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The Chicago Piles unearthed

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The divergence of the Chicago Pile 1 (CP-1) on December 2nd, 1942 marks the birth of the nuclear age. CP-1 was the first nuclear reactor, conceived as a proof-of-principle physics experiment to demonstrate the feasibility of a self-sustained neutron chain reaction. After only three months of operation, CP-1 was dismantled due to safety reasons and rebuilt at the Argonne Site, under the name of Chicago Pile 2 (CP-2). CP-2 had a longer life, contributing vastly to research on material science and nuclear reactor theory, and was finally decommissioned in 1954. These astonishing scientific artifacts remain poorly characterized, in spite of their pivotal historical role. Here, we fill this gap by building fully detailed three-dimensional digital twins of CP-1 and CP-2 using TRIPOLI-4, the Monte Carlo particle transport code developed at CEA, based on the aggregation of information retrieved from published and unpublished documents of the Manhattan Project. Simulation results faithfully reproduce the available experimental measurements and shed light on the early development of fuel and moderator materials.

The Chicago Pile number 1 (CP-1) was the first nuclear reactor, conceived by Enrico Fermi and his collaborators as a proof-of-principle physics experiment to demonstrate the feasibility of a self-sustained neutron chain reaction. The pile consisted of a stack of alternating layers composed of 'dead' graphite bricks, acting as moderator, and 'live' graphite bricks with two drilled holes, each containing a fuel lump of natural uranium, and arranged to form a cubical lattice. The idea of using graphite as a moderator originated in 1939, after previous experiments had shown that light water was unsuitable due to its high neutron absorption rate[1,2]. The fuel lumps were of several shapes (cylinders and specially designed 'pseudo-spheres') and materials (black oxide (U_3 O_8), brown oxide (UO_2), and metal uranium), with various grades of purity. The graphite had also various grades of purity, depending mostly on the parasite boron content. In order to put the best materials as close as possible to the center of the pile and thus optimize the neutron balance, the overall shape of CP-1 was planned as a sphere with an inner metal uranium core (which was available only in modest quantities when the construction of CP-1 was started), an outer uranium oxide core, and an external shell of graphite acting as a neutron reflector. Due to the spherical shape, it was necessary to build a honeycombed wooden scaffold and an external wooden casing, and a graphite pier was used to stabilize the structure and ensure that the control rod slots traversing the pile horizontally did not warp under the weight of the layers above.

The construction of CP-1 took slightly over two weeks, from November 16th to December 1st 1942, but the pile itself was actually the culminating point of a long series of carefully designed and repeated experiments on smaller sub-critical configurations (the 'exponential' piles) aimed at determining the critical dimensions of the full-scale pile and the nuclear parameters of uranium-graphite lattices with varying pitch and fuel/moderator properties. The construction of the exponential piles took place over several months, first in the Schermerhorn Hall at Columbia University in New York and then in a racquets court under the West Stands of the Stagg Field stadium at the University of Chicago within the framework of the Metallurgical Laboratory, and was complemented by a collection of material-testing assemblies (the 'sigma' piles), designed to probe the nuclear properties of various graphite lots. According to the original plans, CP-1 should have been erected at the Argonne Site, conveniently located far from Chicago downtown: contrary to the exponential piles, which were inherently sub-critical, CP-1 was designed to be slightly above critical with all rods out (ARO) and thus presented a considerably higher risk for the scientists and for the population. However, a workers' strike broke out at Argonne mid-October, and to avoid delays it was decided to go ahead with the construction in the racquets court of the Stagg Field, where the exponential piles had been previously built, so strong was the urgency of completing the critical pile for the needs of the Manhattan Project.

