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A Nuclear Jet at Chernobyl Around 21:23:45 UTC on April 25, 1986

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Abstract — *The nature of two explosions that were witnessed within 3 s at the Chernobyl-4 reactor less than a minute after 21:23:00 UTC on April 25, 1986, have since then been the subject of sprawling interpretations. This paper renders the following hypothesis. The first explosion consisted of thermal neutron mediated nuclear explosions in one or rather a few fuel channels, which caused a jet of debris that reached an altitude of some 2500 to 3000 m. The second explosion would then have been the steam explosion most experts believe was the first one. The solid support for this new scenario rests on two pillars and three pieces of corroborating evidence. The first pillar is that a group at the V. G. Khlopin Radium Institute in then Leningrad on April 29, 1986, detected newly produced, or fresh, xenon fission products at Cherepovets, 370 km north of Moscow and far away from the major track of Chernobyl debris ejected by the steam explosion and subsequent fires. The second pillar is built on state-of-the-art meteorological dispersion calculations, which show that the fresh xenon signature observed at Cherepovets was only possible if the injection altitude of the fresh debris was considerably higher than that of the bulk reactor core releases that turned toward Scandinavia and central Europe. These two strong pieces of evidence are corroborated by what were manifest physical effects of a downward jet in the southeastern part of the reactor, by seismic measurements some 100 km west of the reactor, and by observations of a blue flash above the reactor a few seconds after the first explosion.*

Keywords — *Chernobyl accident, jet emission, meteorological dispersion.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Numerous studies have been carried out of the 1986 disaster at the Chernobyl-4 reactor in Ukraine. Many of them have dealt with health effects and the dispersion of radioactive nuclides and contamination of vast areas of land, primarily in Europe. But, there has also been great interest in how the accident proceeded during a few seconds around 01:23:45 local time on April 26, 1986. It appears clear from several witnesses that there were two major explosions, the second, and largest, occurring a couple of seconds after the first. The first one is widely believed to have been a steam or vapor explosion where the energy in the hot cooling water together with the energy generated by a nuclear surge across the reactor core pressurized the steam so much that the reactor ruptured in an explosive way. It was estimated that the power went up a factor at least 100 over its design value of 3.2 GW(thermal) for a few seconds. The next explosion has been described as a hydrogen explosion where

hydrogen, produced by exothermic reactions between zirconium in the fuel cladding and water/steam, soon burned explosively with oxygen in the air. Others have argued that the second explosion was also a steam explosion. There is, however, a plethora of hypotheses and interpretations of what exactly happened during that dramatic minute, and they are often quite contradictory.

In broad terms the accident scenario was that the reactor was about to be shut down for maintenance, and a long awaited experiment should be carried out in connection with that shutdown. It was a regulatory requirement that the reactor unit must demonstrate that in case of an electric power breakdown, it could utilize the kinetic energy in the spinning generator turbines to bridge a short time before emergency systems came online. The plan was to start the experiment at a power level around 700 MW(thermal) on April 25, but after reducing the full power by half to 1600 MW(thermal), the process was postponed for about 9 h on request from the Kiev grid control. When resuming the reduction, the power fell down to almost zero due to ^{135}Xe poisoning and some operational mistakes. To counteract this, all control rods were withdrawn, but no more than 200 MW(thermal) could be reached. This is within an unstable power regime where the reactivity coefficient is dominated by a positive void coefficient. In spite of this the experiment was started at 21:23:04 on April 25 (UTC). For not very well-documented reasons, the so-called EPS-5 scram button was pushed 36 s later, and then the big explosions followed within a few seconds.

Our analysis suggests two different mechanisms behind the two explosions. One is a nuclear surge across the core driven by a positive reactivity coefficient, where the void part played an important role. Voids, formed by boiling cooling water in the fuel channels, caused the power to self-amplify in the chain: power increase, more boiling of the cooling water, higher neutron flux in the fuel, power increase, and so on. This surge produced overheated steam in the whole cavity until the reactor tank ruptured and sent its 2000-ton upper lid some tens of meters up through the reactor hall before it fell back on the rim of the tank and came to rest bent open at an angle of about 75 deg. Many fuel channels were still attached to the lid, the core was effectively exposed to the atmosphere, and significant amounts of the radioactive inventory could escape. The bottom lid was pressed downward by 4 m.

The other mechanism suggested is what has been termed the positive scram effect, where one or a few fuel elements got a very fast reactivity boost when the control rods were inserted and stuck with their 4.5-m-long graphite displacers close to the lower parts of the fuel elements.[1] The resulting significant increase in thermal neutrons and

local reactivity then led to local nuclear explosions.[a] These formed upward jets through the refueling tubes. This means that the tubes must have been intact, which in turn implies that the nuclear explosions must have preceded the peak of the surge and its destruction of the tank. The loose 350-kg caps on top of each channel were easily lifted, and the jets shot into the reactor hall and then through the relatively thin roof of the building and high up into the atmosphere where they injected their contents of fission products.[b] Upward was obviously a much more preferred escape direction of a hot plasma than downward into the massive bottom foundation and sideways into the heavy graphite structure. The fission products in the jets were made up of what was in the channels at near equilibrium just before the explosions and what was freshly produced in the nuclear explosions inside the channels.

