NPP Unit 4 immediately before the accident are provided in many publications (see e.g. References [1 - 3]).
The most general properties of Unit 4 nuclear fuel are described below.

Before the accident the core of Unit 4 contained 190.2 t (U) of irradiated nuclear fuel, the average burnup being about 11 MW×day/kg (U). The data on activity of main long-lived radionuclides accumulated therein are summarized in Tables 1 and 2 [3].

Table 1. Characteristics of main β and γ -active nuclides in fuel of Unit 4 before the accident

	Radionuclide	Half-life	Total activity (Bq)	Activity per 1 g of U (Bq)
1	^{89}Sr	50.5 d	$4.0 \cdot 10^{18}$	2.1×10^{10}
2	$^{90}Sr + ^{90}Y$	28.6 y	$2.3 \cdot 10^{17}$	1.2×10^{9}
3	^{95}Zr	64 d	$5.8 \cdot 10^{18}$	3.05×10^{10}
4	^{95}Nb	35 d	$5.7 \cdot 10^{18}$	3.0×10^{10}
5	^{103}Ru	39 d	$3.8 \cdot 10^{18}$	2.0×10^{10}
6	$^{106}Ru + ^{106}Rh$	368 d	$8.6 \cdot 10^{17}$	4.5×10^{9}
7	^{125}Sb	2.77 y	$1.5 \cdot 10^{16}$	7.9×10^{7}
8	^{134}Cs	2.06 y	$1.7 \cdot 10^{17}$	8.9×10^{8}
9	$^{137}Cs + ^{137m}Ba$	30 y	$2.6 \cdot 10^{17}$	1.37×10^{9}
10	$^{144}Ce + ^{144}Pr$	284 d	$3.9 \cdot 10^{18}$	2.1×10^{10}
11	^{154}Eu	8.8 y	$1.4 \cdot 10^{16}$	7.4×10^{7}

Table 2. Characteristics of main α -active nuclides in fuel of Unit 4 before the accident

	Radionuclide	Half-life	Total activity (Bq)	Activity per 1 g of U (Bq)	Total mass (kg)
1	^{238}Pu	87.7 y	1.3×10^{15}	6.8×10^{6}	2
2	^{239}Pu	2.4×10^{4} y	9.2×10^{14}	4.8×10^{6}	412
3	^{240}Pu	6.56×10^{3} y	1.5×10^{15}	7.8×10^{6}	185
4	^{241}Pu[1]	14.4 y	1.8×10^{17}	9.4×10^{8}	48
5	^{242}Pu	3.75×10^{5} y	2.9×10^{12}	1.5×10^{4}	20
6	^{241}Am	433 y	1.6×10^{14}	8.4×10^{5}	12
7	^{243}Am	7.38×10^{3} y	9.7×10^{12}	5.1×10^{4}	1.3
8	^{242}Cm	163 d	4.3×10^{16}	2.3×10^{8}	0.35
9	^{244}Cm	18.1 y	4.0×10^{14}	2.1×10^{6}	0.13

Specific decay heat of fuel equaled about 200 kW per ton and decreased over time in accordance with the plot in Fig. 1.

[1] ^{241}Pu, virtually a pure β-emitter, is included into the table for the following reason: after β-decay ^{241}Pu transits into α -emitter - ^{241}Am.

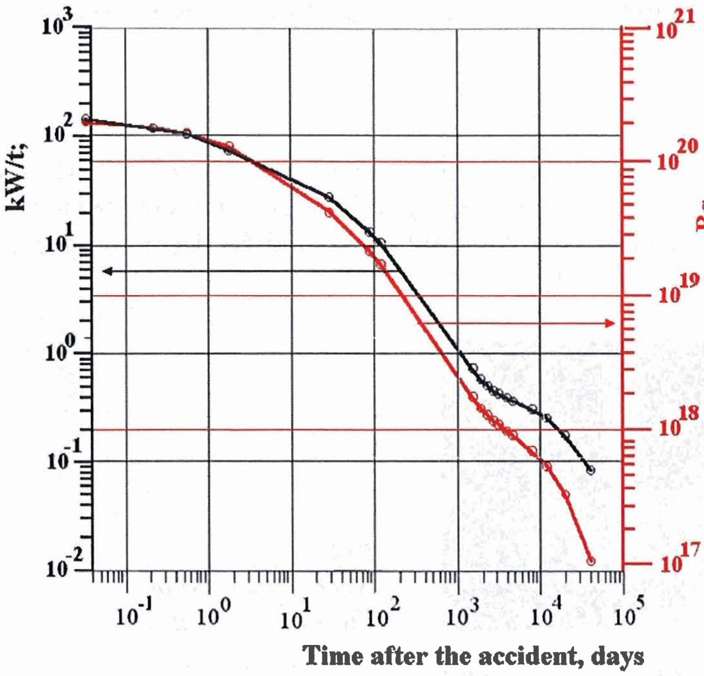


Fig. 1. Dependence of decay heat (upper curve) and activity (bottom curve) of Unit 4's fuel on the time elapsed after the accident

1.1.2. Devastations Observed

What was known on the damaged power unit and its fuel approximately one day after the accident onset, i.e. by the beginning of work of the Governmental Commission?
In brief, the pattern of devastations was viewed as follows.

Reactor Unit (Figs. 2a and 2b) [redacted]

The core was destroyed, and its fragments were thrown by the explosion into the Unit's wreckage, onto roofs of neighboring buildings and vent tube areas, etc.; they were also scattered about the adjacent territory.
The upper plate of biological shield ("E" component) was torn away and stood aslant across the reactor vault. Walls and floors of the central reactor hall were destroyed. Floors in rooms of steam-separator drums were displaced and walls were broken down. The refueling machine was torn off and fell down. Rooms of the northern and the southern primary coolant pumps were destroyed.

Deaerator Stack
Upper floors were destroyed.

Turbine hall
The roof was destroyed in many locations due to fire and fall of debris.

Unit of auxiliary systems of the reactor compartment
Local destructions were observed.

Emergency reactor cooling system
The emergency reactor cooling system was fully destroyed and covered with debris of building constructions.

In addition to the above devastations, numerous breaks in individual structures and rooms were observed as well.

Site

After the explosion the area immediately adjacent to the destroyed unit was contaminated with scattered core fragments: debris of fuel elements, blocks of graphite stack and elements of constructions. They were thrown onto the roof, into the turbine hall and the deaerator stack, onto the roof of Unit 3, metal supports of vent tube, etc.

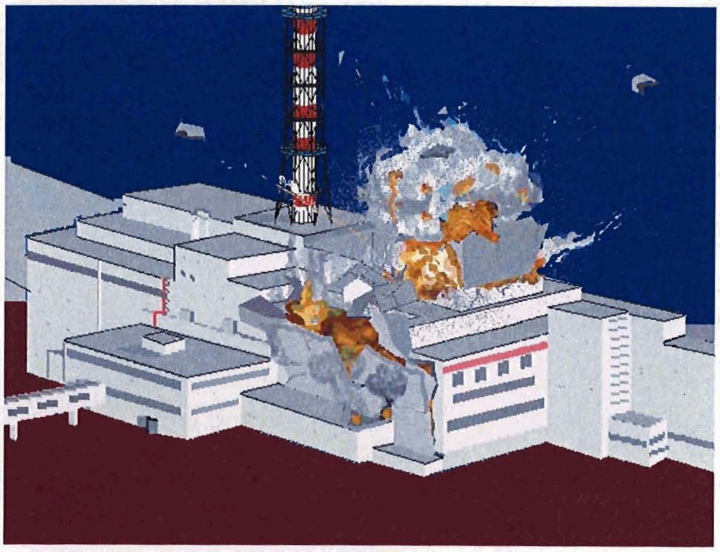


Fig. 2a Reconstruction of the explosion at Chernobyl NPP Unit 4 (April 26, 1986)

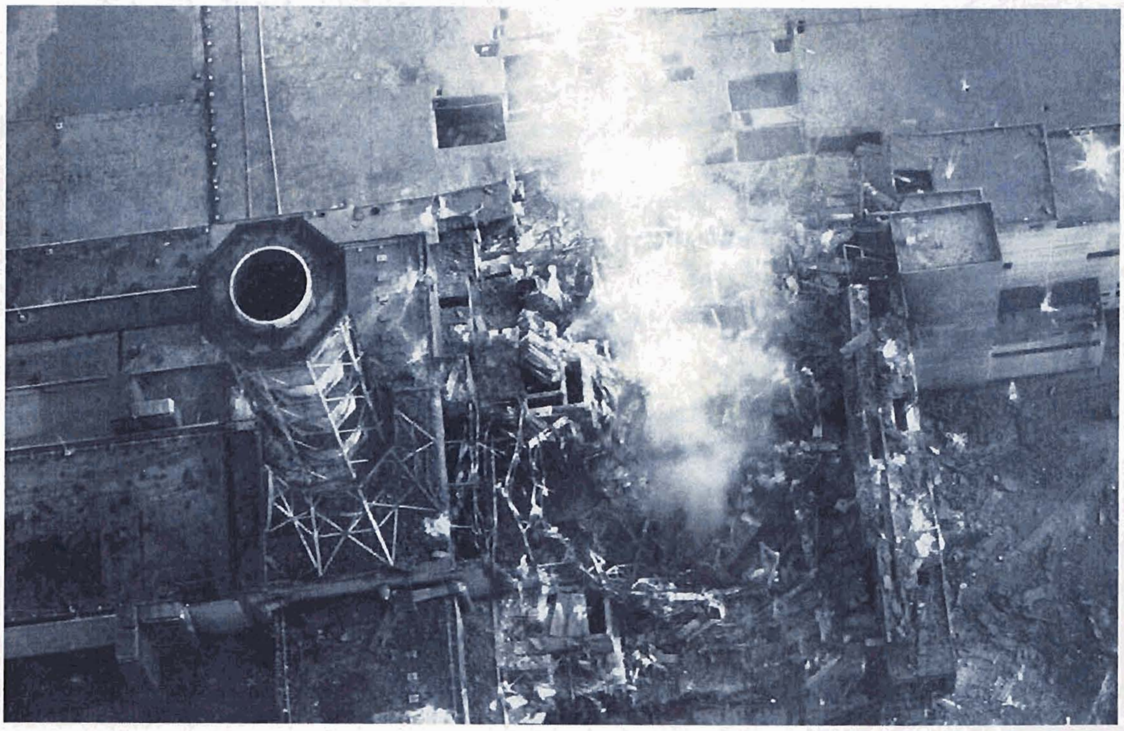


Fig. 2b Destroyed Unit 4 of Chernobyl NPP: view from helicopter at the time of the active accident phase

In the vicinity of Unit 4 gamma fields were mostly determined by radiation of the reactor wreckage.

In the course of early post-accident hours, there was no reliable official data characterizing the radiation situation inside and outside the destroyed power unit.
For instance, according to the measurements performed close to Unit 4 by S.S. Vorobiev, Chief of the Civil Defense Headquarters, the gamma Exposure Dose Rate (EDR) exceeded 200 R/h (the limit value for the used gauge 'DP-5') [4]. However neither the Chernobyl NPP administration, nor the chiefs of the Kiev region Civil Defense Department took those data into consideration. In compliance with their reports, according to measurements of the Chernobyl NPP's Civil Defense Department, on April 26 at 04:10 a.m. EDR close to the emergency unit equaled only 15-20 R/h.
It was only by 14:00 p.m. that officers of the Ukrainian Civil Defense Headquarters reported the EDR values above 700 R/h [5].

At 14:00 p.m. an interdepartmental team of specialists arrived in Pripyat-town and began immediately the identification of the radiation situation. Jointly with specialists of the Chernobyl NPP's Civil Defense Department and military personnel of Chemical Troops of the Ministry of Defense they charted the very first trustworthy maps of dose fields.
One of such maps characterizing the radiation situation around the emergency Unit by the evening of April 26 is demonstrated in Fig. 3. It was charted on the basis of generalized data transferred to Kurchatov Institute, Biophysics Institute, etc. (see e.g. Ref. [6])[2].
Due to non-uniformity of radioactive contamination the measured dose rates varied from tens of milliroentgen per hour up to thousands of R/h. Such large values were either measured close to the destroyed unit or characterized the core fragments.