During October and November 1942, a 'factory' was established close to the hall where CP-1 was going to be built, and the production of the graphite bricks and of the fuel lumps was standardized. Graphite was delivered from various manufacturers in blocks of different sections and lengths, which were cut into bricks of regular size. Uranium was delivered in the form of brown oxide UO_2 (but stocks of black oxide U_3 O_8 were reused from earlier experiments in the exponential piles, due to lack of material) and metal. The brown oxide was pressed into pseudo-spheres using special dies designed by Walter Zinn to obtain an approximately spherical shape, which is optimal for the neutron balance. Cylinders of pressed brown and black oxide were also reused from previous

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experiments. Metal uranium was cast in the form of cylinders by three manufacturers. In order to accommodate the fuel lumps, two holes were drilled into the graphite bricks.

Thanks to the delivery of increasingly purified materials (for both fuel and moderator), the critical conditions of CP-1 were met earlier than originally planned (57 completed layers instead of 75), and the final shape of the reactor was therefore closer to an oblate ellipsoid than to a sphere, having a polar radius of about 309 cm and an equatorial radius of about 388 cm. The completed pile contained about 40,000 graphite bricks (350 metric tons used as moderator and reflector) and about 20,000 fuel lumps (32.9 t of brown oxide, 3.7 t of black oxide, and 5.6 t of metal uranium).

The divergence of CP-1 on December 2nd 1942, marked the birth of the nuclear age: under the guidance of Enrico Fermi, from the balcony of the hall where the pile stood, George Weil withdrew a few extra centimeters of the control rod number 21 (a simple wooden stick covered with a cadmium sheet) and made the reactor slightly super-critical. The neutron population was left free to grow exponentially for about half an hour, with an estimated peak thermal power of 0.5 W, then the safety rods were inserted and the pile was shut down.

After about three months of testing, including some experiments conducted at 200 W to probe temperature effects, the operation of CP-1 was officially terminated on February 28th 1943, mainly due to safety reasons, since the pile had no radiation shielding nor cooling system. The bricks of CP-1 were moved to Argonne Site A, and a new reactor was assembled there in an approximately cubic shape of 6.5 m on the side. The new pile also used newly delivered materials (in particular, metal uranium and high-quality graphite): the entire operation was carried out in 21 days. A few photos of the rebuilt pile, which was named CP-2, have survived. The completed pile included 54 layers, corresponding to about 430 t of graphite and 17 700 fuel lumps (about 38 t of uranium oxide and 9 t of metal uranium)[3]. On March 20th 1943, the pile went critical and began operation. Thanks to a number of experimental facilities (including a thermal column, a neutron chopper and a control rod oscillator), CP-2 contributed outstandingly to research activities related to nuclear material testing until May 1954, when the pile was finally decommissioned.

The fascinating story of CP-1 (and to a somewhat lesser extent of CP-2) has been told by several authors, in view of the prominent place that these technological artifacts have in the history of science[4–8], and many accounts exist based on the personal reminiscences of the protagonists of those events[9–16]. Yet, the Chicago Piles have not ceased to attract research efforts focused on both historical and technical aspects, especially in connection with the retrieval of previously inaccessible or forgotten reports[17–19]. It seems fitting, on the occasion of the eightieth anniversary of the Chicago Piles, to celebrate them by revisiting their features using modern high-fidelity simulation codes and nuclear data libraries. For this purpose, we have developed fully detailed three-dimensional models of the two piles using the Monte Carlo code TRIPOLI-4®, developed at CEA[20], and compared our simulation results to existing experimental measurements and estimates made by Fermi and his group based on diffusion theory. Central to this investigation is the knowledge of the geometry and material compositions of CP-1 and CP-2: data required for the TRIPOLI-4 models have been retrieved from published and unpublished documents of the Manhattan Project.

Results

Characterizing the nuclear materials of the piles

In the CP-413 report, where the construction of CP-1 is detailed, Fermi wrote[21]:

> The exceptionally high purity requirements of graphite and uranium which were needed in very large amounts probably made the procurement of suitable materials the greatest single difficulty in all the development.

This is a rather bold statement concerning CP-1. In some respects, eighty years later we might similarly say that reconstructing the geometry and the material compositions of CP-1 based on the available documentation is the major difficulty of building a Monte Carlo model of the pile. For this purpose, we have cross-referenced CP-413 report, which includes a few plans of the completed pile, and several technical reports included in Ref. [1]; complementary pieces of information have been inferred based on the 'Neutronic reactor' US patent by Fermi and Szilard[22], and on the photos of the partially completed layers of the pile.