Just to be clear, in this paper we reserve the word "surge" for the reactivity coefficient–driven energy generation across the full core and the phrase "nuclear explosion" for what is here suggested to be the positive scram–driven explosive energy generation in a number of close fuel channels. The surge started a bit slowly and then accelerated strongly just after the jets, which probably had acted as spark plugs for the surge. The slower start is derived from a report by the reactor section foreman Valeriy Perevozchenko, who 3 min before the big explosions stood on an open platform some 15 m above the floor of the reactor hall. He then observed how the 350-kg caps atop the fuel channels jumped up and down, and he felt shock waves through the building structure.[2]

A nuclear explosion interpretation gained momentum when it was reported from the V. G. Khlopin Radium Institute in St. Petersburg that they in late April 1986 had measured radioactive noble gas nuclides in air at Cherepovets 370 km north of Moscow and 1000 km north-northeast of Chernobyl.[3,4] These nuclides were two fairly short-lived radioactive xenon isotopes/states: ^{133}Xe ($T_{1/2} = 5.243$ days) and ^{133m}Xe ($T_{1/2} = 2.19$ days), which clearly indicated by their ratio that they had been partly produced very recently in nuclear fission. At least three samples exhibited ratios that significantly deviated from the ratio one would expect from the bulk reactor inventory a few days after the accident. The authors of the Khlopin report

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[a] This nuclear explosion concept *must not* be confused with a nuclear bomb as the two differ considerably in their principles of operation, neutronics, released energy, and temperatures involved.
[b] The tubes and caps in the floor of the reactor hall were parts of a design to make it possible to refuel single channels during full operation, which is a typical characteristic of the RBMK reactors.

concluded that the detected activities "point to a local character of instant nuclear outburst stipulated by extremely non homogeneous distribution of the neutron flux in an active reactor zone at the moment of the accident."[4] This is very interesting, but the analysis lacked an explanation for how this fresh xenon signature could be seen in Cherepovets in competition with the reactor equilibrium xenon isotopes that were some thousand times more abundant in the core.

In 1987 we published a report about how Chernobyl debris reached and were deposited in Sweden.[5] When learning about the Khlopin data at a workshop in St. Petersburg in 2008, a figure in our report surfaced that showed simple trajectory calculations for injections of debris at different elevations above the reactor. Lower-altitude injections from the reactor rupture and the fires went initially toward Scandinavia while potential higher ones bent around the Gulfs of Riga and Finland and headed back eastward. Maybe that could solve the mystery of the fresh xenon isotopes: a local "nuclear explosion" in the reactor that ejected its debris as a jet from one or several fuel channels to those high altitudes from where these debris could be transported toward Cherepovets without being much mixed with the bulk, near equilibrium, reactor xenon. We decided to analyze this scenario in detail, but the project was postponed at the time due to the lack of high-quality, high-resolution gridded weather data covering April-May 1986 for driving the dispersion model. When in 2016 the high-resolution regional reanalysis for Europe was published and extended back in time to 1980, it became possible for us to perform good-quality dispersion modeling.

II. THE FINDINGS AT CHEREPOVETS

The noble gas sampling at Cherepovets was not done for the purpose of detecting radioisotopes. The noble gas fraction was a by-product at a liquid air factory built to satisfy the needs of industrial gases at the Cherepovets Iron and Steel Complex. In the process of producing mainly liquid oxygen and nitrogen, the noble gas fraction was also separated. The Khlopin scientists exploited these commercial samples in the immediate aftermath of the Chernobyl accident to search for radioactive xenon isotopes by high-resolving gamma-ray spectroscopy. Their results are shown in Table I of Ref. 4. One column in that table shows the $^{133}Xe/^{133m}Xe$ ratio recalculated back to the accident moment by assuming simple decay of the xenon isotopes. From that, one could easily deduce the times the authors referred their measured activity concentrations to. It turned out to be 01:00 local time on April 28, 29, 30, and May 2 for the four samples where $^{133}Xe/^{133m}Xe$-ratios could be analyzed.

According to the meteorological dispersion analysis described below, the April 26 emissions from Chernobyl passed Cherepovets at ground level between 07:00 and 19:00 local time (03:00 to 15:00 UTC) on April 29. The original data were therefore corrected for decay to the midpoint, 13:00 local time (09:00 UTC), on that day. Table I gives these time-corrected values for the four samples where both the ground state and the metastable state were detected such that ratios could be calculated.

From the Khlopin data it is obvious that there were two production lines at the factory that provided the samples resulting in detections of both ^{133}Xe and ^{133m}Xe: one filling cylinders April 27 to 29 and April 29 to May 2 and the other one filling cylinders April 27 to 30 and April 30 to May 3. The cylinders were regularly changed around noon.[6] The cylinders in the first production line were obviously changed during the passage of the major radio-xenon "cloud," and as it is not known how long it took to change the cylinders, the concentration data from this production line are less reliable than the data from the second one. The first sample in the second line with a concentration of 1.52 ± 0.12 Bq/m^3 of ^{133}Xe in a 3-day sample is therefore adopted, and that gives a time-integrated concentration of 109 ± 9 Bq·h/m^3 (the small detections in the second sample of line 2 were obviously due to a laggard of the main cloud not resolved in the calculation. The

TABLE I

^{133}Xe and ^{133m}Xe Activity Concentrations and Ratios Observed at Cherepovets in April/May*

Line Number	Cylinder Filling Up	^{133}Xe (Bq/m^3)	^{133m}Xe (Bq/m^3)	$^{133}Xe/^{133m}Xe$
1	April 27–29	0.608 ± 0.061	0.0156 ± 0.0037	39.1 ± 9.4
1	April 29–May 2	1.64 ± 0.14	0.0363 ± 0.0094	45.3 ± 11.7
2	April 27–30	1.52 ± 0.12	0.0350 ± 0.0085	43.3 ± 10.6
2	April 30–May 3	0.330 ± 0.035	0.00659 ± 0.00161	50.1 ± 12.2

*All data refer to 13:00 local time (09:00 UTC) on April 29, 1986.

^{133}Xe/^{133m}Xe activity ratio, which does not depend on the details of the cylinder changes, can be estimated from the average of all four samples to be 44.5 ± 5.5.