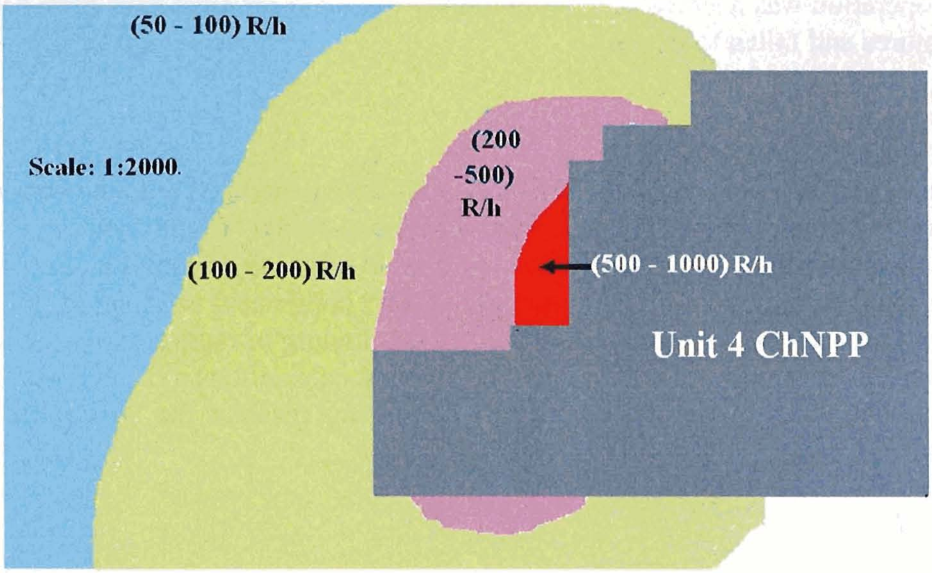


Fig. 3. Radiation fields (EDR values) around the destroyed Unit 4 of Chernobyl NPP as of April 26, 1986

[2] To improve the radiation monitoring, on April 29, 1986 the Governmental Commission placed the responsibility for its conducting within the 10-km zone upon the Chief of Chemical Troops of the Ministry of Defense. After that a radiation-monitoring network comprising at first 29 and next 36 monitoring stations was established. EDR was measured at each monitoring station once a day.

1.1.3. Three Types of Hazard

The Governmental Commission identified three major types of hazard that issued from nuclear fuel of the destroyed reactor at that time.

Nuclear Hazard

The fact of possible survival of a considerable intact cluster of uranium-graphite stack inside the destroyed reactor was of major concern. Even the first calculations completed by early May 1986 [7] demonstrated that "…in case of no water and rods of the control-and-protection system the multiplication factor K_∞ equals ~ 1.16 at a temperature of ~ 1000°C".
According to other calculations, the initiation of Self-sustaining Chain Reaction (SChR) was considered possible in a cluster with more than 154 channels (~1/10th of the stack) in a case that, by any reasons, it contained no absorber rods. Average fuel burnup was taken equal to 10.3 MW×day/kg (U).
The situation of release of a hazardous fragment of the stack during the explosion and its fall to the Central Hall was considered less probable though possible.
In our knowledge, among other possibilities of appearance in the destroyed reactor of a system comprising fuel and moderator capable of initiating SChR, a case was studied involving spillage of dispersed fuel to the bottom part of the stack in the event of fuel element destruction and zirconium melting (both tubes and fuel element claddings). In such a case a column of uranium dioxide ~200 cm in height is generated in each channel (K_{eff} exceeds 1 only at temperatures below 1000°C [7]).

However in opinion of reactor-physics specialists, survival of such a large reactor cluster after the explosions was considered low provable, whereas the period of its hypothetical uncontrollable operation was deemed of short duration – such cluster must have been heated up to high temperatures and fallen to pieces.

Heat Hazard

According to early views, a portion of nuclear fuel might have penetrated onto the bottom reactor plate – the 'OP' component. The heat hazard or the so-called "China Syndrome" (name of the same-title feature film that became frequently used in Chernobyl) consisted in the possibility of gradual burning with glowing fuel of the 'OP' component and then of floors of bottom rooms of the reactor compartment followed by descending of radioactivity down to the groundwater level and groundwater contamination. The first calculations of such processes performed at Kurchatov Institute produced not very comforting results – the "syndrome" might have become real.

Radiation Hazard

First of all, that type of hazard was caused by non-stop release of activity from the destroyed reactor, mainly, due to burning of graphite.

Radioactivity was released to the atmosphere together with smoke and, as it became known soon, millions of Ci per day were released and tens of thousands of square kilometers of lands were contaminated [8].

1.2. First Countermeasures

1.2.1. Water Delivery to the Destroyed Reactor

Attempts at stopping heating of the core and preventing burning of graphite began immediately after the accident initiation. In particular, an attempt was made on delivering a maximum possible amount of water to the reactor using both emergency and auxiliary feed pumps. Generalized analysis of many publications[3] (despite the presence therein of contradictory data as well) has allowed the following reconstruction:

- Water deliveries to the reactor began soon after the explosion between 2:00 a.m. and 3:00 a.m.
- Valves that impeded normal water flow were fully opened (manually) not until 4:00 a.m.
- According to evidences of eyewitnesses, only a minor portion of water penetrated into the destroyed core; its main flow passed via the reactor vault periphery and via auxiliary rooms.
- Highly radioactive water flowed over bottom level marks of power units ##3, 2 and 1. Water also penetrated into the room of electrical assemblies that provided power supply to cooldown systems (including emergency ones designed to cool the cores of those power units). Water pumping out of those rooms was soon stopped, all reservoirs at the NPP being full.
- The duration of water-delivery period estimated in several publications at ~ 12 hours is likely overestimated. Most probably, the efficient water delivery lasted 7 hours at the most.

1.2.2. Decision of the Governmental Commission

The Governmental Commission at its very first meeting on the night of April 26 made a decision on dropping many different materials from helicopters into the open reactor vault to localize the accident. At a later time, after consultations, the types of materials to be dropped down were specified [9].

Some of the materials (boron compounds, in particular, B_4C), being neutron absorbers, were aimed at ensuring nuclear safety.

Other materials (clay, sand, dolomite) were dropped to create a filtering layer and diminish the radioactive release. In addition, it was expected that dolomite $(MgCa)(CO_3)_2$, while attaining the high-temperature area, would decompose and generate carbon dioxide capable of providing a "gas shutoff", i.e. deprive burning graphite of oxygen.

The last type of dropped-down material – lead - must have taken upon itself the heat released, melted and thus gave no way for the "China Syndrome" development.

---

[3] Among them:
Memoirs by V.G. Smagin, Shift Supervisor at Unit #4, published in: Medvedev, G. (1989) The Chernobyl's Writing-book, *Russian Literary Monthly Journal "Novyi Mir"*, **6**, pp. 3-108 (in Russian);
Andreev, V. (1996) We worked in knee-deep water, *Daily Newspaper "Vseukrainskiye Vedomosti"*, April 25, 1996 (in Russian);
Ignatenko, E.I. (1996) The most difficult days, in "*Chernobyl: Catastrophe, Feat and Lessons Learned*", Inter-Vesy Publishers, Moscow, pp. 95-130 (in Russian).
Popov, N.N. (2003) *The Chernobyl Tragedy Pages*, Kiev (in Russian), and many others.

1.2.4. Materials Dropped from Helicopters to Localize the Accident

The publications available contain a variety of versions related to dropped down materials that is mainly due to data use from the "third hand". The first attempt at applying to primary documents was made in Ref. [10].
At a later time a special work was performed during which many logbook records of the Air Force Operational Group of the USSR Ministry of Defense were collected and generalized [11]. These data are summarized in Table 3 and are charted in Fig. 4. A description of dropped down dry materials is provided in Table 4.

Table 3. Active phase of the accident (April 26 – May 6, 1986)

Date	Number of flights	Mass of dropped down materials (t)	Full amount of materials in package (t)
April 26	-	-	-
April 27	44	150	150
April 28	93	300	450
April 29	186	750	1200
April 30	?	1500	2700
May 1	?	1900	4600
May 2	?	420 (?)*	5020 (?)*
May 3	0	-	-
May 4	0	-	-
May 5	0	-	-
May 6	0	-	5020

* different versions are available.

By 18.05.86 ~ 5000 t of various materials were dropped down.
By 18.06.86 ~ 11400 t of various dry materials were dropped (in our opinion, the data accuracy may be estimated at ± 20%).

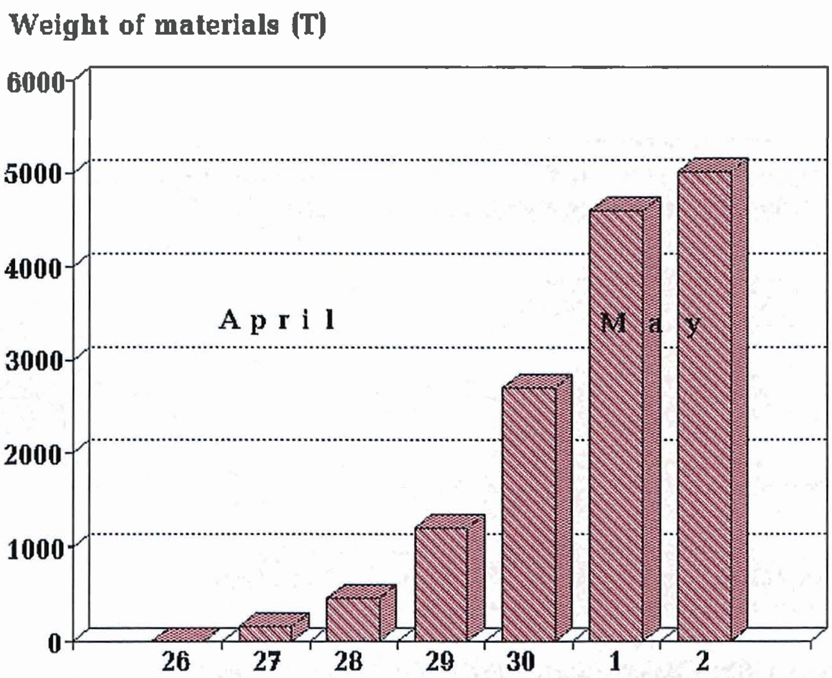


Fig.4. Amount of materials dropped from helicopters into the reactor wreckage

Table 4. Description of dry and liquid materials dropped into the reactor wreckage by 18.06.1986

Material	Chemical formula	Mass (t)
Boron carbide	B_4C	~40
Dolomite	$MgCa(CO_3)_2$	~1200*
Marble aggregate, clay, sand, etc.	-	~3500**
Lead (grit +ingots, etc.)	Pb	~6700***
Three-sodium phosphate (solution)	Na_3PO_4	~2500
Other dust-suppressing compositions (solutions)	Latex SKS-65gp, "barda" (waste of pulp-and-paper industry), liquid glass, polyvinyl alcohol, caoutchouc SKTN, etc.	~2700
Total		~16600

* during the active phase ~ 600 t of materials were dropped down;

** about 1800 t of clay and sand were dropped during the active phase;

*** in the course of the first five post-accident days 2400 t of lead were dropped down.

In addition, by 29.06.1986 1890 t of zeolite were dropped down as well.

A photo of collapsed Unit 4 (view from above) taken after termination of the active accident phase and the release drop is demonstrated in Fig. 5.
One can see heaps of dropped materials in the central hall and on ceiling panels of rooms of steam-separator drums. The same heaps are visible in Fig. 6.

