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Evaluation of the 17 June 1997 Criticality Accident at Arzamas-16

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Morris Klein

Los Alamos
NATIONAL LABORATORY
Los Alamos, New Mexico 87545

EVALUATION OF THE 17 JUNE 1997 CRITICALITY ACCIDENT AT ARZAMAS-16

Morris Klein

Abstract

On June 17, 1997, a criticality accident occurred at Arzamas-16, which resulted in the death (within three days) of A. N. Zakharov, a Russian scientist with 20 years' experience conducting multiassembly experiments. In this case, the multiplying assembly was a fast metal system consisting of a ^{235}U (90% enriched) core and a copper reflector.

According to the Russian press, "Zakharov misjudged the degree of criticality of the breeding system and committed several gross violations of regulations." As we see it, there were three major causes of this accident. First, the experiment was flawed by Zakharov's misreading of the appropriate size of the assembly, which he took from a notebook that described the old experiment he was attempting to repeat. Second, he disregarded the appropriate procedures and safety regulations. Third, these two mistakes were compounded by an improperly set audible alarm system and Zakharov's unsafe use of the table.

We also discuss our reconstruction of the accident based on information given by the Russians to US scientists and information culled from Russian newspaper and magazine articles. We also describe our thoughts on the behavior of the assembly following the accident and the radiation dose level Zakharov may have received. These levels match values we have lately obtained from translations of Russian news articles.

This accident clearly points out the penalty for weak administrative control of work with multiplying systems. Criticality experimentation requires formality of operation. The experimenter, his peers, and a trained safety person need to document that they understand the experiment and how it will be conducted. Knowing that the experiment was successfully run several decades ago does not justify bypassing a safety evaluation.

Section I. The Experiment and the Accident

On June 17, 1997, a criticality accident occurred in an underground bunker at Arzamas-16. A. N. Zakharov, a Russian scientist with 20 years' experience conducting multiassembly experiments, received a lethal radiation dose, 500-800 rad to the whole body and 2,000-2,500 rad to the hands, as a result of this accident.[1] We infer from a Russian magazine report that when the assembly went prompt critical, Zakharov saw a bright flash and felt a thermal shock.[2] The assembly itself remained in a critical state for six days before being successfully dismantled. The bunker is probably still contaminated.

The Russian press reported that Zakharov died within 40 hours of the accident.[3] Death from an acute radiation dose in this time period is symptomatic of damage to the gastrointestinal and neurovascular systems. Such damage indicates a whole-body dose of at least 2,000 rads.[4] If the doses reported above are gamma dosages, then his total rad dose was approximately four times higher. Indeed, one Russian magazine article reported that he received 4,400 rem.[5] We can safely assume that shortly after the accident, Zakharov suffered nausea, fatigue, vomiting, and disorientation.

This report describes our reconstruction of the accident based on secondary sources. Our description is consistent with Russian news reports on the subject, as well as third-hand verbal accounts. Section II provides background information on the experiment. Section III describes calculations performed at LANL to understand the technical aspects of the accident. At the time of this writing, we are waiting for the official accident reports to be released by Russian authorities.

Causes of the Accident. According to the Russian press,[6] "Zakharov misjudged the degree of criticality of the breeding system and committed several gross violations of regulations." As we see it, there were three major causes of this accident. The experiment may have been ill fated from the beginning because Zakharov misread the appropriate size of the assembly, which was listed in a notebook that described the old experiment he was attempting to repeat. Second, he disregarded the appropriate procedures and safety regulations. Third, these two mistakes were compounded by an improperly set audible alarm system and Zakharov's unsafe use of the table.

Zakharov made a serious judgment error during this experiment, and his superiors failed to ensure administrative control of the criticality operation. Highly experienced in criticality experimentation, Zakharov knew and yet ignored universally accepted safety rules for hand-stacking operations. He was permitted by his management to repeat an unfamiliar criticality experiment, using only an old, handwritten notebook as a guide, without vetting the experiment to a peer review assessment,[a] without exercising a cautious respect for the multiplying assembly, and without following minimal radiation safety procedures.

Zakharov was a headstrong researcher who performed the dangerous hand-stacking operation without exercising due caution. He was in a hurry to complete this experiment so that he could make some extra money. Rushing, he took shortcuts that circumvented procedure and cost him his life.

The first gross disregard of procedure was for Zakharov to conduct an unfamiliar experiment without having an independent reviewer analyze his procedure beforehand. We concluded from reports on the accident that Zakharov misread (from an old report) the size of the outside diameter of a copper reflector, interpreting a 0 as a 6.[7] Sn calculations we performed indicate that the suspected configuration is highly supercritical, having a $k_{eff} = 1.1$ when fully closed and a $k_{eff} = 1.08$ when the shells are separated by a 1-cm gap.[8] At this level of criticality, the assembly would have dismantled violently. Further calculations

[a] Peer review would have requested calculational estimation of reactivity in the proposed experiment.

reported in Section III show that even a partial configuration of the assembly with a gap is highly supercritical. Because he was using the incorrect outside diameter, this experiment became extremely dangerous.

Zakharov's behavior during the experiment indicates that he was performing it alone, without the help of a professional colleague. His failure to verify the dimensions of the copper reflector leads us to believe that he confused the experiment he was planning to repeat with experiments with which he was familiar. We interpret his words, "I miscalculated," to indicate that he did not suspect a problem either before or during the assembly.[9] Had Zakharov been working with a peer, we believe he would have used the word "we."

It is possible that a technician or guard may have been present before the accident to assist Zakharov with the assembly operation or to safeguard fissile material.[10] This would satisfy security and two-man fissile-material-handling rules common in the US, but press releases state that no one other than Zakharov was present in the bunker at the moment of the accident.[11]

The hand-stacking assembly process is known to be dangerous. Standard procedure requires following a 1/M approach to critical with limits placed on the amount of material and can be added to the assembly in any given step. The proper 1/M approach to critical requires a source and detection, audible warning, measurement, and analysis of the data before proceeding to the next step. A prudent experimenter performing an unfamiliar hand-stacking operation would be cautious and proceed in small steps.