As mentioned above, the Khlopin group recalculated the ^{133}Xe/^{133m}Xe ratio back to accident time by assuming simple decay of the xenon isotopes. The explosion time ratios were then compared to the calculated near-equilibrium ratio in the core channels and the ratio produced in a thermal neutron mediated nuclear explosion. We chose to do the opposite and follow a full mass-133 one-channel inventory just before the accident and a thermal nuclear explosion in the same channel at accident time, as both developed into early May (including full precursor feed, i.e., without any precipitation scavenging). The sum of both is then compared to the measured data at the time of sampling.

III. NUCLEAR ANALYSIS

The decay calculations were done with Xebate, a Mathematica© program written by one of us (De Geer). The code represents the full Bateman decay of all fission product mass chains that include xenon isotopes of interest in airborne fission products (A = 131, 133, 135, 137, 140, and 141). It also allows for cutting out the precursors of xenon isotopes at selected times to estimate, e.g., how much the results depend on precipitation scavenging of nonnoble gas nuclides during parts of the transport. Xebate has been carefully tested for several years and contains a number of internal checking routines.[7]

It is assumed that the explosions happened in channels with maximum operational power. The reactor had 1659 fuel channels loaded, and there was in the full core both an axial and a radial distribution of power. The maximum channel power in an RBMK-1000 reactor like Chernobyl-4 was 3 MW (Ref. 8, Table 1). At the time of the accident, the core contained three major fissile isotopes: 4.5 kg/ton ^{235}U, 2.6 kg/ton ^{239}Pu, and 0.5 kg/ton ^{241}Pu (Ref. 9, Annex D, paragraph 18). As similarly done by Pakhomov and Dubasov in Ref. 4, we divide these numbers with the individual mass numbers and multiply with respective thermal fission cross sections 585, 747, and 1012 b. Then, dividing by the sum, we get the relative contributions to the number of fissions from each major fissile isotope. From this and the recoverable energy per fission (Ref. 10, Table 1.2), we arrive at an average of 195.7 MeV/fission, which in turn gives a fission rate of $3 \times 10^6/(195.7 \times 1.602 \times 10^{-13}) = 0.96 \times 10^{17}$ or nearly 1×10^{17} fissions/s in a maximum power channel.

To calculate the equilibrium activity content of different fission products in a certain decay chain, like the

mass-133 one, the fission rate is multiplied with the cumulative yields tabulated in different databases available on the Internet.[11–13] Here, the JEFF 3.1.1 yield tabulation was selected, but using the other data sets, it had only negligible impact on the conclusions [JEFF 3.1.1 (Joint Evaluated Fission and Fusion File) can be reached via the JANIS 4 website (under JANIS 3.2) (Ref. 11)].

At accident time the core was not at full equilibrium, however, as the power had been reduced during the preceding day. The power history has been slightly differently portrayed in different studies. The one used[14] was further simplified by applying instantaneous power reductions instead of two linear ones with 1- to 3-h duration and disregarding the some 15-min, 30-MW(thermal) visit in the last hour (Fig. 1). It was checked, however, that these changes had no significant impact on the results of the study.

The resulting independent fission yields for the fuel mix of Chernobyl-4 in late April 1986 based on JEFF 3.1.1 data are shown in Fig. 2 together with the decay structure, half-lives, and branching factors that are taken from the ENSDF data file.[15]

Loading these data into Xebate, the ^{133}Xe and ^{133m}Xe activities were calculated as a function of time for 1 week, separately for the near-equilibrium xenon (in one maximum power channel) and the xenon produced by a 75-ton[c] explosion in the same channel. In Fig. 3, this and the sum of the two contributions are displayed for ^{133}Xe, and it can specifically be read that there was 6.63 PBq ^{133}Xe in the

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[c] When referring to explosions, "ton" is the TNT equivalent mass yielding the same energy when exploded. 1 ton equals 4.184 GJ.
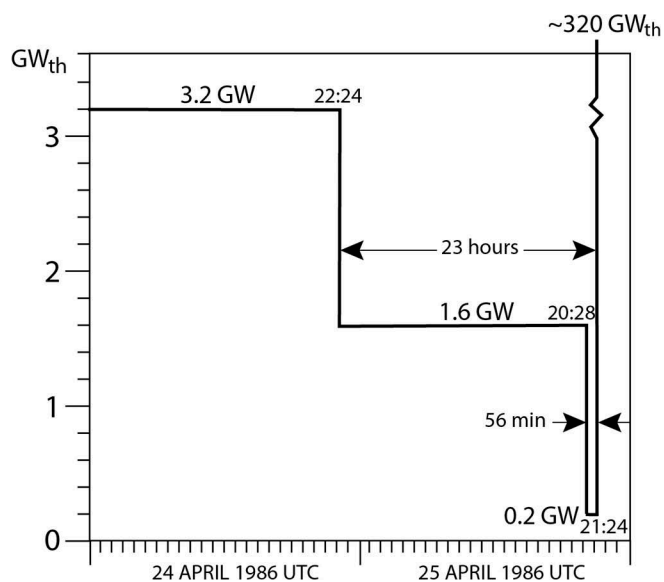