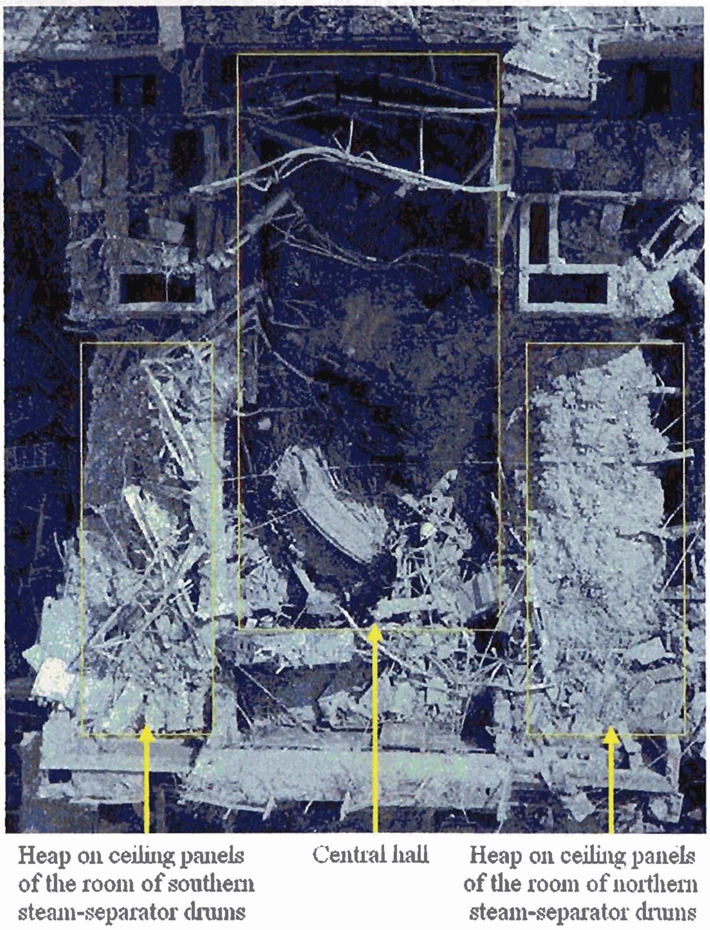


Fig. 5. Destroyed constructions and heaps of materials in the central hall and on ceiling panels of rooms of steam-separator drums

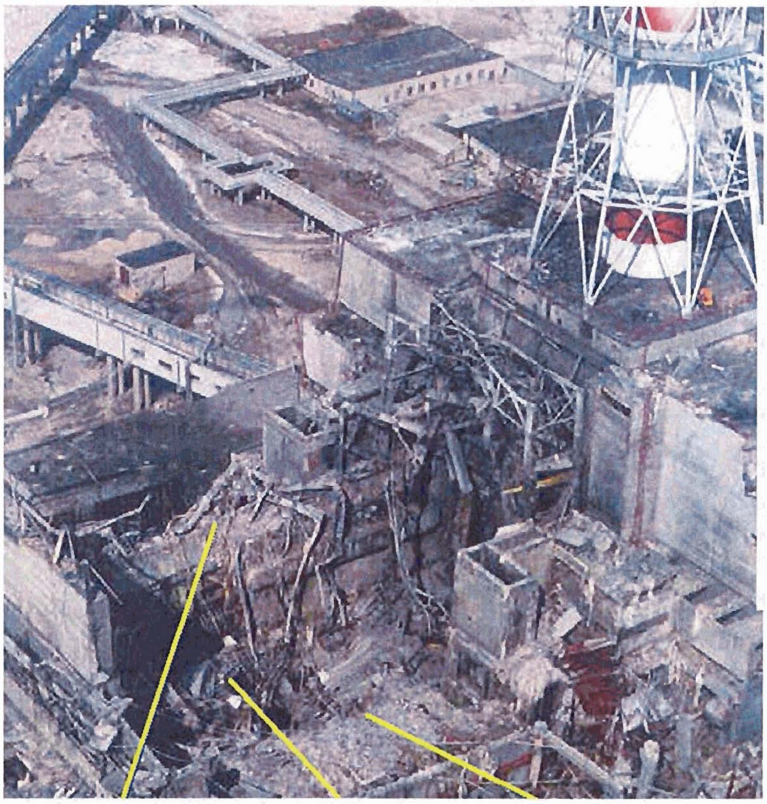


Fig. 6. Destroyed constructions and heaps of materials (including those dropped down from helicopters) at upper level marks of Chernobyl NPP Unit 4 after the accident

Heap on ceiling panels of the northern steam-separator drums — "E" component Central hall — Heap on ceiling panels of the southern steam-separator drums

1.2.4. Attempts at Cooling of Unit 4 Bottom Rooms

On the first of May 1986 the Governmental Commission took a decision on pumping liquid nitrogen into the reactor vault for purposes of: -cooling of bottom reactor rooms; and -depriving burning graphite of oxygen.

Works on nitrogen conduit laying were completed on May 5. The first tank with liquid nitrogen arrived on the 6th of May, and attempts at delivering cool gas to the pressure-suppression pool began.
The "nitrogen epopee" is described in more detail in Ref. [12].

Unfortunately, the attempts at using nitrogen for cooling purposes were unsuccessful for many reasons and were soon stopped.

1.2.5. Measurements of Radioactive Release from the Destroyed Power Unit

First of all, the efficiency of countermeasures taken to localize the accident and diminish the radioactive release was estimated via aerosol sampling above the damaged reactor and studying radionuclide composition of the samples.

Regular aerosol samplings above the wreckage of Chernobyl NPP Unit 4 using a special laboratory plane 'An-24' began on the night of 27-28 April, 1986. Later on helicopters were employed for that purpose as well [13].
Samples were taken above the destroyed reactor and the Unit 4 site as well as within the 30-km area.
Special gondolas carrying radiation-survey plans and helicopters were employed (the procedure of measurements is described in more detail in Refs. [14-16]).

However for many objective reasons such as: non-stationary type of the release; changing meteorological conditions; methodic difficulties of sampling under significant radiation fields; active impacts on the destroyed reactor (dropping of materials from helicopters); measurement errors of dosimeters etc., the release-identification accuracy turned out to be rather low.

This statement is illustrated in Fig. 7 showing the results of measurements (Ref. [17]).

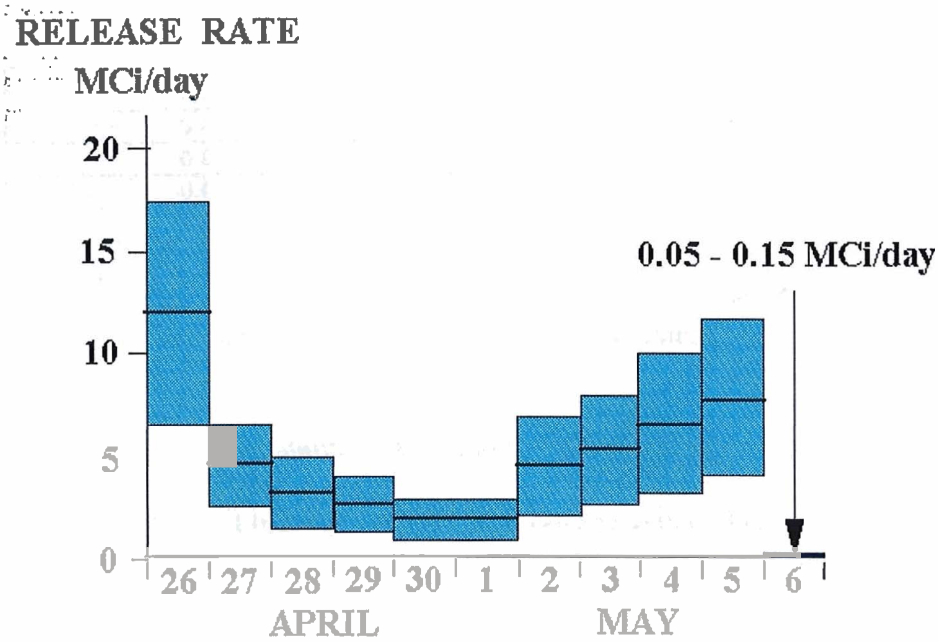


Fig. 7. Intensity of radionuclide release during the active accident phase (April 26 – May 6), the error area (± 50%) is colored blue

In Fig.7 one can see that the active accident phase, accompanied with radioactive release of about several MCi/day, lasted 10 days and terminated on May 6. After May 6 the release diminished by hundreds and thousands of times.
Several outcomes of performed investigations are demonstrated in Table 5.
The Table 5 data may be commented as follows:
- the error estimate is, in our opinion, far from being conservative;
- the recalculation of activity as of May 6 led to formal neglect of short-lived (~ 1 day and less) radionuclides. Consequently, all short-lived radionuclides with half-life of about 1 day made no appreciable contribution to the integral release estimate - 50 MCi[4].

---

[4] The role of short-lived radionuclides was reviewed for the first time and supplemented in Ref. [18]. This study contains: -the release data by the instance of its onset rather than the data recalculated by the end of the active accident phase; -a consideration of accumulation and release of hour-long radionuclides; and –estimates of the release based on the data of recent publications, especially concerning radionuclides of cesium and iodine.
The ultimate value of integral release (for radionuclides with $T_{1/2} \geq 20$ h) was estimated at ~ 90 MCi, noble gases being neglected.

Table 5. Radioactivity release from Unit (*) according to the USSR's delegation report at the IAEA [17])

Isotope	Release (%)**	Isotope	Release (%)**
Xe-133	~100	Ce-141	2.3
Kr-85m	~100	Ce-144	2.8
Kr-85	~100	Sr-89	4.0
I-131	20	Sr-90	4.0
Te-132	15	Np-239	3.2
Cs-134	10	Pu-238	3.0
Cs-137	13	Pu-239	3.0
Mo-99	2.3	Pu-240	3.0
Zr-95	3.2	Pu-241	3.0
Ru-103	2.9	Pu-242	3.0
Ru-106	2.9	Cm-242	3.0
Ba-140	5.6		

* Release estimate error ± 50%.
** Released activity values are recalculated as of 06.05.86 (end of the active accident phase) taking account of radioactive decay.

1.2.6. Further Actions against the "China Syndrome" Development

After a considerable drop in radioactive release it might have seemed that the main hazard was due to the "China Syndrome".

Yet the "China Syndrome" was remembered all the time. It was on the night of 2-3 May (i.e. before unsuccessful termination of attempts at delivering liquid nitrogen to the pressure-suppression pool) that the Governmental Commission examined additional measures on prevention of groundwater contamination.

The following three alternatives aimed at stopping spreading of very hot nuclear fuel were discussed:

- laying pipelines cooled with liquid nitrogen under the reactor compartment foundation;
- pumping magnesite-basis concrete with high thermal conductivity into the under-reactor space (to the pressure-suppression pool); and
- constructing a water-cooled under-foundation plate.

Finally, the last-mentioned alternative was implemented.

In accordance with a special decision of the Governmental Commission taken in May 1986, the establishment of reinforced-concrete under-foundation plate under the reactor compartment of Unit 4 was placed on the following USSR's Ministries: Minugleprom, Minsredmash and Minenergo.

The plate shape represented a square of ~ 30·30 m, its width being ~ 2.5 m. In the central part of the plate water-cooling pipes (D=10 mm) were laid. Above the pipes a shielding graphite covering was established.

The plate body was provided with temperature sensors.
It may be considered that the plate construction began on May 5-6 when the first lot of building mechanisms and materials was delivered.

To provide adequate conditions for underground works in very straitened conditions and increased heat release, special ventilation and air-cooling schemes were developed. Moving of miners to the work zone was organized with maximum possible - at that time - safety. Workers were provided with individual protectants.

Nevertheless, the work conditions, including radiation conditions, were extremely hard. Miners worked in eight three-hour shifts twenty-four hours a day.

Thanks to really heroic work of miners, engineers and auxiliary personnel the under-foundation plate under the reactor was completed by June 28.
However already several week later the data of survey groups evidenced either a rather slow development of the under-reactor floor melting or its full stopping.

The "China syndrome"-development model used in 1986 was incapable of taking correctly into account the fact of not only melting by heated fuel of its surrounding materials but also the phenomenon of fuel dissolution in their melt (see § 3.2.5). Such a phenomenon results in a rapid increase in volume and surface of heat-liberating mass and thus in a quick decrease in both specific heat liberation and local temperature.

The "China syndrome" produced melting of ~1/4th of the "Reactor Basement" ('OP')'s metal structure and partial destruction of concrete of the under-reactor room floor but it affected virtually no coverings between rooms of the Steam-Distribution Corridor (SDC) and the Pressure-Suppression Pool (PSP) (2nd floor).
Thus it had no effect on the foundation plate of the Unit either.
There was, however, no way at that time to exclude entirely the possibility of the foundation plate melting that predetermined the decision on construction of the above-described "catcher".

The decision on undertaking of such a hard and expensive (from the dose-burden and financial standpoints) work was due, in our opinion, to the following reasons:

- *insufficient information on the condition of bottom rooms (the main reason);*

- *no adequate model for calculations; and*

- *psychological effects of the huge scale of the Chernobyl accident.*

1.2.7. Main Countermeasures Undertaken at the Active Accident Phase

Main countermeasures undertaken at the active phase to localize the accident are described briefly in chronological order in Table 6.