Zakharov believed he was assembling a subcritical assembly. An experienced operator, he rushed to obtain data and ignored the need to be cautious. He may have thought that the assembly table's scram system would protect him were the system to go delayed critical. He did not suspect that the system had the potential to go prompt critical.

The accident may have changed Russian thinking about the use of material protection, control, and accounting surveillance equipment. Before the accident, the Russians did not like the idea of having a camera view the experimental facility to observe people at work, a practice common at the Los Alamos Critical Experiments Facility. The Russians believed that the use of a surveillance camera was an intrusion and suspected hidden spy technology. As a consequence of the accident, the Russians are reevaluating their use of surveillance to enforce their regulations for handling nuclear materials, in particular to enforce the two-man rule, and to enhance response capability in the control room should a problem arise. A camera was reported to have been functional in the experimental area in which the accident occurred. It is unknown, however, whether the video from this camera was recorded .[12]

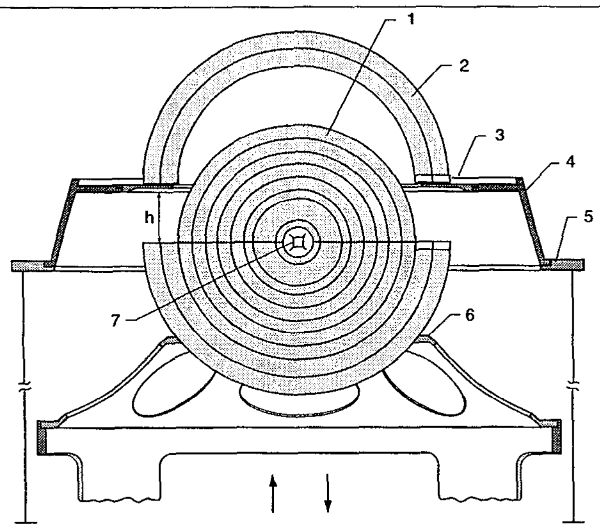
The second major procedural oversight Zakharov made was that he did not use a neutron source in the center of the *"matroshka"* during the hand assembly operation; his reason for this was to minimize the neutron dose to his hands. Because he did not use a source and did not use an audible monitor in the bunker, he did not know how close to critical the *matroshka* assembly was. Mikhailov, in speaking about the accident, reported that the mandatory audible monitor did not function properly.[13]

Safe procedure demands that the neutron source and an audible warning system be used during hand-stacking operations. That Zakharov failed to follow the procedure in this instance indicates his headstrong nature and willingness to violate administrative control. He did not realize that the copper shell he was assembling, perhaps the second of three, would bring the assembly to prompt critical. The lack of a working audible warning signal and the absence of an individual monitoring the assembly for radiation levels leads us to suspect that he was using the assembly table as his safe link and believed that the table would drop as he approached delayed criticality. Did others in the area not wish to assist Zakharov or did he ask them to leave the area as a precaution, knowing he was about to do a dangerous procedure?[14]

The use of a neutron source located in the center of the assembly provides a large neutron population that is easily detected. An increase in the detected radiation level indicates that the assembly is multiplying and system response to geometrical changes is fast and apparent. Without the source, determination that the system is multiplying awaits a stray neutron entering the assembly; a delay that can be on the order of seconds. This delay is longer than the time it takes one to perform a manual operation. Thus, Zakharov may have moved the copper foil above delayed critical without being aware that he had done so.

The third major mistake in procedure was improper use of the assembly table. Properly configured and operational, the table would have minimized the consequences of the accident when the assembly went critical. The fixture on the upper table would have maintained a separation gap and the automatic scram would have rapidly dropped the lower table, bringing the assembly below critical.

We suspect that the assembly machine involved in the accident resembles the machine illustrated in Figure 1. A section of the support bracket, labeled 3 and 4 in the figure, was either not in place and he was using spacers or if it was in place the separation distance, labeled h, was too small to prevent the assembly from reaching prompt critical. For some reason the mechanism to scram the system did not function as designed. Perhaps it was disengaged or perhaps the entire assembly fell and the copper shells partially melted to the shims. In any event, the system did not scram properly, and the assembly remained in a critical state until physically dismantled. These factors are described in more detail in Section II.



Sectional View of the Assembly on the CTF

Numbered parts are identified as follows:

1-lower core unit
2-upper core unit
3-steel diaphagm
4-upper support
5-attachment
6-lower support
7-neutron source

Fig. 1. Schematic of the assembly suspected of being involved in the June 17, 1997 criticality accident at Arzamas-16. The fissile material component is an inner ball consisting of nine nested ^{235}U (90% enriched) shells having a net weight of 44,845.18 grams. A segmented copper reflector surrounds the central fissile ball. The inner fissile ball and a half-portion of the reflector form the lower movable section of the assembly table. The upper fixed section shows a fixture holding the upper-half portion of the reflector. Arzamas described this assembly in several final documents (NEA/NSC/DOC/(95) 03/II, HEU-MET-FAST-018, HEU-MET-FAST-022, HEU-MET-FAST-029) included in the Criticality Benchmark Databank. A. N. Zakharov was listed as an evaluator on the first two of these documents.

Interpretation of the Events. After the accident, Zakharov berated his colleagues, saying, "I told you; the gloves were too slippery."[15] One explanation for this is that the copper shell he was holding slipped out of his hand and came to rest in a position that brought the system to prompt critical.[16] Another plausible explanation is that, in the tradition of Russians involved in prior criticality accidents, he attempted to remove the copper shell after the assembly became critical. To explain his inability to separate the shell from the assembly, he blamed those who had insisted he wear gloves.

Because we strongly suspect Zakharov suffered neural damage, we believe that he was weak, disoriented, and most likely incoherent shortly after leaving the facility. Thus, aside from his words above, he would not have been able to present a detailed description of what happened.

Having ignored more serious safety rules, we do not fully understand why Zakharov wore gloves, which he considered an inconvenience. If slippery, then perhaps the copper shell had been recently machined or had been stored in a greasy compound. It is possible that he wore these gloves to satisfy safety regulations and to protect his hands from possible uranium contamination or low-level alpha radiation. Other possibilities are that he had been handling plutonium for another experiment or that he may have wanted to protect his hands from burrs on the metal parts.