Fig. 1. Simplified Chernobyl-4 thermal power history on April 24–25, 1986 UTC.
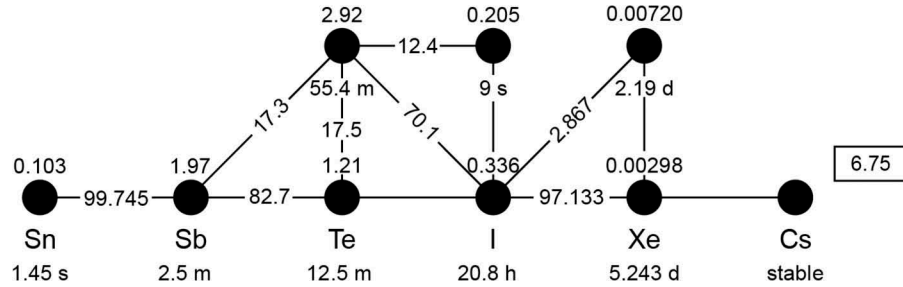
Fig. 2. Mass-133 fission product decay structure. Below the isotope symbols are the half-lives and above are the independent yields in percent for thermal neutron fission in the Chernobyl-4 core on April 26, 1986. In addition, there are branching factors in percent and the chain yield also in percent. The decay proceeds from left to right and from up to down.
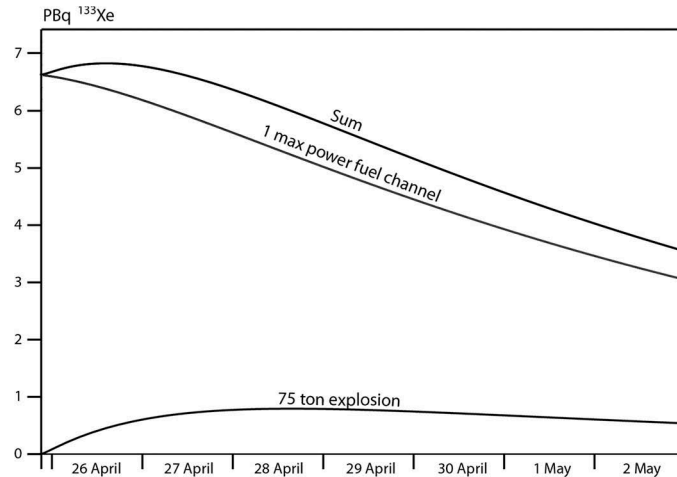

Fig. 3. The development of the ^{133}Xe activity in the mass corresponding to one maximum power fuel channel with an internal 75-ton explosion ("Sum") and its two components: core and nuclear explosion.

channel at accident time, which developed into 5.54 PBq after 84 h, when the cloud passed Cherepovets.

Further, the near-equilibrium ^{133}Xe inventory in the whole core was calculated to be 7.1 EBq, just 0.1 EBq less than 7.2 EBq, the calculated full equilibrium inventory. The latter compares well with other estimates in the range of 6.2 to 7.2 EBq for an equilibrium core in Chernobyl-4 just before the accident sequence.[16]

Xebate does not include neutron capture reactions, so a separate check was done to see whether this could significantly change the equilibrium content of ^{133}Xe and ^{133m}Xe. The thermal neutron capture cross sections for these nuclides/states are 187 and 522 b, respectively [from TENDL-2015 (TALYS Evaluated Nuclear Data Library), which can be reached via the JANIS 4 website (under JANIS 3.2) (Ref. 11)], which given the equilibrium values of 4.40×10^{23} and 5.45×10^{21} nuclides/maximum power channel calculated by Xebate yield total microscopic capture cross sections of 88 and 2.8 cm^2 in the channel. As the core was loaded with 190 tons of fuel in 1659 channels, the corresponding total microscopic

fission cross section of ^{235}U is $(190/1659) \times (4.5/235) \times 6.023 \times 10^{27} \times 585 \times 10^{-24} = 7727$ cm^2 (with additional numbers, except the Avogadro one, recognizable from the calculation of the fission rate above). Adding the same for ^{239}Pu and ^{241}Pu results in a total microscopic fission cross section in one channel of 14781 cm^2. This means that just about 0.6% of the ^{133}Xe and 0.02% of its metastable state are deviated by neutron capture in equilibrium. For its precursors the effect is at least 100 times less, so in summary, thermal neutron capture can be totally ignored in the present analysis.

The explosive yield of 75 tons is of course not chosen arbitrarily. It results from the measured ^{133}Xe/^{133m}Xe activity ratio when compared with the calculated one as shown in Fig. 4. There is also a vertical line at 09:00 UTC on April 29 that represents the measured average ratio of 44.5 ± 5.5 as derived above. That gives a 1σ confidence interval of 25 to 160 tons with 75 tons as the central ratio.

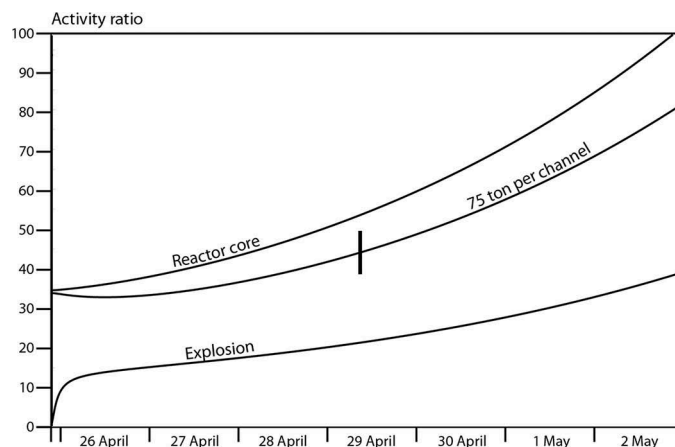At time zero the ^{133}Xe/^{133m}Xe activity ratio is 34.6 for the near-equilibrium fuel channel and just 0.17 for the

Fig. 4. The development of the ^{133}Xe/^{133m}Xe activity ratio in the near-equilibrium reactor core and a thermal neutron mediated nuclear explosion. The black line marks the data measured at Cherepovets, and the "75 ton per channel" curve is the one that best fits these observations.

explosion. During the decay through the week, the calculations are based on the assumption that there is no precipitation scavenging of xenon precursors. Estimates of the scavenging effect are, however, easy to make by cutting out a given share of the precursors at a given time in the Xebate calculation. Precipitation scavenging has naturally less effect if it occurs closer to the sampling time as a greater share of the mass content has then already decayed to xenon. For example, for a 50% depletion or scavenging of the precursors 12, 24, 48, or 72 h after the accident, the effect would be that the explosion needs to increase to about 150, 130, 100, and 80 tons/channel, respectively, in order to get the same ^{133}Xe/^{133m}Xe activity ratio. Precipitation scavenging thus implies a higher nuclear yield per channel. But, according to the meteorological analyses in Sec. IV, the high-resolution, two-dimensional (2-D), 5.5-km weather data show almost no precipitation along the track from Chernobyl to Cherepovets. Precipitation scavenging can therefore safely be disregarded in this analysis.