Table 6. Main countermeasures taken at the active accident phase (Ref. [12])

Date	Hours	Description
Saturday, April 26	**~ 01**	**Accident. Reactor collapse.**
Saturday, April 26	01:30 - -06:30	Extinguishing of fires (there were more than 30 sources of combustion caused by explosions in the reactor and release of hot core fragments).
Saturday, April 26	02	Onset of water delivery to the reactor to cool fuel and prevent burning of graphite
Saturday, April 26	Morning – day-time	Disconnection of pumps that delivered water to the reactor (bottom level marks of all power units became flooded with radioactive water).
Saturday, April 26	Day-time - evening	The accident scale was realized for the first time.
Saturday, April 26	Night	The following decisions were taken at the Governmental Commission meeting: shutdown of Units 1 and 2; transfer of Unit 3 to subcritical condition; evacuation of the population of Pripiat-town and Janov-settlement; start of dropping of materials into the destroyed reactor to localize the accident.
Sunday, April 27	~ 10:00	Onset of dropping of various materials into the reactor from helicopters.
Sunday, April 27	Night	Boron carbide is dropped down.
Thursday, May 1	The whole day	Decision on start of reactor cooling with nitrogen to prevent the "China syndrome"
Friday, May 2	By the end of the day	About 5000 t of materials were dropped down.
Saturday May 3 and Sunday May 4	Throughout the night	Chernobyl NPP personnel opened valves to drain radioactive water from the PSP of Unit 4. The Governmental Commission took a decision on construction of under-foundation plate under the Unit 4 reactor compartment to prevent the "China syndrome" development.
Monday, May5		The nitrogen-delivery system to the PSP is assembled. Onset of delivering construction equipment and necessary materials to build the under-foundation plate.
Tuesday, May 6	~01:00	Arrival of the very first car with liquid nitrogen. Shortly thereafter delivery of gaseous nitrogen to the second floor of PSP. Failure of cooling attempts.
Tuesday, May 6		**The release intensity (Ci/day) decreased by three orders of magnitude. End of the active accident phase.**

1.3. Models of the Behavior of Nuclear Fuel in the Destroyed Reactor

1.3.1. Early Assumptions

Since the first post-explosion hours, attempts at generating models of further behavior of the rest of Unit 4's nuclear fuel were undertaken.
Unfortunately, at first such models were based on very limited measurement-and-observation data. As a consequence, many decisions taken on their basis turned out to be far from optimal at a later time.

Hasty conclusions based on a few measurements and intuitive ideas were made quite often at that time as well.

One typical example is cited below.
In the daytime of April 26 the very first data on radiation fields measured around Unit 4 were received at "Kurchatov Institute". Those data were horrifying: most often thousands of Roentgen per hour were measured. Based on those data, it was suggested (and even reported to the

Governmental Commission) that release of an appreciable portion of nuclear fuel – tens of percent – onto the Chernobyl NPP's site took place. No calculation of radiation fields from a unit of quantity of irradiated fuel was performed.

However already one day later by far more complete experimental on-site dose-rate data were obtained, and calculations of the doses created by 1 g of fuel having been in the reactor by the accident instant were performed. The first-type data turned out to be considerably lower, as compared to those reported to the Governmental Commission (Fig. 3); by contrast, the dose-calculation data were very large.
Their comparison allowed concluding that the entire release of fuel onto the territory around Unit 4 had equaled only tenths of percent of the whole fuel load in the core[5].

1.3.2. Model of Progression of the Active Accident Phase (1986)

As the work on the accident localization and release elimination progressed further, the very first sequential model of the active phase development was generated. That model was reported by the USSR's delegation at the IAEA meeting [17].

The Report stated that:
"At the first phase of the accident a release of dispersed fuel from destroyed reactor took lace. Radionuclide composition of the release at that phase approximately corresponded to that of irradiated fuel but was enriched with volatile nuclides of iodine, tellurium, cesium and noble gases.
During the second phase (April 26 through May 2, 1986) the release rate beyond the damaged unit decreased thanks to the countermeasures on stopping of graphite burning and filtration of release...
The third accident phase characterized by a rapid increase in fission product release rate beyond the reactor unit...
That was caused by fuel heating in the core up to 1700^0C and more due to decay heat.
For the final – the fourth – accident phase (after May 6) a rapid decrease of release was typical".

The model under consideration was described in more detail in several subsequent publications (see for example Ref. [19]).
The main processes were explained as the effects of dropped-down materials.
In the authors' opinion, at first the cooling process took place due to absorption by lead of a portion of released heat.
Next, covering of the reactor vault with loose materials resulted in release decrease.
Simultaneously, due to a decrease in heat pick-up by airflow, an increase in temperature took place.
At the active phase end a "break of radioactivity" through the layer of materials of the covering occurred, i.e. the release increase; after that the release decreased drastically.
It seemed then that the above-described release dynamics explained the situation in full measure.

However in the course of the first years of systematic investigations at the "Shelter" that model – quite orderly and logic in 1986 - was refused.

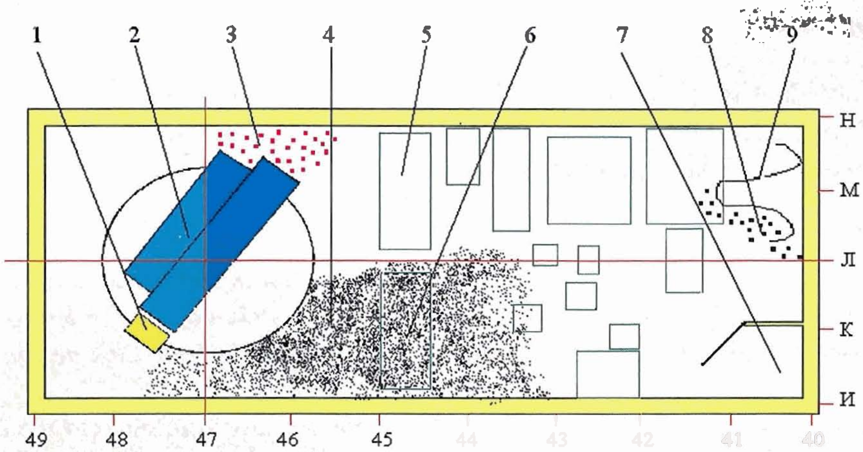
---

[5]According to calculations, if 0.3% of the whole of fuel had been released uniformly to the NPP's site, by May 6 the mean-over-NPP-site dose rate 1 m from the earth surface would have equaled 50 R/h.

1.3.3. Locations Attained by Dropped-down Materials

The investigations of 1987-89 performed inside the "Shelter" demonstrated that the main assumption of the reactor vault filling with a thick layer of dropped down materials – used as a basis in the model of 1986 – turned out to be untrue.

There were indications for that fact even in 1986. For example, on some photos of the Central Hall (CH) it can be clearly seen that it is literally filled with dropped down materials, which formed there many-meter "hills" (Fig. 8). At a later time that fact was confirmed by survey teams, which had penetrated into CH after a long preparative period. Nevertheless, the fact of location within the reactor vault of a portion of materials dropped was still deemed possible.



Legend

1- reinforced-concrete plate; 2-metal construction of scheme "E"; 3-pipes of bottom water communications; 4-wreck of materials dropped down from helicopters; 5- northern cooling pond; 6- southern cooling pond; 7- control room; 8-core fragments; 9-part of metal construction, scheme "КЖ"

Figure 8. - Central Hall of Unit 4 after the accident (scheme)

In mid-1988 the investigators managed to observe the reactor vault content using optical devices and TV cameras [10].

Virtually no dropped down materials were found therein. One may, however, argue: those materials reached high-temperature areas, melted and spread over bottom reactor rooms. Such a process could have occurred indeed, for large solidified lava-like fuel-containing masses were discovered on bottom floors.

Under such conditions lead could have been a proper indicator of lava generation not only from reactor constructions, concrete, etc. but also from materials dropped down from helicopters. However virtually no lead has been discovered in the Unit 4's lava so far; moreover, lead has not been found in accumulations of molten metal masses either.

The data on lead content in different types of Lava-like Fuel-Containing Materials (LFCM) are demonstrated in Table 7 [1].

Table 7. Lead contents in LFCM samples

LFCM type	Coal-black ceramics	Chocolate-brown ceramics	Slag from piles in PSP	Pumice from PSP
Pb (weight %)	(6.5 - 110) $\times 10^{-3}$	(12-240) $\times 10^{-3}$	(1.1 ±0.1) $\times 10^{-2}$	(1.2 ± 0.2) $\times 10^{-2}$

Such are the known-by-now facts.

What factors did impede the pilots to fulfill their task?
Most likely, both the risk of colliding with the 150-m ventilation duct and the enormously radioactive column of smoke did not favor successful "bombing".
One more reason is also conceivable: the scheme "E" released by explosion rose almost vertically and –together with the pulled out jumble of pipes – created a specific "shield" that threw the materials dropped to the central hall.

There was a bright luminous spot in the central hall nearby the reactor vault (hot graphite?). In Fig.8 its location is indicated by figure "4". That spot could have been erroneously recognized as the vault opening, and the pilots could have directed the dropping materials to that spot. This version is discussed in detail in a study by A. Sich [12].

So far the data on dropped down materials have been published more than once (see e.g., References [10], [16] [20]).
Nevertheless, the model based on crucial effects of those materials is still used and appears from time to time in various articles and reviews (e.g., Reference [21]).

Thus, despite undoubtedly heroic efforts of the pilots, their attempts at reactor filling with dropped down materials failed.
Were their efforts useless?
There are opinions that they were even harmful. E.g. a viewpoint is known that, due to dropping of tens of thousands of tons of materials onto Unit 4, damaged constructions could have been destroyed further. That could have produced negative effects on stability of the "Shelter" at a later time.
We would like, however, pointing out positive effects of the measure under consideration (note that only the technical side of the problem is considered here).
Boron-containing materials attained the central hall, wherein during the explosion many reactor core fragments and fuel dust had been thrown in. Having covered reactor fuel, they diminished its nuclear hazard (most likely, "transferred" the fuel it to a nuclear-safe condition). In many locations sand, clay and dolomite had covered radioactive debris with a thick layer that facilitated subsequent works of the "Shelter" builders, operational personnel and investigators. Still a minor portion of materials could have attained the reactor vault and could have been involved into lava-generation processes.

1.3.6. The "Flying-Reactor" Model

For the first time that model was proposed by E. Purvis III during his work at the ISTC "Shelter" (1990) [22].
Being contradictory to many established facts, that model would not deserve our special consideration if peculiar circumstances were not concerned. The fact is that several "magic words" used many times in the E. Purvis's study (such as: as "air-blast", "reactor flying to the central hall", "nuclear runaway", "nuclear explosion", "solar temperatures", etc.) have inspired a

number of his followers (K. Checherov, *et al.*) for further speculations. Some of them are still discussed today, mostly in mass media (see e.g., Refs. [23-24]).

For these reasons let us consider the E. Purvis's model in more detail.

A quotation from the study by E. Purvis is given below.
"The accident at Unit 4 of the Chernobyl Nuclear Power Plant began between 1:23 a.m. and 1:24 a.m. of April 26, 1986. The fuel fragmentation process caused by a rapid increase in the reactor power level was the initiating event for a series of subsequent destructive phases.
Fuel fragmentation and interactions of the generated fragments with coolant produced an air-blast that, in its turn, led to destruction at about the same instant of virtually all bottom crossover joints of fuel channels.
Via the generated breaches coolant was released from the primary circuit to the reactor core and produced intense steam generation therein. That resulted in steam explosion and lifting of the whole core - graphite moderator stack, fuel channels, fuel, reactor upper head (upper biological shield) and refueling machine – up to at least 14 m above the reactor compartment flooring.
Due to loss of the whole of coolant in the core, nuclear runaway led to explosion (expansion of gas-like fuel) in air above the reactor vault at the indicated level mark.

It was that explosion that destroyed the core and many constructions surrounding the reactor. The same explosion threw fuel, graphite and other core fragments onto the roofs of the nearby buildings and the area surrounding the reactor compartment".

Let us consider the main statements of this model.

"Fuel fragmentation and interactions of the generated fragments with coolant produced an air-blast that, in its turn, led to destruction at about the same instant of virtually all bottom crossover joints of fuel channels".

This is the author's crucial statement to which he recurs again and again.
Indeed, interactions of fragmented fuel with water could have resulted in the initiation of air-blast.
At the same time, there is no way of suggesting simultaneous break of all 1659 process channels. According to subsequent calculations, accidental increase in neutron flux lasted only a few seconds and was very non-uniform over the reactor core volume. Thus the break of fuel channels must have occurred non-simultaneously.

"That resulted in steam explosion and lifting of the whole core - graphite moderator stack, fuel channels, fuel, reactor upper head (upper biological shield) and refueling machine – up to at least 14 m above the reactor compartment flooring.
Due to loss of the whole of coolant in the core, nuclear runaway led to explosion (expansion of gas-like fuel) in air above the reactor vault at the indicated level mark".