The large radiation dose received to his hands implies that he remained at the assembly for a few minutes after the flash in an attempt to reduce its reactivity. The gloves may have hindered his efforts to remove the top shell immediately after it had fallen, and his lingering near the assembly may have cost him his life. We suspect that the temperature of the system soon became too hot for Zakharov. Fortunately, the heating and resulting thermal expansion reduced the system's reactivity.

His failure to immediately leave the site indicates a sense of duty to his colleagues to do what he could to reduce the assembly's reactivity. Had he left the facility immediately, as US criticality safety operators are instructed to do, the dose to his hands and perhaps to his body would have been considerably lower. We do not know, however, whether the initial prompt dose he received was lethal.

The assembly remained critical for six days following the initial burst. One report stated that it was radiating at a power level of about 0.5 kW. If we ignore thermal conduction and assume that the copper was slightly oxidized (emissivity=0.15), then the assembly temperature was between 800 and 1000°C (see Fig. 2). Because copper melts at a temperature of 1,083°C, we suspect that at the time of the accident some melting of the copper shell occurred. The high temperature and the partial melt probably complicated the efforts of the facility managers to disassemble the critical unit.

A radiating power level of 0.5 kW is the heat produced by 1.6×10^{13} fissions/sec. For this power level, the neutron radiation dose man-equivalent at 1-m distance from a fast metal system (slightly less than 1 MeV neutrons) is approximately 10 rem/sec or 1 rad/sec. Because Zakharov received a dose of 500-800 rads to his whole body (40-cm distance) and a dose of 2000-2500 rads to his hands (25-cm distance), he could not have lingered near the assembly more than 90 sec following the accident. Because he died within three days and probably left the assembly area sooner, we believe he also received part of the prompt burst.

At a 0.5-kW power level, in six days the critical assembly would have produced approximately 8.0×10^{18} fissions, exclusive of the fissions produced during the prompt burst. Thus, we strongly suspect that the room in which the assembly was located was hot, both at the time of the disassembly procedure and for several days thereafter. From the above reported dose rates, we can estimate the number of fissions. Using the values 1.44×10^{-15} rad-air/fission at 2 m[17] and 500 to 800 rads whole body dose at one-half meter, we infer that 8.3 x 10^{16} to 1.3 x 10^{17} fissions may have occurred while Zakharov was close to the assembly.

During the first stage following the accident, the Russians attempted to use equipment imported from abroad to disassemble the multiplying assembly. Unfortunately, radiation in the reactor room damaged the equipment's electronic circuitry.[18]

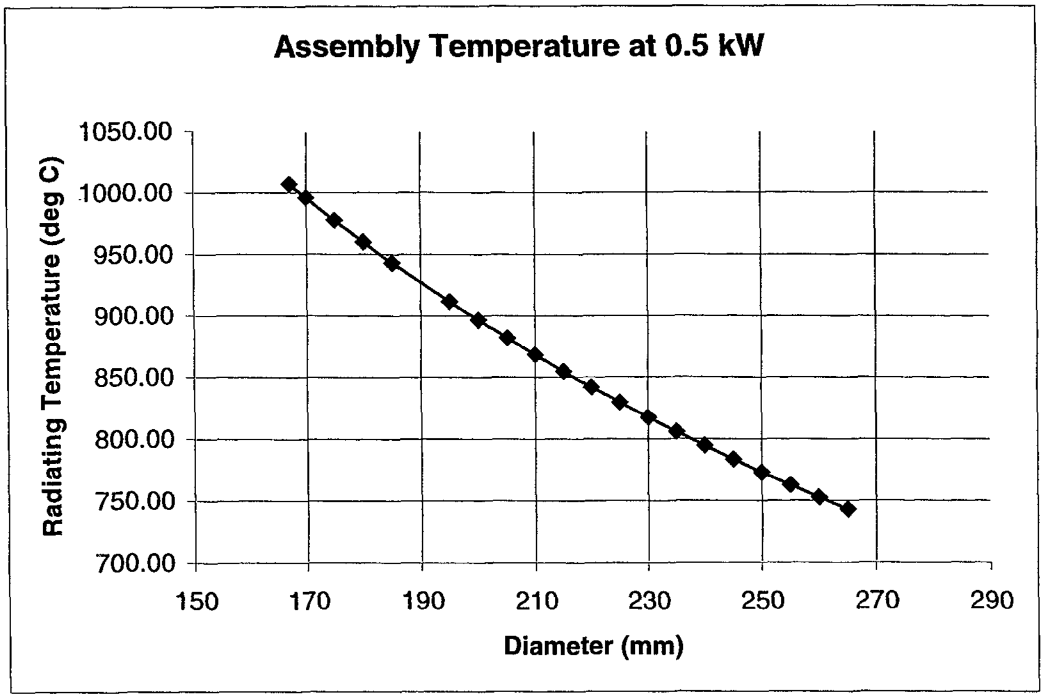


Fig. 2. The dependence of internal temperature on size for a spherical, solid ball radiating one-half kilowatt of power to normal room temperature. The outer surface is assumed to be slightly oxidized copper (emissivity=0.15). Our criticality calculations indicate that the outside copper reflector diameter lies between 167 mm and 202.5 mm (see text).

Reports indicated that a special robot was devised to separate sections of the assembly. If melt did occur, then this operation would not have been easily accomplished with a vacuum fixture designed to pull the upper copper shell away from the unit. Thus, we suspect that portions of the top shell were somehow sheared off.

The Russians informed us that after six days, they were able to stop the reaction.[19] However, the assembly was still near critical ($-\beta_{eff}$). This information supports our suspicion that slight melting of the assembly occurred. According to a Segodnia article, it took the responder teams five tries with robots to normalize the assembly.[20]

Section II. Background

We see strong circumstantial evidence that A. N. Zakharov was conducting this experiment to gather data for a preliminary analysis report for submittal to the International Criticality Safety Benchmark Evaluation Project (ICSBEP) when he was fatally injured in the Arzamas-16 criticality accident that occurred on June 17, 1997. This type of work brings extra money to a cash-starved facility. (LANL visitors to Russia have stated that their Russian hosts firmly state that Zakharov was not working on a military experiment at the time of the accident.)