IV. METEOROLOGICAL ANALYSES

The jet hypothesis is primarily founded on two observation sets: (1) the clear indications of fresh nuclear debris at Cherepovets a few days after the accident and (2) a meteorological situation from April 26 on, which took a significant fraction of the large amount of set-free radioactive fission products at low altitudes northwest toward Scandinavia but at higher altitudes made a sharp turn back east around the Gulfs of Riga and Finland. To study the case as carefully as possible, a new meteorological dispersion analysis was carried out utilizing the best modern data available and a modern three-dimensional (3-D) software package.

Our study was performed using both 2-D and 3-D gridded weather data for the time period April 25, 1986, to May 5, 1986, from a high-resolution regional reanalysis project for Europe. The 3-D reanalyses were produced with the HIgh Resolution Limited-Area Model (HIRLAM) forecast model and data assimilation system.[17] Surface and upper-air variables were analyzed on a 3-D grid-mesh with 22-km spacing and 60 vertical levels covering Europe. A number of surface parameters were further downscaled on a 2-D grid mesh with 5.5-km grid spacing over Europe using a large number of additional surface observations.[18] From this, it became clear that precipitation played no major role along the track from Chernobyl to Cherepovets.

The Eulerian dispersion model MATCH (Ref. 19) with the same horizontal and vertical resolution as applied for the 3-D gridded weather data was used to simulate concentrations of the decaying radionuclide ^{133}Xe. In a few cases, MATCH and the HIRLAM semi-Lagrangian dispersion model (Enviro-HIRLAM) have been run with identical emission data and compared to observed concentrations. One such case refers to the ETEX-1 passive tracer experiment over Europe in 1994 (Ref. 20). MATCH, based on HIRLAM weather data, took part in real time during this experiment and was ranked No. 1 among a large number of dispersion models from around the world in the following evaluation made by the Institute for Defense Analyses in the United States. The HIRLAM semi-Lagrangian model was run later, and the model output was compared to the measurements.[21] The statistical scores showed that the model reproduced the tracer fields satisfactorily, but no detailed specification of scores was given.

A second case where the MATCH and Enviro-HIRLAM models took part in a comparative study referred

to tropospheric ozone.[22] In the comparisons with observed data, the scores were a bit better for MATCH.

In MATCH, the Bott advection scheme is used, which gives a very high degree of mass conservation, which is of large importance in dispersion modeling. In semi-Lagrangian dispersion models, mass conservation needs some extra focus since the scheme applied for the meteorological parameters is often not sufficient.

Time resolution of the stored model concentrations was 1 h for the studied time period. Model simulations were performed for altogether 17 cases with different injection heights above the Chernobyl-4 reactor of debris from one fuel channel with a 75-ton nuclear explosion. The different model emissions were extended for 1 h between 21:00 and 22:00 UTC on April 25 equally distributed within each of the 17 height intervals/cases. The applied emission height intervals for the different cases were case 1: 0 to 250 m, case 2: 250 to 500 m, and then for all 500-m intervals up to 8000 m.

MATCH followed the dispersion and decay of ^{133}Xe from the accident up to May 14 [as we here, however, deal with a full decay chain (see Fig. 2), the results are first recalculated back to the accident and then calculated forward in time by Xebate to the time of interest]. Figure 5 gives the surface concentration at 09:00 UTC on April 29 due to an injection of one channel with a 75-ton explosion into the 2.5- to 3-km layer. The pass over Cherepovets is very clear. The inset shows the same trail at midnight the day before at 3 km where the turn around the easternmost gulfs of the Baltic can be seen. It then hit a cold front from the north, and the trail moved southward passing with its broadside over Cherepovets.

Figure 6 plots the maximum concentrations at Cherepovets on April 29 for all 17 cases. It shows a fairly sharp maximum for emissions at an altitude of 2.5 to 3 km. It also shows, however, that emissions at lower altitudes like between 0 and 1 km, where a substantial part of the bulk reactor inventory was injected on the first day, reach Cherepovets in the same time window. As the core contains about 1000 times more ^{133}Xe than a channel jet with a 75-ton explosion, even a tenth of that (Fig. 6) is 100 times more than the jet and would totally mask any information of the explosion part in the jet. That is, however, only if the core contribution is emitted during the first hour after the accident.

Information on the core xenon emission history is naturally quite scarce. The only reference to it can be found in the reports compiled by the USSR State Committee on the Utilization of Atomic Energy for the International Atomic Energy Agency expert's postaccident review meeting in August 1986 (Ref. 23). There it is claimed that only about 2.5% of the core ^{133}Xe was released from the reactor during
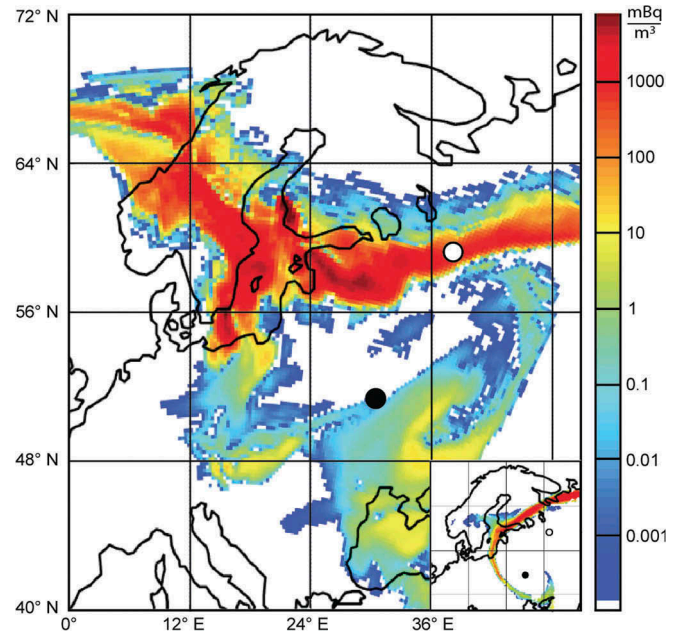