Question #1 Why did steam release from 1659 channels occur synchronously providing vertical motion of the reactor in the vault (otherwise the reactor must have been jammed)? Such a phenomenon seems to be a real wonder.

Question #2 While "catapulting to air" (the author's expression), graphite blocks under conditions of missing OP's lower head must have been spilled down from zirconium fuel channels welded to the upper reactor head for they had been literally "stringed" to those

channels. Consequently, the author's suggestion on "a single whole" that "catapulted to air" seems fantastic.
There is also another way of looking at the issue of graphite and other reactor materials.
In the author's opinion, the whole core had flown out quite uprightly and had reached the central hall wherein nuclear explosion took place. E. Purvis III and his followers estimated the maximum temperature of heating of the core materials at ~ 7000 °C (such a temperature is enough to produce evaporation of uranium dioxide) and 40000^0C (!), respectively.
In both cases all materials – fuel, metal and graphite – must have been evaporated.

Thus the questions are:

What material did burn in the reactor vault at a later time?

What materials 1200 t of lava were generated of in the Unit 4 bottom rooms? and

What is the explanation of the fact that ~ 95% of fuel was found within the "Shelter" a later time?

Question #3

Let us address now the Chernobyl's hot particles.
Those particles were investigated by tens of research institutes, and a consensus was reached that the release had consisted of two major components.

The first component comprised volatile radioactive substances released by aerosols (the volatile fraction). It was namely the volatile fraction containing iodine radionuclides, ^{137}Cs and ^{134}Cs that produced radioactive contamination of large territories.

The second component of the release consisted of radionuclides with high boiling temperature. They were also released in the aerosol form, however, not independently but as components of uranium matrix wherein they had been generated during normal operation of the reactor. Those were the so-called "fuel particles", which deposited then mostly within the Chernobyl zone. Tens of radionuclides, including ^{90}Sr, isotopes of plutonium and other transuranic elements, were identified in those particles.

If "solar temperatures" had been available during the explosion, other-type specific "explosive" particles (e.g. purely plutonium or purely uranium particles) much studied by nuclear-explosion investigators would have been generated.

The fact is that during a nuclear explosion the process of fractioning of refractory non-volatile fission products takes place in the generating hot particles.

However in the Chernobyl's case no "explosive" particles were discovered.

The only exceptions were purely ruthenium particles discovered really in several studies. However such particles should be considered as the "volatile fraction". They did not contain ruthenium metal (which evaporation temperature is 4100°C) but ruthenium oxide easily sublimating at temperatures below 100^0C. That was ruthenium oxide that deposited on particles of graphite and dust released from Unit 4.

Though the model by E. Purvis III and his followers contains many other enigmatic statements, we will not address them more in this study.
Thus in our opinion, the authors developed a rather impressive model of the Chernobyl accident:
... The reactor, moving first under the "liquid-propellant-jet-engine" mode, next under the "nuclear-jet-engine" mode and ejecting jets sometimes of water and sometimes of plasma, leaves

easily the reactor vault, soars up as a whole, flies and, finally, evaporates under the central hall's roof at solar temperatures...
It only remains to regret that this model has nothing to do with the reality, and thus its predictions are useless for our further work.

1.3.7. The E. Pazukhin's Model

The behavior of fuel at the 2nd accident phase is studied in the most consecutive way in E.M. Pazukhin's publications (see Ref. [25] and references therein).

They contain the very first description of main post-accident mechanical, chemical and heat processes in the destroyed reactor complying with the factual data - observations, measurements, and analyses of samples of fuel-containing and constructional materials.
The developed model describing the generation of ~ 1200 m^3 of lava of real chemical composition did not involve considerable quantities of dropped down materials.

The fuel-decay-heat phenomenon (with a minor addition of energy caused by burning of graphite and zirconium oxidation) was quite sufficient for the author to explain the lava-generation processes. The duration of processes till lava surface cooling down to 700^0C - 800^0C and below and the release cessation was estimated in the model at about three days.
Though such estimate should not be considered as a quite accurate one for lack of knowledge of heat transfer processes at each phase of lava generation and spreading, its order of magnitude coincides with the active accident phase duration.

The logic of that model has been much used in the course of development of the KI–IBRAE model.

2. LAVA-GENERATION MODEL DEVELOPED AT KI-IBRAE

2.1. Major Phases of the Model Development

2.1.1. Database Generation

In 2005 specialists of the Russian Research Center "Kurchatov Institute" (RRC KI) and the Nuclear Safety Institute of the Russian Academy of Sciences (IBRAE RAS) started work under the Project #2916 – **"Development of the Models for Nuclear Fuel Behavior during Active Phase of Chernobyl Accident (CHESS)".**
The Project is being performed under a special Agreement between the International Science and Technology Center (ISTC) and the RRC KI.
As expected, the work outcomes will be used in subsequent "Shelter" transformation activities as well as in solution of a series of nuclear power safety problems.

To develop such a model and describe the processes of LFCM generation a spreading, a comprehensive and trustworthy database on the locations and physico-chemical condition of fuel of Chernobyl NPP Unit 4 both before and after the Chernobyl accident is necessary.
Such a database should also contain information on the post-accident status of Unit 4 constructions and materials.

Accordingly, the database development involved verification, analysis and structuring of a huge amount of experimental data achieved in investigations at the "Shelter" in 1986 – 2005.

Such a work was performed in 2005 – 2006.

During the database development a variety of data taken from publications, reports, survey certificates, construction drawings, etc. were verified and analyzed. Photo- and video-materials were studied as well.
The integral amount of information records used in the database exceeds 6000.
They are grouped into the following major sections:
- fuel, materials and constructions of Unit 4 of Chernobyl NPP before the accident;
- status of fuel, materials and constructions half an hour after the accident (the lava generation onset);
- heat sources during lava (corium) generation;
- physical and chemical processes during lava generation; and
- lava spreading.
The work outcomes are published in Ref. [3].

2.1.2. Reconstruction of the Post-explosion Status of the Destroyed Power Unit

While generating the KI-IBRAE model, the first task consisted in a reconstruction of the post-explosion status of the destroyed power unit (by convention the time of half an hour after the accident was taken for consideration).

The reconstruction process is described in detail in Ref. [26].
We managed to: -reconstruct the geometry of rooms involved into the lava-generation process (these are the reactor vault and the under-reactor room #305/2 unified as the result of explosions and 'OP' component descending); and -describe the condition of fuel, materials and constructions of the reactor half an hour after the accident (Fig. 9).

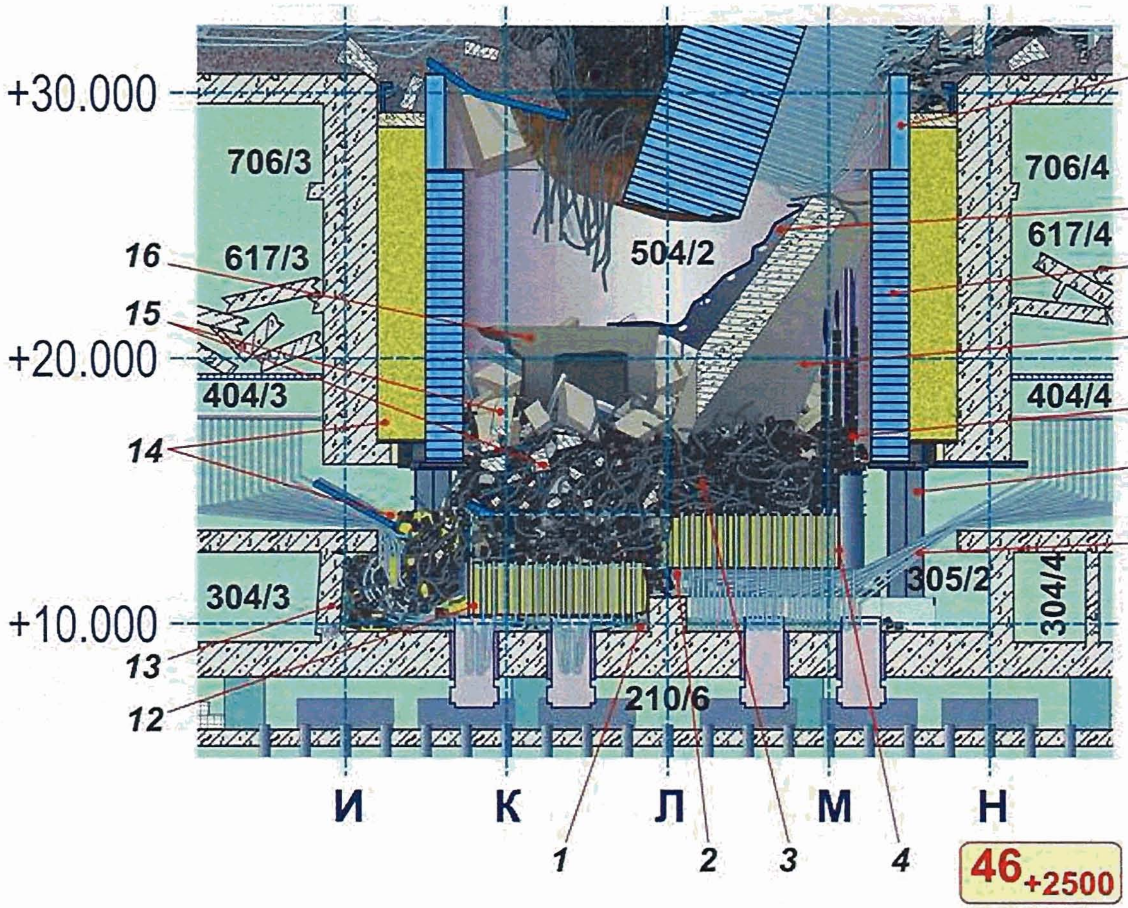


Fig. 9. Reactor vault and Room 305/2 half an hour after the explosion

1. Serpentinite of both "OP" component and the inter-compensatory gap
2. Crushed "C" component ("Cross")
3. Fuel, fuel assemblies, fuel elements, process channels, graphite blocks, fragmented concrete
4. ¾ OP
5. BWC tubes
6. Additional support
7. Reflector (channels and graphite blocks)
8. Reinforced-concrete plate (fragments of wall of separator box)
9. "Л" tank
10. Heat shielding lining of separator box's wall
11. "Д" tank
12. ¼ OP
13. Damaged wall
14. Sand of vault-filling-up origin
15. Debris of reinforced-concrete constructions
16. Fragment of reinforced-concrete construction

After a thorough analysis in Ref. [26] the composition of materials available in the reactor vault (Room #504/2) and in the under-reactor Room #305/2 at the initial lava-generation instant and then incorporated therein was identified (Table 8). Thereby the input data necessary for description of lava-generation processes were achieved.

Table 8. Materials in the reactor vault (Room #504/2) and in room #305/2 at the beginning of the second accident phase

Material	Amount in rooms #504/2* and #305/2, t	Incorporated into LFCM, t
Fuel (U)	120	90
Steel	1300**	< 20***
Serpentinite mixture	580	160
Concrete of the under-reactor plate		130
Concrete of building constructions dropped into the vault from upper level marks	950	480
Sand of the vault's filling material	300	280
Zirconium	?	45
Graphite	750	Virtually N/A

* within the reactor space boundaries;
** excepting materials of "C" component and non-melted communications of the reactor bottom;
*** 330 t melt and spread over the under-reactor rooms.

2.1.3. Heat Sources

While simulating the lava-generation processes, the following three heat sources were taken into consideration:

- decay heat of fuel of Chernobyl NPP Unit 4;
- heat due to burning of graphite;
- heat due to zirconium-steam reaction.

The first-mentioned heat source made the major contribution.
To represent the contribution of different heat sources, a plot of calculations using the model for one of the lava-generation scenarios is demonstrated in Fig. 10.