Zakharov was in a hurry to repeat a series of criticality evaluations in order to satisfy Russian management's concerns that data taken from old reports was accurate and complete. He was not performing new work; he was repeating an experiment performed 25 years ago.[21] The experiment was one of a series whose results would appear in the "International Handbook of Evaluated Criticality Safety Benchmark Experiments." Russian management had overreacted to a previous outside criticism of other Russian data and requested that Zakharov redo the experiments on their list of proposed evaluations. The ICSBEP is an international activity sponsored by DP-45 and managed by Blair Briggs, INEL. The project is paying the Russians for documentation of old criticality experiments. LANL is project lead lab for lab-to-lab information exchanges with Arzamas and Chelyabinsk.

The Handbook is a compendium of data collected internationally from experiments done on critical assemblies. A contract was in place with Arzamas-16 (as was a similar one with Chelyabynsk-70) for approximately $25,000 US. It does not support experimental work.

The contract mandates payments when each of three states is completed. The first stage is a call for a list describing 20 previously performed experiments to be considered for inclusion. Out of the 20 experiments listed, the criticality benchmark selects 7 for inclusion in the database. The second stage is to write a preliminary analysis on selected subset. The third stage is to finalize the preliminary documents for publication. We suspect that Zakharov was repeating an experiment as part of the second phase, following directions of Russian management, who had over-reacted to the scrutiny of prior work. Phase 1 was worth approximately $5,000 and phase 2 was worth about $12,000.

In mid-May, the crew at Arzamas-16 (A. N. Zakharov was one of the authors) submitted the "List of VNIIEF-Experimental Critical Assemblies Proposed for Benchmark Critical Assemblies Databank." The list was deliverable phase 1 under Contract No. B70240017-35 (between LANL and VNIIEF) and Contract No K97-176997 (between LMITCO and VNIEEF). A group of 30 experiments were listed for potential inclusion in the database. A copy of this deliverable is presented in Appendix 1.

On June 11, 1997, LANL sent Arzamas-16 management its seven choices.[+] One of the choices, experiment 17, was ^{235}U (90% enriched) (28/167) + Cu (167/265),[*] the experiment during which we suspect the accident occurred. Results of post-accident calculations (presented in Section III) indicate that this configuration is highly supercritical. On September 24, 1997, V. Yuferev of Arzamas-16 sent LANL preliminary analysis reports for the 7 chosen experiments. Experiment 17 had been removed from the list and in its place experiment 29 had been substituted.[∇]

[+] A selection of e-mail correspondence is attached as Appendix 2.

[*] Dimensions are diameters in units of millimeters.

Section III. Calculations Of The Accident

We have performed a series of Sn and Monte Carlo calculations on ^{235}U (90% enriched) uranium balls reflected with a copper shell. We are able to describe some of what happened without a full knowledge of the actual geometry. The results of these calculations strongly support our suspicions that Zakharov was redoing experiment 17. This experiment had been proposed by VNIEEF and accepted by the US for eventual inclusion in the Handbook. Zakharov was a member of a Russian team that had plans to visit the US in early September 1997.

We ran an MCNP Monte Carlo calculation of experiment 17 using ENDF/B-VI Rev. 3 cross-sections. Values for the uranium composition were taken from a previously documented final benchmark report written by investigators from VNIEEF.[22] The copper was assumed to be pure. This calculation predicted $k_{eff} = 1.0947 \pm 0.0006$, a value so large that the assembly would have violently disassembled. Because the Russians reported that the assembly held together following the accident and that Zakharov was not killed instantly, we believe that the accident assembly could not have been fully configured with an outer copper reflector shell having a diameter equal to 265 millimeters.

For a critical assembly to remain intact, its k_{eff} cannot exceed 1.0088.[#]

To explore how reactive possible assembly configurations were, we ran a series of ONEDANT calculations. The calculations included an air gap between the upper and lower sections of the outer copper shell. Results are shown graphically in Figures 3 and 4.

Figure 3 is a plot of the gap width as a function of reactivity for the 265-mm shell. For this configuration, we expect the critical assembly to be prompt critical (reactivity at 100 cents) at an approximate spacing of 50 mm, and to vaporize at a spacing closer than 48 mm (reactivity of 120 cents.)

Figure 4 shows similar behavior for a 205-mm outer diameter shell. For this case, vaporization will occur at a gap spacing closer than 4 mm. This configuration is to be contrasted with the summary work statement for Experiment 17 (see page 3 Appendix 1). With the 205-mm diameter outer copper reflector, the assembly has a multiplication of 131 at a separation of 2 mm.

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[*] β_{eff} is assumed to be between 0.0067 and 0.074. An assembly that has a worth (worth in dollars = $[k_{eff} - 1]/ k_{eff}*\beta_{eff}$) greater than \$1.15 will melt. If its worth is above \$1.20, the assembly will begin to vaporize and the assembly will burst apart. Because the Russians reported that the assembly held together after the accident and had to be manually disassembled, we have imposed the approximate condition $k_{eff} < 1 + \beta_{eff} \times 1.15$.

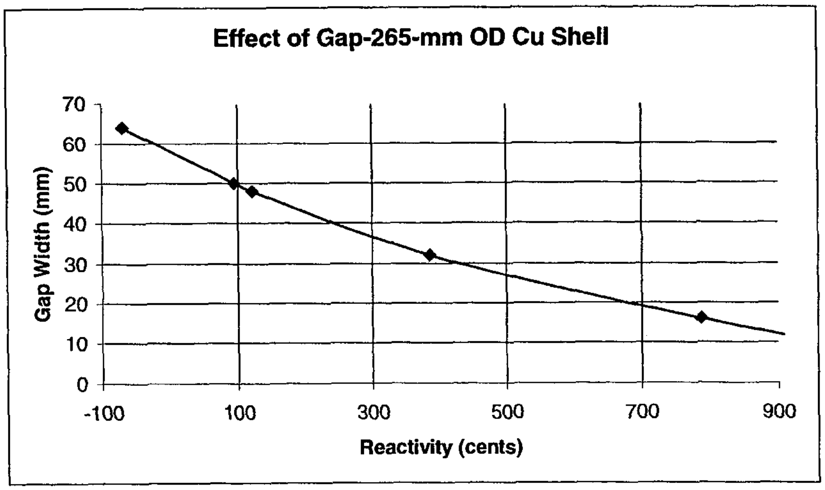


Fig. 3. Results from a ONEDANT calculation that simulated the effect of a gap in the outer copper reflector upon reactivity.[23] The configuration's nominal outside diameter with no gap is 265 mm. Reactivity is measured in cents, where β_{eff} = 0.007.