Fig. 5. A calculated surface air ^{133}Xe concentration map at 09:00 UTC on April 29 for one maximum power channel with a 75-ton explosion injecting its full debris into the 2.5- to 3.0-km altitude interval between 21:00 and 22:00 UTC on April 25, 1986. Note that "●" indicates the power plant and "○" marks Cherepovets. The inset in the lower right shows the cloud at the altitude of 3 km at midnight the day before the detection.

April 26 and probably 100% up to May 6. A MATCH dispersion analysis with 178 PBq (2.5% of 7.1 EBq) evenly released during the first day yielded an average concentration of 17.2 Bq/m^3 between 06:00 May 1 and 06:00 May 2 UTC in Freiburg, Germany.

In that city, during the same 24 h, the Bundesamt für Strahlenschutz that ran the only ^{133}Xe laboratory hit by the Chernobyl low-altitude cloud measured 106 Bq/m^3 of ^{133}Xe (Ref. 24). That is about six times more than the calculation. Since the uncertainty in the first day release fraction is reported to have been, and must have been, quite high, we assume that this comparison can be used to calibrate the first-day xenon release to have been 15% instead of 2.5% of the full core. The measured values then fit quite well the calculated ones during the full week of May 1–8 (Fig. 7). According to the calculations, releases later than April 26 had no impact on the concentration in Freiburg before around 06:00 on May 2, i.e., while the first two samples were collected (later emissions did, however, to a varying degree contribute ^{133}Xe to the later samples). The 15% release fraction during the first 24 h is therefore used for the analysis of the Cherepovets data.

At Cherepovets, the time profiles of all 17 emission intervals analyzed for the jet were nearly identical with
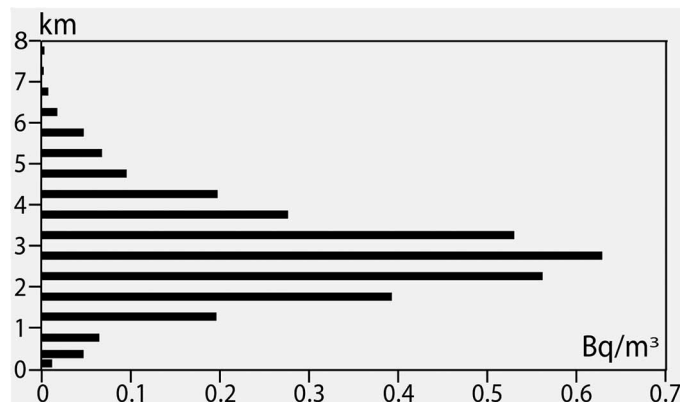
Fig. 6. Diagram showing calculated maximum concentrations at Cherepovets on April 29 at around 09 UTC for injections of one channel with a 75-ton explosion into each of the 17 intervals between 0 and 8 km.
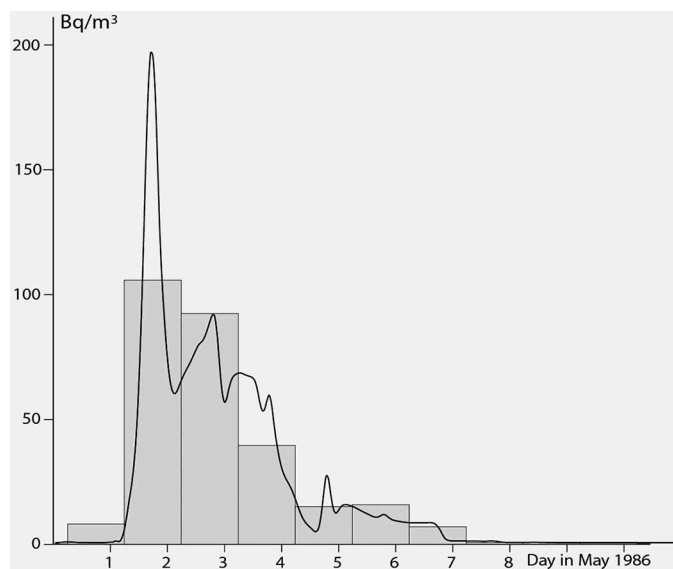

Fig. 7. Surface air ^{133}Xe concentrations April 30 to May 10, 1986, in Freiburg, Germany. Date marks at 00 UTC. The histogram shows 24-h measured values, and the solid black curve shows the 1-h resolution calculated values based on a release of 15% of the core in Chernobyl during the first 24 h after the accident.

essentially no features outside the April 29 peak during the first week. Up to May 2, all 17 cases exhibited a single distinct peak at Cherepovets, which occurred between 03:00 and 15:00 UTC on April 29 (Fig. 8).

At the time of the accident, there was an extensive ridge of high pressure with its center over northwest Russia. Warm air moved at lower altitudes with a southeast wind toward the Baltic. A temperature inversion reached from the ground up to an altitude of 400 to 500 m over Chernobyl during the night of the accident. Above the inversion, there was a strong east-southeast wind with a speed of 12 to 14 m/s.