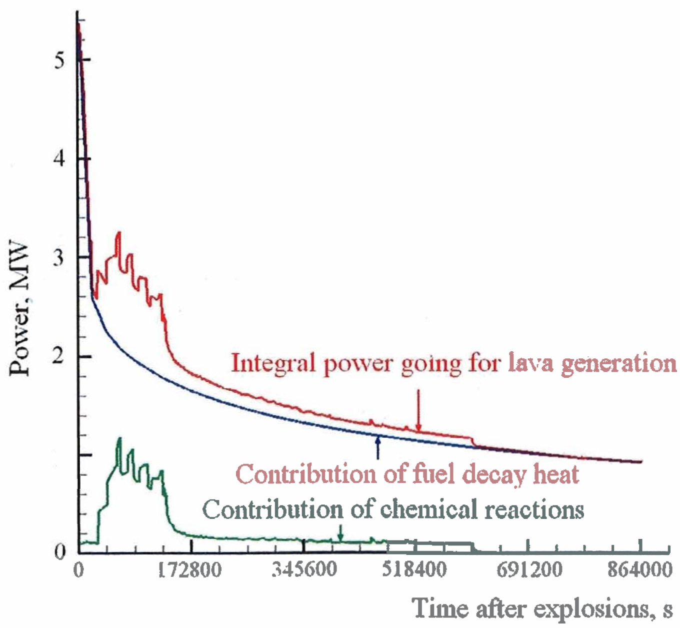


Fig.10. Contribution to the integral thermal power going for lava generation from different heat sources (for one of the lava-generation scenarios)

2.1.4. General Flow Diagram of the Studies Conducted while Generating the KI–IBRAE Model

The general flow diagram of work implementation is demonstrated in Fig. 11.

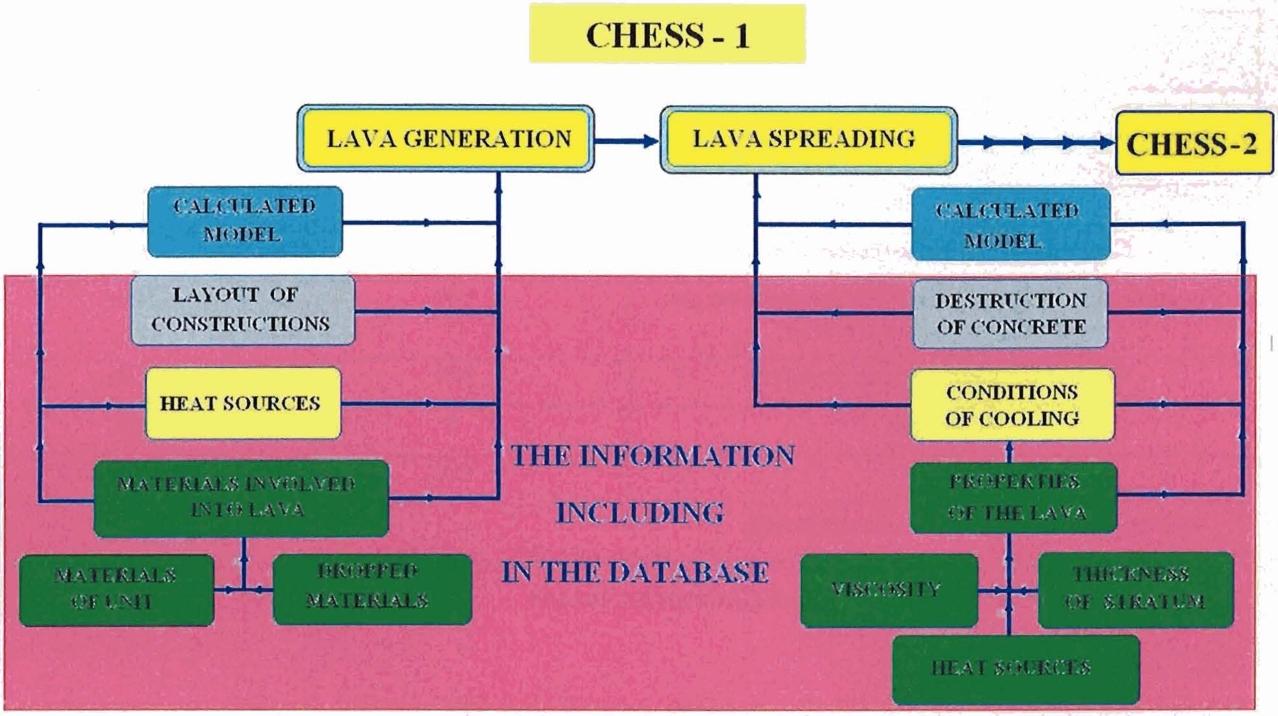


Fig.11. General Flow Diagram and Work Sequence while Developing the Model 'CHESS-2' designates planned continuation of the work

2.2. Several Results Achieved in Simulation[6]

2.2.1. Sequence of Physical and Chemical Processes of Lava Generation

The sequence of the Chernobyl lava-generation phases used as a basis in the model may be described as follows:

1. At a specific time instant an increase in neutron flux in the Unit 4 reactor core of Chernobyl NPP (the south-eastern section) took place that produced an increase in the number of fissions, heat release and a drastic increase in steam content in coolant that circulated in zirconium process channels of the graphite stack of the core[7].
The RBMK steam reactivity coefficient (an element of the integral reactive power coefficient) is positive. Intensification of the fission reaction could result in the generation of a larger amount of steam producing an increase in the K-factor leading in its turn to further intensification of the reaction, etc.

2. Due to failure of cooling regime the temperature of fuel increased drastically that caused fuel dispersion and break of fuel element claddings and fuel channels.

---

[6] Only the results directly related to the subject of this report are presented below.

[7] The causes of such a burst are not discussed here: there are many versions of the Chernobyl catastrophe, and their analysis is beyond the scope of this paper.

3. Explosions that had destroyed the core allowed fuel fragments to interact with constructional materials: at first with zirconium and then with metal of "OP" component, serpentinite filling, sand, concrete, etc. (Fig. 9).
Zirconium melting began as well as the dissolution of uranium dioxide therein with the generation of uranium-zirconium eutectic [27 - 29].

4. When uranium-zirconium eutectics contacted silicon dioxide (the major lava component), the following triple system was generated: UO_2-SiO_2-ZrO_2. Minimum temperature of liquidus surface in that system was equal to the melting point of the triple eutectic and made up approximately 1500 °C (Fig. 12.) [8].

It was in such a way that most of the lava, the so-called "brown ceramics" and "black ceramics" was generated.

Due to interactions of irradiated fuel with constructional materials, LFCM, in addition to uranium and zirconium, silicon and oxygen, incorporated a considerable amount of other elements (element analysis of LFCM identified about two tens of such elements).

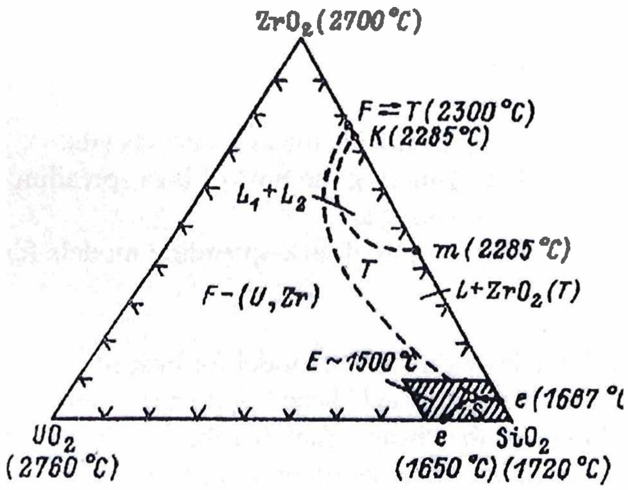


Fig. 12. Approximate projection of liquidus surface of the triple system 'UO_2-SiO_2-ZrO_2'
F – field of primary crystallization of solid solutions based on U and Zr oxides with fluorite-type structure;
T - field of primary crystallization of tetragonal ZrO_2;
S - field of SiO_2 crystallization (cristobalite).
The shaded area corresponds to possible composition of LFCM.

5. It is worth noting that the conditions for other paths of lava generation might have also realized at individual locations of Room #305/2.
Indeed, as demonstrated above, the temperatures might have reached a range of 1500°C ÷ 2600°C. The minimal value of indicated temperature is conditioned by melting of a large mass of metal (in 'OP' component); the maximal value is confirmed by the presence in the silicate matrix of fuel globules with zirconium admixtures ('ZrO_2 – UO_2' system).
Analysis of both established and possible events that took or might have taken place at first after that accident reveals the possibility of existing a variety of compositions of fuel with other materials which attained Room #305/2 and the reactor vault after the explosion. It would be reasonable suggesting rather non-uniform fuel distribution over the room; consequently, local conditions for lava generation and characteristic temperatures might have varied depending on the composition and heat-pick-up conditions.

In a case that silicon and other materials were lacking, it was the 'ZrO_2–UO_2' system. UO_2 dissolution in SiO_2 proceeds very slowly [27] (eutectic in 'UO_2-SiO_2' binary system is generated at 13% relative concentration of uranium oxide and has the melting point of 1650 °C). At the same time 10% addition of Al_2O_3 to melt results in a violent dissolution of fuel [27]. Addition of ZrO_2 brings to similar results.

At individual lava-generation centers the temperatures of 2850 °C and above producing melting of UO_2 pellets were possible.
On the other hand, at individual locations in case of "successful" range of materials and an "appropriate" heat regime the process of lava generation could have also started at a lower temperature limited by concrete-decomposition temperature equaling, according to estimates, at ~ 1200°C.

6. While considering lava-generation processes, it should be remembered that in the under-reactor room lava is found not only in "the pure form" but also as a mixture with non-melted core fragments (UO_2).
Such facts were established in investigations of samples of fuel-containing FCM from Room #305/2 performed in 1992–1993 [1].
In addition, visual observations allowed discovering core fragments immediately contacting lava formations.
Such facts are rather important from the nuclear safety standpoint because, according to calculations, in many cases the composition "lava + core fragments + water" is more hazardous than the "lava + water" composition due to the possibility of containing a considerably higher concentration of enriched uranium.

2.2.2. Simulation of Heat Processes during Lava Generation

Such simulation pursued the following two major objectives:

first, to demonstrate that the selected sequence of physico-chemical processes (see previous section) agrees with experimental data considering the time of lava spreading and its spatial distribution within the under-reactor room; and
second, to obtain some input data enabling the generation of lava-spreading models for bottom rooms of the power unit.

There is no way of developing a detailed quantitative lava-generation model for lack of necessary data, such as the data on geometry of initially-generated "heap" of materials and constructions, trustworthy data on cooling conditions of the "heap", fuel distribution therein, etc. Thus, to achieve the objectives put by, we have had to use information of a rather general character based, on the one hand, on the before-accident status of the power unit and, on the other hand, on the Unit 4 condition 3 to 4 years after the accident.

The following LFCM-generation phases were simulated:
- Generation of the melt of core materials on "OP" and interactions of the melt with steel and serpentinite filling;
- Interactions of the melt with concrete within under-reactor rooms;
- Spreading of the melt over Unit 4's rooms.

<u>Generation of the melt of core materials</u>

A simplified geometry used in calculations is demonstrated in Fig. 13. It assumes the distribution of materials in the reactor vault similar to that within the volume of a cylinder 16.5 m in diameter. The location of basic materials is demonstrated in Table 2. As assumed, a layer of debris was generated in Zone No 5 containing, along with other materials, concrete of building structures collapsed after the explosion. It is also assumed that a portion of concrete penetrated into Zone No 4 (enriched with fuel and zirconium) as well.
Walls of the survived process channels are damaged to such an extent that shattered concrete/sand have a direct contact with fuel.

The filling factor for Zone No 5 is ~40 %, for Zone No 4 it is about 93 %.
Both air and water steam have a free access to cavities between concrete debris (Zone No 5) and to the upper part of Zone No 4 via an annular gap between the tank "Л" and the component "OP".
About 3/4 of the bottom part of "OP" are washed with water steam and air; at the same time the mass exchange in this area (Zone No 2) is not so significant.