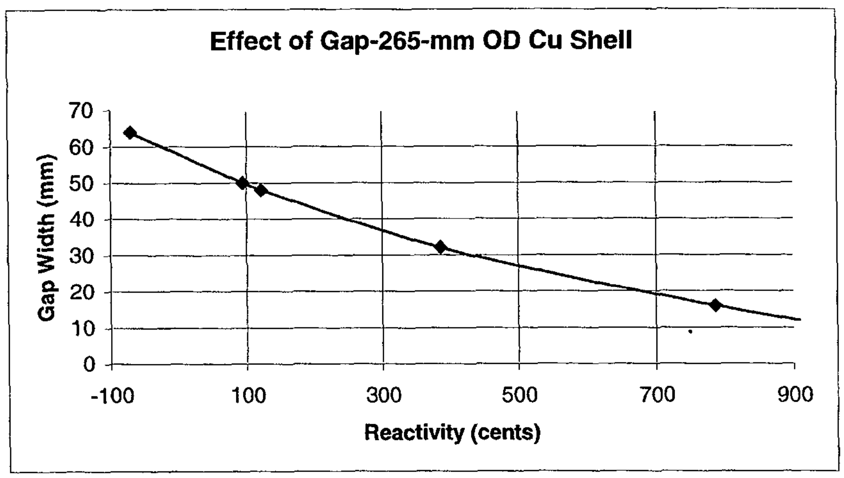


Fig. 4. Results from a ONEDANT calculation that simulated the effect of a gap in the outer copper reflector upon reactivity.[24] The configuration's nominal outside diameter with no gap is 205 mm. Reactivity is measured in cents, where β_{eff} = 0.007.

We continued the study and used interpolation on a bracketing series of MCNP Monte Carlo k-calculations. Compositions for the inner ^{235}U (90% enriched) ball were taken from a final report in the Handbook on an equivalently sized ball that VNIIEF personnel submitted in August 1996 to the ICSBEP.[25] This ball has a 28-mm-diameter internal void and a 167-mm outer diameter. The study (see Fig. 5) indicates that if the assembly were a complete sphere with upper and lower sections having the same diameter, then the outer diameter of the copper shell could not have exceeded 202.5 mm.

Zakharov was assembling the second-to-last copper reflector when the assembly went critical.[26] The lower hemi-shell was overloaded when he added the upper shell.[27]

Using the same ^{235}U (90% enriched) ball described above, we explored with MCNP the reactivity of assembly configurations in which the lower section is a copper reflector shell with outside diameter equal to 265 and the upper section is a copper shell of smaller diameter. We present a summary of results in Table I and Figure 6. From Figure 6 we infer that to remain below prompt critical, the maximum outside diameter for the upper shell is 174.5 mm with no separation, and about 177 mm with a 2-mm gap. These shells weigh 3 to 5 pounds. Use of a thicker shell would have increased the reactivity above prompt critical.

Clearly this experiment as we have configured it is highly reactive. Based on early rumor, we ran ONEDANT calculations for a series of solid ^{235}U (90% enriched) cores reflected by 2.6- and 2.9-cm-thick copper reflectors.[28] A 35.24-kg core reflected by a copper shell 2.6 cm thick is just at delayed critical ($k_{eff} = 1$), while adding three additional mm makes it highly super critical ($k_{eff} = 1.009995$). We estimate that the central 28-mm-diameter void reduces k_{eff} by 0.00042.

We anticipate receiving the Russian report that accurately documents and assesses the accident. However, we do know now that whatever details we may be lacking, this experiment required more care than was given. Sloppy procedure caused a fatal accident.

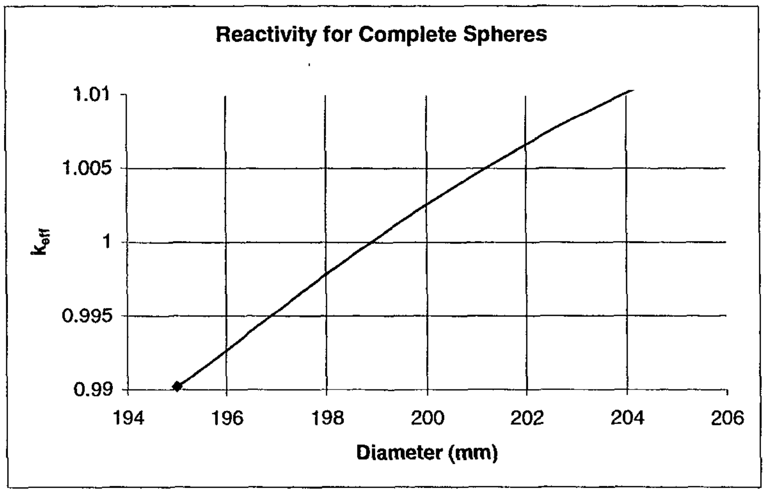
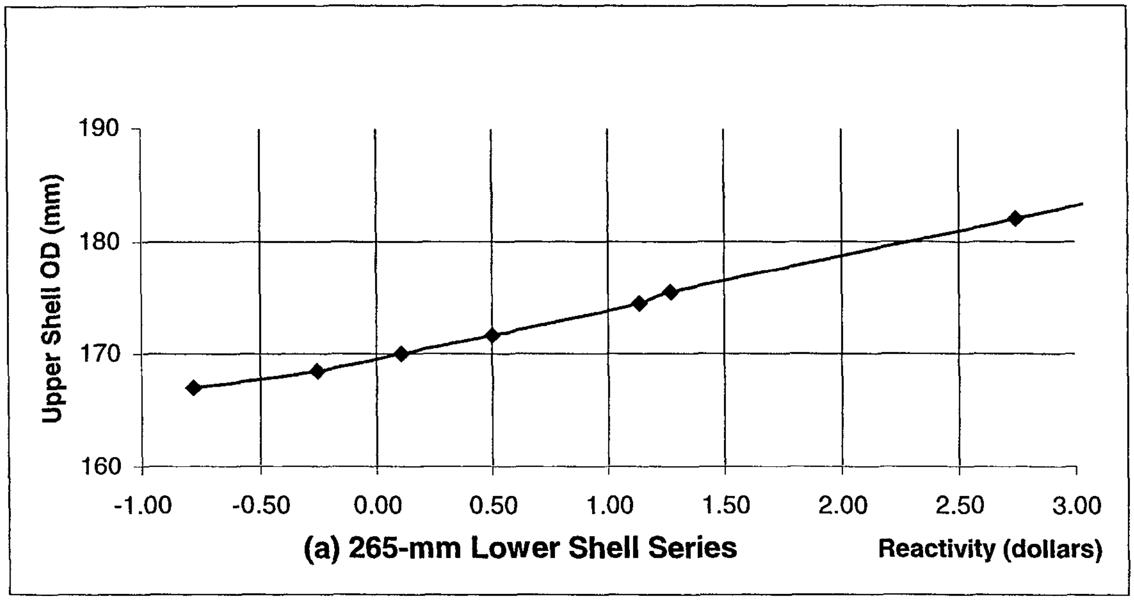