The high-pressure situation influenced the Chernobyl area and large parts of northeast Europe until May 8 and caused a subsidence (downward motion) of tropospheric air toward the ground surface, which influenced the transportation of the higher-level jet emission during the first days of transportation.

The calculations show that the near-surface cloud basically caused by the subsidence passed Cherepovets during 12 h centered at 09:00 UTC on April 29, 1986. For one channel with an injection of 6.63 PBq ^{133}Xe plus its precursors into the 2.5- to 3-km layer, the calculated time integrated ^{133}Xe concentration of the cloud passing was about 4.6 Bq·h/m^3.

The large core release resulting from the steam explosion also has to be considered, as a small part of it will reach Cherepovets. A MATCH calculation with 15% of the core ^{133}Xe released evenly during the first 24 h into the first 500 m gives, as can be seen in Fig. 8, a 3-h
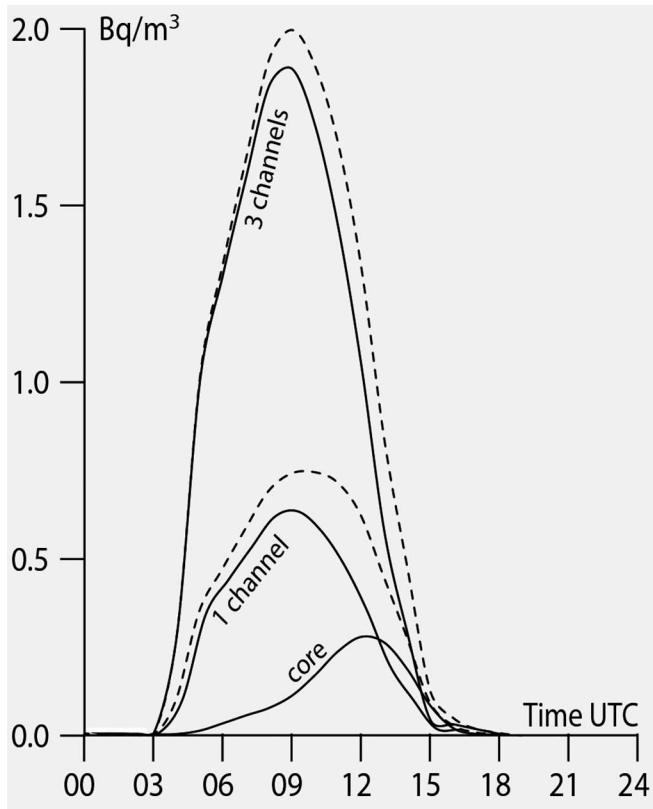
Fig. 8. Calculated surface-air ^{133}Xe concentrations on April 29 at Cherepovets for one and three maximum power channels, each with a 75-ton explosion injecting its full debris into the 2.5- to 3.0-km altitude interval between 21:00 and 22:00 UTC on April 25, 1986. The bottom curve represents the contribution from the initial 24-h release of 15% of the full-core content. The dashed curves are the respective channel curves with the core contribution added.

delayed xenon signature in Cherepovets with an integrated concentration of 1.6 Bq·h/m³. That adds 35% to the 1 maximum power–fuel channel curve in Fig. 3 and a corresponding increase in the nuclear yield needed to sustain the observed ratio in Fig. 4. That is not very significant for our conclusion and becomes even less significant if there was more than one channel in the jet, as the core fraction will decrease by the same factor as the increase in number of channels.

To sum up the meteorological analysis, the measurement gives an integrated concentration of 109 ± 9 Bq·h/m³, and the MATCH simulation gives for one channel in the jet 6.1 Bq·h/m³ including the non-jet core contribution. That is a disagreement by a factor of about 20. A very plausible interpretation is that there was more than one channel contributing to the jet. A second possibility is that the dispersion model itself or the driving 3-D weather data used for the model cause an underestimation of the calculated jet contribution. A stronger subsidence would bring air with high concentration closer to the surface leading to higher concentration at the surface. Other factors may also contribute to the uncertainty of the model calculations, but it is difficult to make a quantitative estimate of the total uncertainty.

As noted below from seismic observations, the explosion part of the jet is limited to some 300 tons (TNT). That allows for four channels with a 75-ton explosion each. But, if the lower limit of 25 tons in the analysis would correspond to the truth, there could have been up to some 12 channels contributing to the jet. So, there is leeway in the uncertainty of the seismic limit, in the number of channels, and in the meteorological analysis to resolve the discrepancy.

V. CORROBORATING EVIDENCE

V.A. Observations at the Bottom of the Reactor Tank

It is reasonable to assume the nuclear explosions happened in the southeastern quadrant of the core where it was later found that the 2-m-thick–bottom, 4-cm steel-encapsulated serpentinite plate had disappeared. Burnthrough observed in the subinstrumentation room below suggests there were brief and sharply directed streams of high-temperature plasma entering from above.[25] This strongly supports the hypothesis of a much stronger plasma jet aimed in the opposite direction where because of the refueling tubes through the 4-m-thick upper plate, there was substantially less resistance. Outside the southeastern quadrant the bottom plate was relatively intact, but it had dropped about 4 m into the subinstrumentation room.[25] This probably occurred during the subsequent steam explosion, which did not create temperatures high enough to melt the plate but generated sufficient pressure to push the bottom plate down nearly 4 m and throw the top lid some 20 to 30 m above the floor of the central hall. The top lid weighed some 2000 tons. Like the bottom plate it was made of serpentinite encapsulated in a 4-cm-thick jacket of steel. Remember that this scenario requires that the jet was ejected before the steam explosion while the pressure tubes and refueling tubes were relatively intact. Based on witness accounts of the direction of the sound, these two explosions have been referred to as the lower and the upper ones. Some also perceived that the first, lower explosion consisted of two combined blows, something that could support that there were several channels taking part within a very short moment of time.[26]