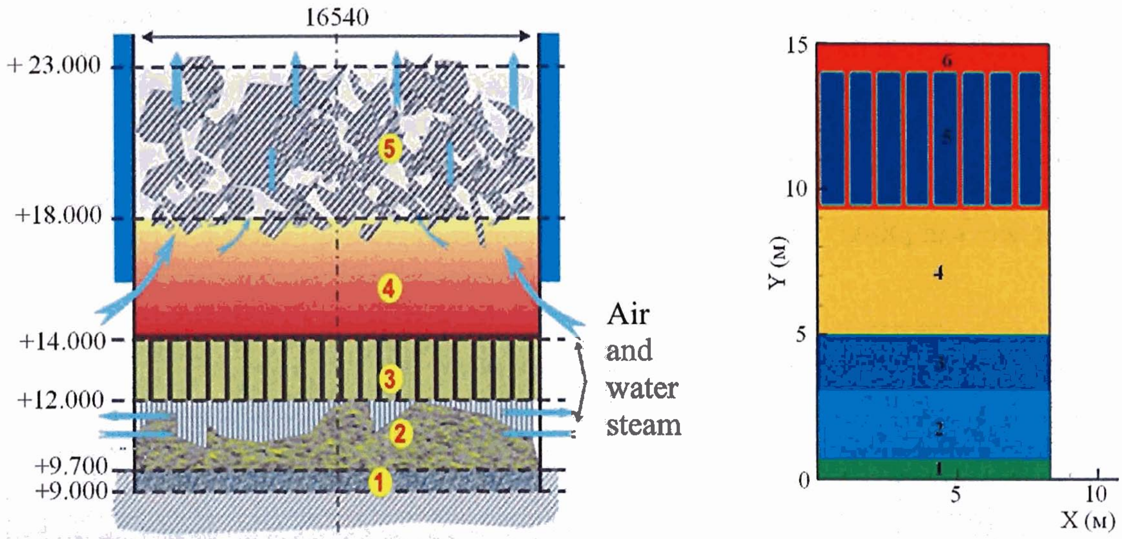


Fig.13. Layout of materials in the reactor vault in the course of lava generation and spreading (on the left) and the calculated scheme (on the right)
Materials: 1- concrete (the under-reactor plate); 2 – sand of the vault's filling; 3- "OP" metal, serpentinite; 4- lava; 5- structural concrete, 6- air.

The results of numerical simulation included the following items:

- dynamics of burning-out of carbon and zirconium and dynamics of decomposition of serpentinite-type concrete;
  simulation of effective heat transfer in both air and melt via convective transfer and bubbling;
- dynamics of melt progression (namely, progression of the 2D interface boundary between the melt and constructional materials);
- determining 2D temperature fields corresponding to the dynamics of melt progression;
- determining variations in the melt volume agreeing with the rate of carbon burning-out.

The graphite-burnup rate was determined in the model by the velocity of steam-air mixture passing via filling materials. As assumed, the oxidant-delivery rate varied within 0.7-1.26 m^3 per second for the whole of volume (that corresponded to 7 and 4 days of carbon burnup, respectively).

3. EVALUATION OF THE COUNTERMEASURES TAKEN AT THE ACTIVE ACCIDENT PHASE BASED ON THE KI-IBRAE MODEL

3.1. General Statements

This chapter has not for goal either critic or disapproval of the decisions taken to localize the Chernobyl accident in the course of its active phase[8].
It is obvious that under conditions of virtually no information on the processes that went on in the destroyed reactor making of optimum decisions involved major difficulties, and as it turned out at a later time many countermeasures were excessive or even useless.
We are making an attempt at both reconstructing the situation that existed at that time and explaining real effects of the taken countermeasures on the processes that went on in the destroyed Unit 4 based on the present-day knowledge and using the KI-IBRAE model. In our analysis the data of Table 6 (taken from Chapter 1) summarizing the main countermeasures taken at the active accident phase will be used. For convenience of reading, Table 6 is provided below once more.

Table 6. Main countermeasures taken at the active accident phase

Date	Hours	Description
Saturday, April 26	**~ 01**	**Accident. Reactor collapse.**
Saturday, April 26	01:30 - -06:30	Extinguishing of fires (there were more than 30 sources of combustion caused by explosions in the reactor and release of hot core fragments).
Saturday, April 26	02	Onset of water delivery to the reactor to cool fuel and prevent burning of graphite
Saturday, April 26	Morning – day-time	Disconnection of pumps that delivered water to the reactor (bottom level marks of all power units became flooded with radioactive water).
Saturday, April 26	Day-time - evening	The accident scale was realized for the first time.
Saturday, April 26	Night	At the Governmental Commission meeting a decision was taken on the start of dropping of materials into the destroyed reactor for accident localization purposes.
Sunday, April 27	~ 10:00	Onset of dropping of various materials into the reactor from helicopters.
Sunday, April 27	Night	Boron carbide is dropped down.
Thursday, May 1	The whole day	Decision on start of reactor cooling with nitrogen to prevent the "China syndrome".
Friday, May 2	By the end of the day	
Saturday May 3 and Sunday May 4	Throughout the night	Valves are opened to drain radioactive water from the PSP of Unit 4. The Governmental Commission took a decision on construction of an under-foundation plate under the Unit 4 reactor compartment.
Monday, May5		The nitrogen-delivery system to the PSP is assembled. Onset of delivering construction equipment and necessary materials to build the under-foundation plate.
Tuesday, May 6	~01:00	Arrival of cars with liquid nitrogen. Shortly thereafter delivery of gaseous nitrogen to the second floor of PSP. Failure of cooling attempts.
Tuesday, May 6		**The release intensity (Ci/day) decreased by three orders of magnitude. End of the active accident phase.**

[8] Such disapprovals are expressed quite often. It is worthy of note that, if absolutely speculative publications are rejected, the rest of publications in most cases neglect specific conditions under which decisions on localization of the accident were made.

3.2. Peculiarities of Wreckage in the Reactor Vault

3.2.1. Whether or Not a Part of the Reactor Stack Survived after the Explosions

The first rows of Table 6 demonstrate that survival in the reactor vault of a fragment of the core (possibly, of its major part) was expected after the accident.
Such a view persisted for quite a long time and was deemed true up to the spring of 1988.
In conditions of no reliable information such a concept was reasonable for it represented the conservative standpoint (maximum nuclear hazard).

In May 1988, thanks to the holes drilled, it was found out for the first time that the reactor vault contained no undamaged structure of fuel and graphite. Further investigations using boreholes and next by means of robots as well as direct visual observations confirmed total destruction of the core.

As established, due to descending of the "OP" component by ~ 4 m and melting of the southeastern sector of the "OP" component the reactor vault became unified with the under-reactor room (#305/2). A portion of fuel (individual core fragments and solidified fuel lava) is located in this room, another fuel portion (in the form of lava) penetrated into rooms at lower level marks (Fig. 14).

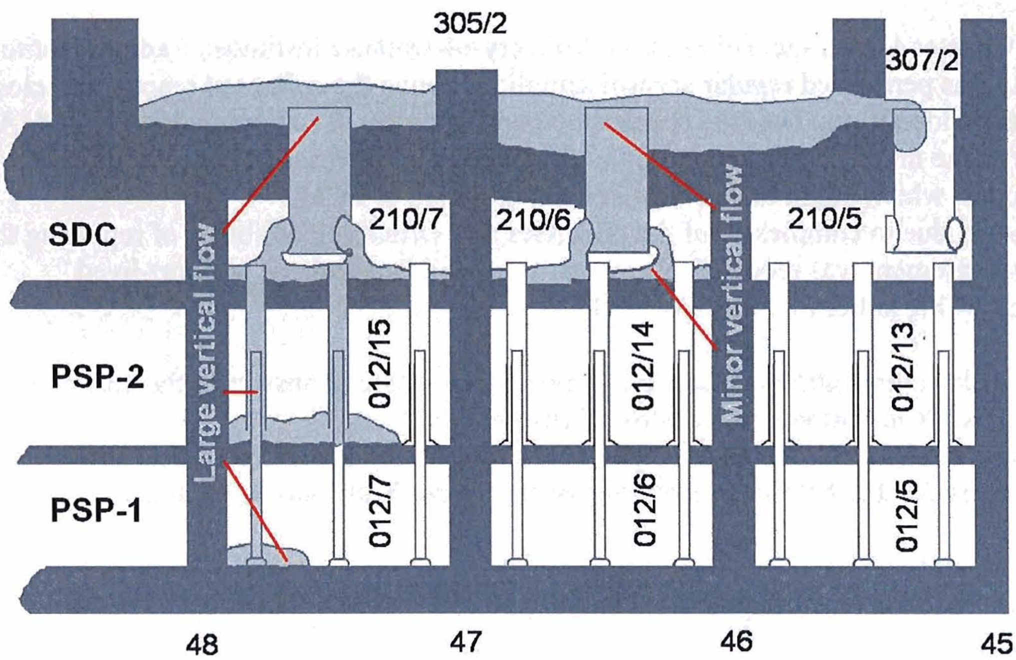


Fig.14. Vertical lava flows spread from Room #305/2 via steam-distribution communications to lower level marks of Unit 4

It may be assumed that immediately following the explosions a minor (~ 10%) part of the reactor survived yet and was definitively destroyed (graphite burned down, fuel and zirconium were incorporated into lava, etc.) at a later time during the lava-generation process.
Such a hypothesis does not contradict the reconstruction data characterizing the status of destroyed Unit 4 half an hour after the explosions that have been discussed in Section 2 (see Fig.9).

3.2.2. Efficiency of the Measures on Water Delivery to the Reactor

The efficiency of the countermeasure on water delivery to the destroyed reactor has been discussed above in Chapter 1.2.1, and, as noted, according to evidences of eyewitnesses, only a minor portion of that water might have attained the core.
Several hours later water pumps were stopped.

Inefficiency of the said measure may be also confirmed indirectly by calculations performed for lava-generation-simulation purposes. The effect of water was not taken into account in those calculations. At the same time, a good agreement between the calculated data and the observed parameters (lava composition, time of its generation, heat conditions, character of temperature fields, etc.) indicates that the effects of all main factors have been accounted for in the model.

3.2.3. SChR Possibility in the Course of the Active Accident Phase

Such a suggestion was made at the very first meeting of the Governmental Commission (on the evening of April 26), which from that point on repeatedly asked the specialists concerned about the possibility of SChR within Unit 4.

On the evening of 26.04.1986 Academician V.A. Legasov specially arrived upon the Unit 4 wreckage to measure neutron fluxes. Unfortunately, his attempts were unsuccessful.

As said above (Chapter 1.2.4), specialists of the Ministry-of-Defense institutes, Radium Institute and other institutions performed regular aerosol samplings above the collapsed reactor and close to it for purposes of identifying both the composition and intensity of radionuclides released. A special purpose of the investigations consisted in discovering an increase in concentration of short-lived isotopes, which might have evidenced the initiation of SChR.
Instability of results due to complexity of the processes and virtual impossibility of repeating the conditions of measurement was reported. However, as judged from release of short-lived radionuclides, no SChR indices were discovered.

The heat model of lava generation is incapable of providing a general answer to the question on the possibility of SChR initiation in the destroyed reactor.
However from this model it follows that the power released by the generated critical assembly must have been considerably below the integral power of other heat sources, such as:
- decay heat;
- graphite burning; and
- zirconium-steam reaction (see Chapter 2.1.3 and Fig.10).

Otherwise it has been hard to achieve a satisfactory agreement between the calculated data and the observed parameters.
During the active accident phase (up to May 6) the assembly must have been fully destroyed as mentioned in Chapter 2.3.1.

The suggestions expressed sometimes that an increase in release out of Unit 4 during May 2-5 was due to “restart of operation” of a part of intact core have been confirmed neither by available facts nor by calculated models.

3.2.4. Once More on Materials Dropped down from Helicopters for Accident-localization Purposes

According to the reconstruction data of the Unit 4 status half an hour after the explosions (Ref. [26]), there was a layer of materials in the reactor vault above the core wreckage – mostly fragments of concrete structures fallen from the central hall.
Consequently, the early hypothesis on immediate contact of dropped-down materials with the survived core heated up to high temperatures does not agree with the reconstruction data.
At the same time, a detailed discussion of this issue makes no sense because the most of dropped down materials did not penetrated into the reactor vault at all (Chapter 1.3.3).

3.3. The "China Syndrome" Development

The KI -IBRAE model enables a detailed tracing of the processes of melting and gradual descending of materials heated up to a high temperature as well as of burning by them of concrete floors, i.e. of the "China Syndrome" development process.

According to the model, and in a case that all basic conditions of lava generation and spreading are taken into consideration, the burning-through hazard must have only existed for the concrete floor slab between Room #305/2 and the SDC.

Such a hazard did partly realize indeed.
In Fig.15 a fragment of Unit 4 section via Row "K" is demonstrated.
The location of lava accumulation according to the model is colored red. Lava penetration into concrete of both the floor slab and the wall is visible.