Fig. 5. Graph of Monte Carlo calculation to show how k_{eff} for the assembly depends upon the diameter (thickness) of the copper reflector. The core surrounded by the reflector is a spherical ^{235}U (90% enriched) annular ball. Its internal diameter is 28 mm and its external diameter is 167 mm.



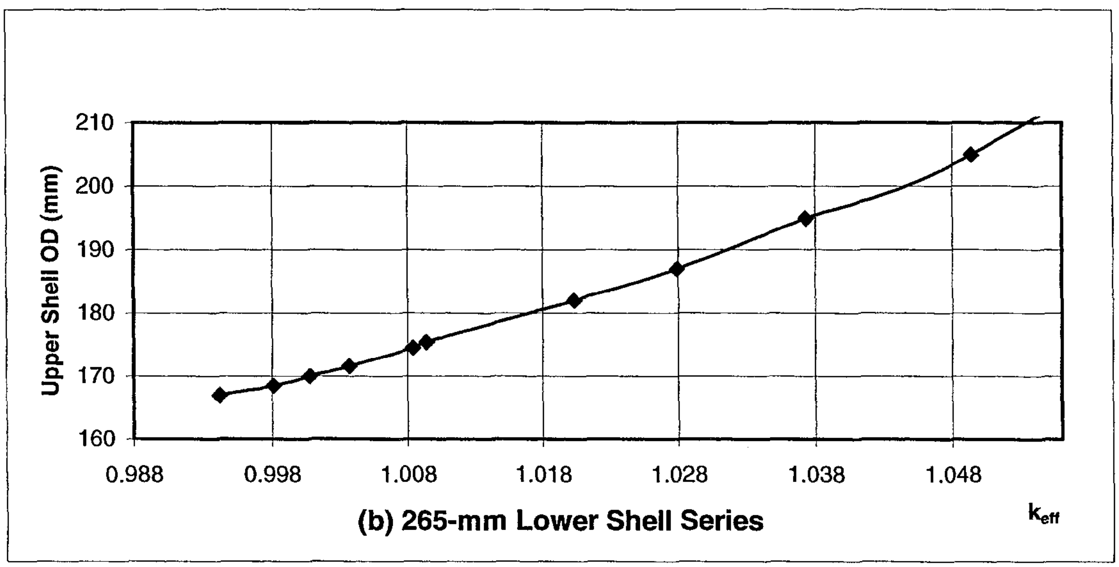


Fig. 6. Graph of Monte Carlo calculation indicating how **(a)** the reactivity (β_{eff} = 0.007) and **(b)** k_{eff} of an assembly reflected by a split copper reflector depends upon the diameter of the upper section. The lower section diameter is held constant at 265 mm. The sections are closed with no gap. The effect of a 2-mm gap is to reduce reactivity about 50-58 cents. The core is a spherical ^{235}U (90% enriched) annular ball. Its inside diameter is 28 mm; its external diameter is 167 mm.

Table I. MCNP (ENDF/B-VI) k_{eff} results for a ^{235}U (90% enriched) core (inner diameter 28 mm, outside diameter 167 mm) reflected by a copper reflector.

Upper OD (mm)	Lower OD (mm)	Upper Copper Thickness (mm)	Lower Copper Thickness (mm)	Separation (mm)	k_{eff}
195	195	14	14	2	0.9878 +/- 0.0006
205	205	19	19	2	1.0054 +/- 0.0006
265	265	49	49	2	1.0887 +/- 0.0006
195	265	14	49	2	1.0332 +/- 0.0006
195	195	14	14	0	0.9902 +/- 0.0006
195	205	14	19	0	1.0014 +/- 0.0006
205	205	19	19	0	1.0117 +/- 0.0006
167	265	0	49	0	0.9942 +/- 0.0006
169.5	265	1.25	49	0	0.9981 +/- 0.0006
170	265	1.5	49	0	1.0008 +/- 0.0006
171.65	265	2.325	49	0	1.0037 +/- 0.0006
174.5	265	3.75	49	0	1.0084 +/- 0.0006
175.5	265	4.25	49	0	1.0094 +/- 0.0006
182	265	7.5	49	0	1.0203 +/- 0.0007
187	265	10	49	0	1.0279 +/- 0.0006
195	265	14	49	0	1.0373 +/- 0.0006
205	265	19	49	0	1.0494 +/- 0.0007
265	265	49	49	0	1.0947 +/- 0.0006

NOTE: Radius of HEU sphere = 8.35 cm

NOTE: The reflector has been split into an upper and a lower section. Several calculations indicate the effect of a gap in the copper. Other calculations indicate the effect of varying the diameter of the upper copper shell when the lower copper shell is sized at 265 mm. Russell Mosteller of Los Alamos National Laboratory performed these calculations.