V.B. Seismic Indications

In late 1996 an article in a Soviet popular science magazine suggested that an earthquake close to the Chernobyl nuclear power plant had triggered the accident. It was based on the fact that seismic surface waves had been recorded at three seismic stations at Norinsk, Podluby, and Glushkeychi 107 to 173 km mainly west of the power plant. The article triggered discussions in the scientific community, which led to the earthquake scenario being largely abandoned, but instead, many straggling speculations were presented in different reports. One group claimed the seismic signal came from a 10-ton TNT explosion in the reactor,[27] something the Khlopin group referred to in its report. Others reported that the emergent event started 21:23:40 when the chief operator tried to insert control rods into the core but they were stopped halfway when their frontal graphite displacers increased the local reactivity significantly in the lower part of the core.[1,28] One report shows the three seismograms, where the Norinsk one is the clearest.[26] There, it can be observed that the S-wave appears 13.5 s after the P-wave, which indicates a distance to the source of around 100 km (Ref. 29) that compares well with the 107 km between Chernobyl and Norinsk. Two Rayleigh surface waves follow 2.7 s apart, and these waves are believed to have resulted from the two explosions that were heard in the reactor within some 3 s by witnesses on-site. Consistent with the rapidly increased reactivity at the bottom of the channels, the first explosion was heard from the lower part of the core, and the latter, conceived to be stronger, was heard from the upper part. The first explosion looks in the seismic data like a double explosion, and its size is quite similar to the upper (second) explosion. That suggests that more than one channel contributed to the jet and that the perceived difference in size of the lower and upper explosions rather was due to different dispersion of the sound locally, first through the massive core and shielding and then more freely from the explosion of the reactor tank. Three exploding channels correspond in the present analysis to 225 tons of TNT, or possibly less, which is quite similar to estimates in the literature of the second (upper) explosion in the range of 100 to 270 tons (Refs. 25 and 30). These estimates are consistent with two seismic signals with similar amplitudes. In the Norinsk seismogram one can also clearly see two similarly sized peaks, which represent the passing of two sound signals in air. They are also separated by 2.7 s, and they arrive about 5.5 min after the explosions. That gives a distance of 5.5 × 60 × (the speed of sound in air at 12°C: 338.5 m/s) = 112 km, again close to the 107 km between the Chernobyl reactor and Norinsk.

V.C. The Blue Flash

At least two people have reported what they saw and heard at distances of half to a few kilometers away from the power plant. Vladimir Chernousenko, former head of the Ukrainian Academy of Science and the scientific coordinator of the Chernobyl cleanup, has reiterated the story of a witness that was out fishing on the cooling pond some 500 m away from Block 4 when the accident happened. He heard a large clap followed by an explosion. Then, in a couple of seconds he saw a bright blue flash that was followed by an enormous explosion.[31] It is well known that criticality accidents emit a blue flash, or rather glow, which derives from fluorescence of excited oxygen and nitrogen atoms in the air. It is obvious that the most impressive explosion was the one that ruptured the fuel channels and threw the 2000-ton lid with its hanging fuel channels high up in the central hall from where it fell down and came to rest nearly vertically on the rim of the reactor tank. With the fuel fully exposed, the air was irradiated, and the typical blue glow was lit. An employee of the power plant, Alexander Yuvchenko, has described how he and a colleague "ran out of the building and saw half of the building gone and the reactor emitting a blue glow of ionized air." But, the flash observed by the fishing man was a bright blue flash before he heard the second explosion. This description is understandably not a scientific logbook, but if it is correct, there is only one interpretation. The first and lower explosions were nuclear, and they created a jet of debris that reached high altitudes. At a distance of 500 m, the fishing man should have heard the first explosion with a delay of some 1.45 s. Then, a couple of seconds later, he observed the bright blue flash. That is around 3 to 4 s later than the first/lower explosion and up to around 1 s earlier than when he heard the second/upper one. As the steam explosion would not create a flash, an explanation could be that the surface of the jet peeled off some hot material to the air and/or that the jet with a temperature of several tens of thousand degrees heated a column of air around its track. Within a few seconds that hot material would cool down through the temperature interval around 7000°K, where for a short time before it cooled down

further, it would radiate blue light by blackbody radiation—a blue flash, not a glow.[32]

VI. CONCLUSIONS

A scenario has been worked out for the dynamics during a part of the first minute of the accident at the Chernobyl-4 power unit in April 1986. The observations driving this scenario have been the detections by a group at the Khlopin Radium Institute in St. Petersburg of freshly produced ^{133}Xe and ^{133m}Xe in the Russian city of Cherepovets a few days after the accident and a very clear transport route to this area at an altitude of 2.5 to 3 km.

It is concluded that the two explosions in the reactor that many witnesses recognized were thermal neutron mediated nuclear explosions at the bottom of a few fuel channels and then some 2.7 s later a steam explosion that ruptured the reactor vessel. The nuclear explosions formed a plasma jet that shot upward through the still intact refueling tubes, rammed the 350-kg plugs, and continued through the quite thin roof and then some 2.5 to 3 km into the atmosphere where the meteorological situation provided a route to Cherepovets.

The release dynamics of xenon after the steam explosion has not been very well known. Meteorological dispersion calculations compared with actual detections of ^{133}Xe in Freiburg, Germany, in early May 1986 could, however, be used to estimate that around 15% of the bulk xenon in the core was released during the first 24 h to a fairly low altitude. This figure was plugged into the calculations for Cherepovets, and it was then concluded that the part of the core that was released by the steam explosion contributed very little to the Cherepovets detections and therefore had little impact on the conclusions.

The scenario is well corroborated by observations of the effects on the lower lid of the reactor vessel, by seismic detections (including sound) about 100 km away from the reactor and by witness accounts of a blue flash that could not be explained by any other process than a nuclear explosion.

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