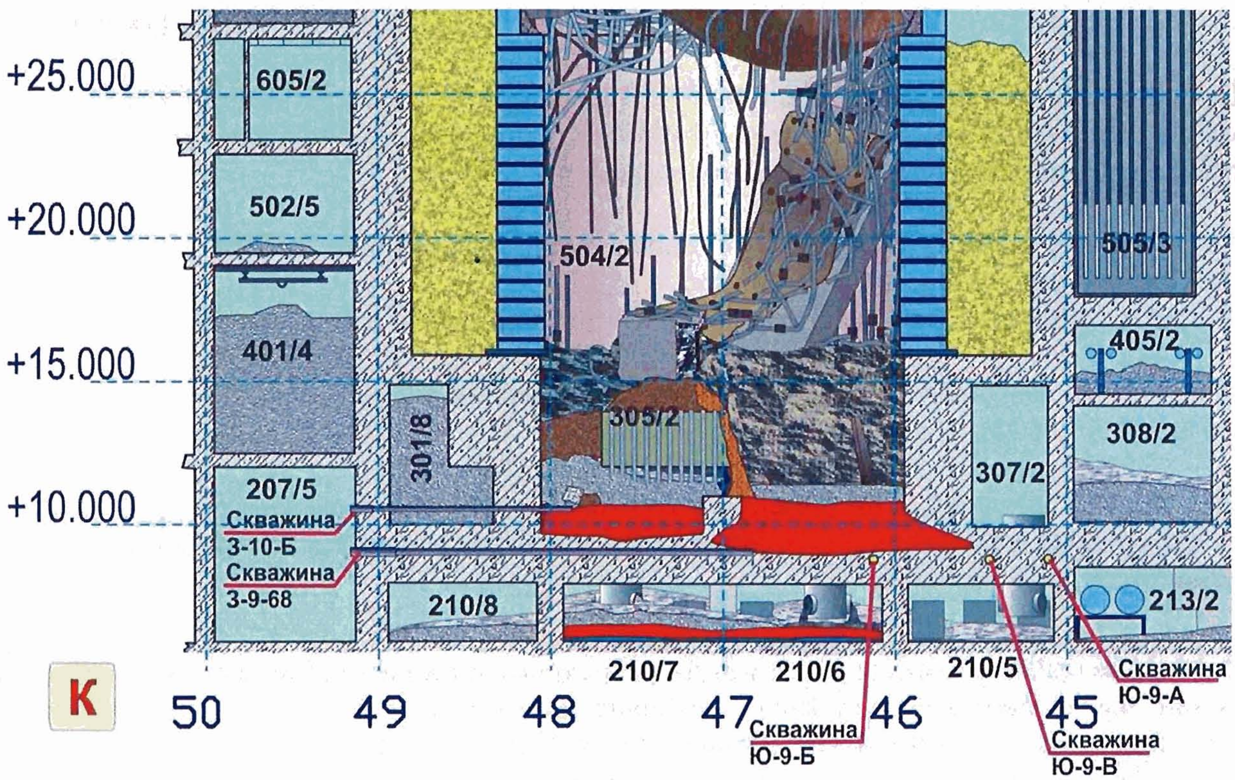


Fig. 15. A fragment of Unit 4 section via Row "K"(→ Hole)

The result of simulation of horizontal burning-through (section via Row "K$_{+240}$") is demonstrated in Fig. 16.

According to the model, cooling of local lava accumulation with high fuel content was possible in that area. The conclusions made are confirmed by investigations of a core sample ~300 mm length extracted from the hole 'Ю-9-B'. The core sample contains solidified molten metal and LFCM. In May 1989 EDR from individual fragments of the core sample made up ~2300 R/h.

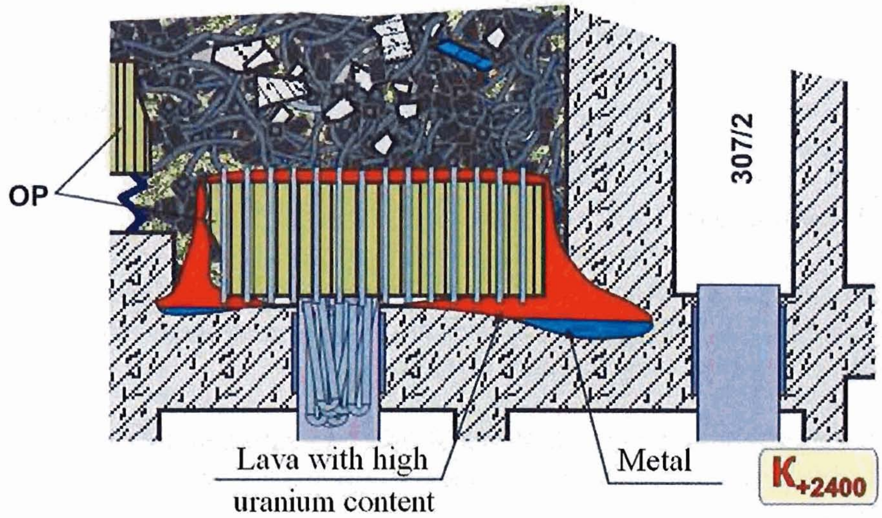


Fig.16. Generation of horizontal burnings-through

It is possible that at individual locations due to contact of the lava with the under-reactor plate vertical burnings-through in the under-reactor plate were formed with the generation of cavities in concrete. However due to a rapid increase in the surface of lava - concrete contact and, consequently, due to the intensification of heat pick-up the burning-through process slowed down.

During examination of the SDC ceiling in Room #210/6 the following was observed (Ref. [3]).

In the Row 'И' area above the middle condenser metal liner of the steel ceiling has a break in welding seam out of which glassy mass flowed down towards the axis #47, the break length being 1 – 1.5 m; metal liner at that location sagged by 20 – 30 cm.

Metal liner of the ceiling above Valves #3 and #4 sagged; organosilicon paint of cladding of the wall located opposite Duct #2 was scorched.
The valves themselves descended by ~ 20 cm as compared to their normal position.

More detailed data on lava spreading in Room #305/2 and burning-through of the support plate are found in Ref. [3].

Thus from the viewpoint of the present-day knowledge and in accordance with the KI-IBRAE model, complex measures on prevention of Unit 4 slab fusion and penetration of fuel into groundwater were excessive.

It should be realized, however, that it was the post-explosion geometry of devastations that "saved" the damaged power unit from catastrophic development of the "China Syndrome".
If the fragment (one fourth) of 'OP' component (which melting took up the most of the energy) had not been located on the path of lava generation and spreading down of scorching lava masses and if the path via steam-dumping valves had been opened, the construction of the under-reactor plate might have been necessary.

REFERENCES

1. *The "Shelter" Current Safety Analysis and Forecast Estimates for the Situation Development* (2001) Responsible Executive: A.A. Borovoi, ISTC "Shelter" Report, n°3836, Chernobyl, P. 337 (in Russian).

2. Borovoi, A.A., Dovbenko, A.A., Stroganov, A.A., *et al.* (1988) *Fuel of Chernobyl NPP Unit 4 (Reference Book)*, Report of Complex Research Expedition under Kurchatov IAE, Chernobyl, P.56 (in Russian).

3. Bogatov, S.A., Borovoi, A.A., Gavrilov, S.L., *et al.* (2007) *Database on the Location and Status of Nuclear Fuel at Unit 4 of Chernobyl NPP before and after the Accident*, Preprint of RRC Kurchatov Institute #130-11/2 of 01.02.2007, P. 146 (in Russian).

4. Vozniak, V.Ja. and Troitskiy, S.N. (1996) Unforeseen knock, in "*Chernobyl: Catastrophe, Feat and Lessons Learned*", Inter-Vesy Publishers, Moscow, pp.76-94 (in Russian).

5. *Chernobyl. Five Difficult Years* (1992), Moscow (in Russian).

6. *Retrospective Dosimetry of Liquidators of the Chernobyl NPP Accident* (1996), Seda-Styl Publishers, Kiev (in Russian).

7. Burlakov, E.V., Zankov, Yu.N. and Kvator, V.M. (1986) On the Possibility of Initiating Self-sustaining Chain Reaction, Internal Report to the Leaders of Kurchatov IAE, manuscript of 07.05.86, Moscow, P.5 (in Russian).

8. Borovoi, A. A. (1996) My Chernobyl, *Russian Literary Monthly Journal "Novyi Mir"*, **3** (in Russian).

9. Diachenko, A.A. (1996) The Governmental Commission, in: "*Chernobyl: Catastrophe, Feat, Lessons and Conclusions*", Inter-Vesy, Moscow, pp.183-193 (in Russian).

10. Borovoi A.A. (1990) *Post-Accident Management of Destroyed Fuel from Chernobyl*, Analytical Report, Work Materials, IAEA, pp. 1-99.

11. *Conducting of Works on Filling of the Reactor and Dust Suppression at the Former Unit 4 of Chernobyl NPP and at Its Adjacent Territory* (1996), Responsible executive: Simanovskaya I.Ja, Certificate #09/05-93 of 16.09 96 (in Russian).

12. Sich, A. R. (1994) Chernobyl accident management actions, *Nuclear Safety*, **35(1)**, pp.1-22.

13. Matuschenko, A.M. (1996) Radiation-survey planes in air, in: "*Chernobyl: Catastrophe, Feat and Lessons Learned*", Inter-Vesy Publishers, Moscow, pp.436 – 456 (in Russian).

14. Rimskiy-Korsakov, A.A., *et al.* (1986) *Investigation of the Release from the Damaged Reactor of Chernobyl NPP Unit 4*, Report of V.G. Khlopin Radium Institute, #14396 (in Russian).

15. Borovoi A.A. (1990) *Fission Products and Transuranic Release during the Chernobyl accident*, Presentation at the International Conference "The fission of nuclei - 50 years",

(Leningrad 1989) and Preprint of the Complex Research Expedition under Kurchatov IAE, Chernobyl, P.20 (in Russian).

16. Belayev S., Borovoi A., *et al.* (1990) Radioactivity releases from the Chernobyl NPP accident, in: Proceedings of the International Conference "*Comparison of Consequences of Three Accidents: Kyshtim, Chernobyl and Windscale*", October 1 - 5, 1990, Luxembourg.

17. *The Accident at the Chernobyl NPP and Its Consequences* (1986) Report of the USSR State Committee on the Use of Atomic Energy at the IAEA Post Accident Review Meeting, Vienna, 25-29 August 1986.

18. Sich, A. R. (1995) The Chernobyl accident revisited, Part 3: "Chernobyl source-term release dynamics...", *Nuclear Safety*, **36(2).**

19. Maslov, V.P., Miasnikov, V.P. and Danilov, V.P. (1987) *Mathematical Simulation of the Damaged Unit at Chernobyl NPP*, Nauka Publishers, Moscow, P.144 (in Russian).

20. Borovoi, A.A., Ibragimov, G.D., Ogorodnik, S.S., *et al.* (1990) *Actual Status of Chernobyl NPP Unit 4 and Nuclear Fuel Stored Therein*, Kurchatov IAE Preprint, P. 72 (in Russian).

21. Sivintsev, Yu. V. and Khrulev, A. A. (1995) Dynamics of radionuclide release from the damaged unit of Chernobyl NPP in 1986, *J. Atomnaya Energija*, **83(2)**, pp. 213—245 (in Russian).

22. E. Purvis III (1995) *The Chernobyl Accident Scenario: a Version of April 1995*, ISTC Report, Chernobyl, P. 146 (in Russian).

23. Versions of explosion at Chernobyl NPP - an interview with K. Checherov (1998) *"Trud" Daily Paper,* February 11, 1998 (in Russian).

24. Kiselev, A.N. and Checherov, K.P. (2001) A model of the process of destruction of the Chernobyl NPP Unit 4, *J. Atomnaya Energija*, **91(6)**, pp.425-433 (in Russian).

25. Pazukhin, E.M. (1994) Lava-like fuel containing masses of the Chernobyl NPP Unit 4: topography, physico-chemical properties and the generation scenario, *J. Radiokhimia*, **36(2)**, pp. 97-142 (in Russian).

26. Bogatov, S., Borovoi, A., Gavrilov, S., Lagunenko, A. and Pazukhin, E. (2005) *Half an Hour after the Beginning of the Accident*, OKPRINT, Moscow, P. 22 (in Russian).

27. Arutyunyan, R.V., Bolshov, L.A., Vasiliev, A.V. and Strizhov, V.F. (1992) Physical models of severe accidents at nuclear power plants, in: *N. N. Ponomarev-Stepnoy* (eds.), Nauka, Moscow, P. 232 (in Russian)

28. Veschunov, M.S. (1991) Kinetics of UO_2-Zr interactions at high temperatures, *J. Atomnaya Energija*, **70(2)**, p. 127 (in Russian).

29. Hofmunn, P. and Kerwin-Pack, D. (1984) UO_2-Zr interaction, *J. Nucl. Mater.*, **124**, p. 80.