Acknowledgements

I wish to express my appreciation to several LANL staff members. Rick Patternoster provided me the initial details of the accident; Robert Kimpland and Russell Mosteller performed the Dant and MCNP calculations, respectively; and Denise Pelowitz provided the information that appears in Appendix 1. Ron Knief of Ogden Associates brought my attention to the Segodnia article. The article confirmed our conclusions in this paper.

Appendix 1
Arzamas-16 – Los Alamos National Laboratory Criticality Benchmark Databank Documents Covering Work by Zakharov and Colleagues

List of VNIIEF-Experimental Critical Assemblies Proposed for "Benchmark Critical Assemblies" Databank

(deliverable 1 under Contract No. B70240017-35 between LANL and VNIIEF and Contract No. K97-176997 between LMITCO and VNIIEF)

M.V. Gorbatenko, V.P. Egorov, V.P. Gorelov, V. G. Zagarov,
A.N. Azkharov, V.I. Il'in, M.I. Kuvshinov, and V.I. Yuferev

1. General Description of Assemblies

Each assembly includes a sphere-shaped core of metallic fissile material surrounded by a spherical reflector, the layer immediately adjacent to the core surface.

Individually, the core and reflector components are shaped as hemispherical shells ~1 cm thick for the core and 1 to 5 cm for the reflector. There are some hemispheres having a hole of ~1 cm radius to be plugged with the shell material.

The assembly constitutive materials have near-standard density.

Assemblies similar in composition and configuration are reported in [1], [2].

2. Experimental Conditions

Experimental conditions are identical to those described previously for studies included in the handbook [2].

The experiments were run using a specialized stand [3]. The stand was in the experimental hall with thick concrete walls to surround it. With this stand, a critical system was assembled of two units, each being obviously subcritical. The upper unit had been put on a steel annular diaphragm or rope-suspended from a crane in a fixed manner. The diaphragm thickness was 0.1-0.4 cm. The lower unit was laid on loosely on a cone- or cylinder-shaped support and movable in vertical direction.

The assembly material for its major part was concentrated in the lower unit. The upper unit included 1 to 3 hemispheres. This would allow lower sensitivity for the system subcriticality to the gap size between the fixed and movable units.

The units were brought together with a neutron source present.

The measurements included the neutron multiplication factor or reactivity as related to the gap size between the assembly units. The assembly design had been selected so that the criticality state would be achieved at/near complete closure of the units to make up a spherical geometry.

Critical dimensions of the assembly were determined by extrapolating the reactivity or inverse neutron multiplication factor of the source in the assembly center Q, as a function of the slit size between units, to a spherically symmetric geometry.

The change from a real critical system, having within it production tolerances density variations and different enrichment by fissionable nuclides for its component materials, clearances and additional reflectors due to stand equipment and surrounding walls, to an idealized system having spherical shape and the core and reflector materials of bulk-uniform density, proceeded using corrections as appropriate, the latters were found experimentally by considering the following contributions to the system subcriticality:

- lower support and diaphragm,
- slit size between units,
- adding a plug, if needed, to a hemisphere.

In particular,

- the lower support contribution to the system subcriticality was measured through adding the same support to the upper part of the assembly;
- the subcriticality versus slit size measurements were made for each assembly;
- the diaphragm contribution to subcriticality was considered by additional experiments where the upper assembly unit was held by a crane rope and then the data were compared with the same assembly on the diaphragm.

With the above-mentioned corrections, the prediction error fof system critical dimensions is estimated to be within (0.1-0.5)% in terms of k_{eff}, effective multiplication factor.

3. Materials in Use

The following materials were used by the assembly cores:

- uranium of ~90% enrichment in U-235;
- uranium of ~36% enrichment in U-235;
- delta-phase plutonium of ~89% enrichment in Pu-239;
- delta-phase plutonium of ~98% enrichment in Pu-239;
- alpha-phase plutonium of ~89% enrichment in Pu-239.

The reflectors used materials that are frequently used in handling fissile materials and essential in terms of nuclear safety problems, as follows: steel, aluminum, copper, lead, titanium, boron, uranium-238, polyethylene. In application to nuclear safety considerations, the latter may serve as water simulator.

4. List of Experimental Critical Assemblies

Table 1. Q-neutron multiplication central source, H-slit between units.

N	Composition (parenthesized-enrichment, ID and OD in mm)	Q	H, mm
1	$^{239}Pu(\delta, 98\%)(63/135)+Fe(135/183)$	385	1
2	$^{239}Pu(\delta, 98\%)(63/135)+Al(135/200)$	137	0
3	$^{235}U(90\%)(80.4/167)+CH_2(167/500)$	244	3
4	$^{235}U(90\%)(63/167)+CH_2(167/440)$	1370	0
5	$^{235}U(90\%)(80.4/183)+Fe(183/245)$	147	3
6	$^{235}U(90\%)(63/183)+Fe(183/220)$	238	4
7	$^{235}U(90\%)(93.2/183)+Fe(183/600)$	1130	9
8	$CH_2(20/135)+^{235}U(90\%)(135/183)+CH_2(183/440)$	>1000	0
9	$CH_2(28/135)+^{235}U(90\%)(135/183)+CH_2(183/500)$	909	3
10	$CH_2(28/80.4)+^{235}U(90\%)(80.4/151)+CH_2(151/500)$	238	3
11	$^{235}U(90\%)(28/167)+Fe(265/460)$	>1000	-
12	$^{235}U(90\%)(28/167)+Fe(183/245)$	238	-
13	$^{235}U(90\%)(28/183)+Fe(430/500)$	239	-
14	$^{239}Pu(\delta, 98\%)(28/120)+Cu(120/152)$	1887	5
15	$^{239}Pu(\delta, 98\%)(28/120)+Pb(120/183)$	200	1
16	$^{239}Pu(\delta, 98\%)(28/120)+B^{10}(120/183)$	500	1
17	$^{235}U(90\%)(28/167)+Cu(167/265)$	131	2
18	$^{239}Pu(\delta, 98\%)(20/120)+Ti(120/183)$	200	1
19	$^{239}Pu(\delta, 98\%)(20/93.2)+^{238}U(93.2/500)$	108	4
20	$^{239}Pu(\delta, 89\%)(20/107)+^{238}U(107/183)$	308	1
21	$^{239}Pu(\alpha, 89\%)(20/80.4)+^{238}U(80.4/500)$	135	2
22	$^{239}Pu(\delta, 98\%)(20/120)+^{238}U(120/135)$	758	1
23	$^{239}Pu(\delta, 98\%)(20/93.2)+^{238}U(93.2/151)$	276	1
24	$^{235}U(36\%)(20/265)+^{238}U(265/330)$	427	4
25	$^{235}U(90\%)(20/63)+^{239}Pu(\delta, 98\%)(63/93.2)+^{235}U(90\%)(93.2/167)$	330	1
26	$^{235}U(90\%)(20/151)+^{238}U(151/245)$	188.7	1
27	$^{235}U(90\%)(20/151)+^{238}U(151/230)$	362	1
28	$^{239}Pu(\delta, 98\%)(20/93.2)+^{235}U(90\%)(93.2/120)+^{238}U(120/183)$	>100	1
29	$^{235}U(90\%)(20/120)+^{238}U(120/183)+^{235}U(90\%)(183/245)$	>100	1
30	$^{238}U(20/183)+^{235}U(90\%)(183/245)+^{235}U(36\%)(245/300)$	>100	1

As compared with the assemblies described in [2], the list of assemblies in Table 1 includes cases with

- more complex geometry, larger central volume (assemblies 1-7), hollow space between the core and reflector (assemblies 11-13), hollows filled with polyethylene (assemblies 8-10);
- new reflector materials (copper, lead, titanium, boron assemblies 14-18);
- thick reflector of uranium-238 (assemblies 20, 21, 24, 26, 27);
- composite core using different materials (assemblies 22, 23, 25, 28-30).

The tabulated assemblies all have multiplication factor above 100.

It is opinion that for the purposes of "Benchmark Critical Assemblies" Databank, the more preferable out of the Table 1 list may be assemblies 3, 5, 8, 10, 14-18, 22-24, 25, 27, 28.

5. Reporting Documents

Our reports on the picked 7 assemblies will cover

- description of the test stand for critical systems and experimental procedures;
- description of assemblies used by experiments;
- data obtained by experiments;
- extrapolation procedure from real experimental data (involving clearances, variable density, etc.) to critical systems of ideal geometry and composition uniformity;
- data on idealized critical systems of spherical geometry and bulk-uniform density of core and reflector materials.

The documents will be delivered in format as required by standards specified for information to be published in the book "Benchmark Critical Assemblies."

6. References

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Appendix 2
E-mail Correspondence

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.om: Denise Pelowitz
Date: Wed Jun 11 17:47:45 1997
To: Yuf_2120@spd.vniief.ru
Subject: Re: benchmark

Dear Vladimir,

     Houts and I have reviewed your list of experiments and have chosen seven
     o be evaluated by the VNIIEF staff.  Our choices include several
c    .gurations with different reflector materials than those that have been
evaluated before and several that combine Pu with U-238 reflection.

Our choices included the following cases (using the numbering system you
provided):

 2      239Pu(d,98%)(63/135)+Al(135/220)
14      239Pu(d,98%)(28/120)+Cu(120/152)
17      235U(90%)(28/167)+Cu(167/265)
18      239Pu(d,98%)(20/120)+Ti(120/183)
21      239Pu(a,89%)(20/80.4)+238U(80.4/500)
22      239Pu(d,98%)(20/120)+238U(120/135)
23      239Pu(d,98%)(20/93.2)+238U(93.2/151)

Let us know if, for any reason, these choices are not acceptable.

We look forward to continuing our collaboration with you and your VNIIEF
specialists.  Your benchmark evaluations continue to be a valuable reference for
the world criticality-safety community.


Sincerely,

Denise Pelowitz, LANL
dbp@lanl.gov

************

> " "m: Michael Houts <u102822@beasley.lanl.gov>
      'ect: Re: benchmark
      dbp@lanl.gov, houts@lanl.gov

> Dear Vladimir,
>
> We received your E-Mail - unfortunately I have been out of the office for
> nearly three weeks and have not been able to respond.  Denise Pelowitz and
> I will review the list, and select the 7 assemblies by tomorrow.  We're
> looking forward to the new evaluations!
>
> Sincerely,
>
> Mike
>
> >Michael Houts, LANL
> >houts@lanl.gov
> >
> >Subject: Agreement B70240017-35
> >
> >Dear Mike.
> >
> >In the middle of May we sent you "List of VNIIEF-
> >experimented Critical Assemblies Proposed for "Benchmark
> >Critical Assemblies" Databank" prepared under the first
> >stage of contract B70240017-35.
> >In accordance with the contract you must select 7
> >assemblies for the following analysis and then to report
> >the results to us. B. Briggs has performed that kind of
> >work on his contract and we are preparing the materials
> >for him.
> '" ask you to report if you received my E-mail with a list
`     critical assemblies and also to report your selection
      7 assemblies. Lack of information from you strongly
  >.iold up our work.
> >
> >Best Regards,
> >
> >V. Yuferev
>
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..om: Supervisor
Date: Wed Sep 24 06:45:50 1997
To: houts@lanl.gov
Subject: benchmark

Mike Houts, LANL
Denise Pelowitz, LANL

Dear Mike and Denise.

1) We have prepared all the 7 reports under the contr-ct for presenting them to collected benchmark critical assembles. At present the reports are in the stage of their approval. After completing this procedure (beginning of October), materials of 7 benchmarks will be directed to you by Federal Express.
2) In a list of the assembles you selected we ask you to make replacements for 2 assembles. Instead of the assemble with a number 17 (U(90%)+Cu) we have prepared the other assemble U(90%)(20/167)+Pb(167/232)), and instead of the assemble with a number 18 (Pu+Ti) the other assemble U(36%)(40/245)+CH2(245/360). In our opinion, the offered assembles are more suitablo for the collection of benchmarks having a more detail description and accuracy of forecasting in the critical and accuracy of forecasting in the critical state.

Best regards V.Yuferev

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Los Alamos
NATIONAL LABORATORY
Los Alamos, New Mexico 87545