The first step towards the development of a Monte Carlo model of CP-1 consists in creating a database of materials, including the dead bricks, the live bricks, and the various structures of the pile. Unfortunately, the descriptions in the documents available from the archives of the Manhattan Project are far from exhaustive. Several assumptions are then required in order to fill the gaps and conjecture the shape, density and isotopic compositions of many key components of CP-1. Once the material properties have been calibrated, the full pile is built as a collection of elementary units.

The basic units of the uranium-graphite lattice were dead and live bricks of two sizes: most of them had a square section of side 10.4775 cm ($4^1/_8\ in$) and a length of 41.91 cm ($16^1/_2\ in$), and were designed to ensure the required lattice pitch of 20.955 cm ($8^1/_4\ in$) throughout the pile; a few (reused from previous experiments in the exponential piles with a different lattice pitch) had a square section of side 10.16 cm (4 in) and a length of 30.48 cm (12 in), and were placed in the periphery of the pile.

For our model of CP-1, given the lack of knowledge on the exact number and precise position of the bricks, and in view of the slight difference in dimensions between the two kinds of bricks, we consider the model to be a regular cubical lattice, with a pitch of 10.4775 cm. In order to accommodate the fuel lumps, two holes of a diameter of 8.255 cm ($3^1/_4\ in$) were drilled into the graphite bricks, separated by 20.955 cm ($8^1/_4\ in$). The geometry and material specifications of the graphite and of the fuel lumps can be inferred from report CP-413[21]. Based on the technological data reported in CP-413[21], we have built Monte Carlo models for the dead and live bricks using TRIPOLI-4. The holes in the graphite bricks and the fuel elements have been carefully represented, including minute details such as the bottom part of the hole and the exact shape of the pseudo-spheres. Some of the resulting models are illustrated in Fig. 1.

The properties of the uranium-graphite lattices were extensively tested prior to the construction of CP-1 through a painstaking series of *exponential* piles. For each lattice type, with given fuel lump shapes and graphite brands, Fermi's group measured the infinite multiplication factor k_∞, i.e. the ratio of the number of neutrons produced by fission to the number of neutrons lost through absorption in a single fission-chain generation. This quantity was used to infer the critical size, i.e. the radius of a spherical reactor with the same lattice that would enable a self-sustaining chain reaction. The moderating properties of graphite were separately tested in the *sigma* piles, aimed at measuring the migration area L^2, i.e. the average squared as-the-crow-flies distance between the birth point and the death point of a neutron, which was key in determining the optimal lattice spacing. These measurements provide invaluable data against which the Monte Carlo models of the dead and live bricks can be calibrated.

For each sigma pile, we have built a simplified TRIPOLI-4 model, i.e. a large graphite box with reflecting boundary conditions and a thermal neutron source. For each exponential pile, we have similarly built the corresponding simplified 'infinite lattice' model for TRIPOLI-4, i.e. a very large lattice with reflecting boundary conditions. In order to calibrate the parameters of the Monte Carlo models, we have two sets of experimental data, i.e. the migration area and the infinite multiplication factor, and two sets of unknowns, i.e. the amount of impurities in the moderator and in the fuel. For the moderator, we have explicitly included in our Monte Carlo models two kinds of neutron-capturing impurities: nitrogen related to the air saturating the pores of the graphite, and natural boron (the isotopes ^{10}B and ^{11}B being present with their standard 19.9 : 80.1 ratio). The amount of air (whence nitrogen) in our models has been determined based on the nominal values of the brick densities, compared to the standard density of pure carbon (taken to be $2.123\mathrm{g\,cm^{-3}}$), which allows estimating the porosity. Natural boron was known to be by far the most relevant impurity in graphite. The amount of impurities in the fuel has been represented (due to lack of detailed specifications) by an 'equivalent' ^{10}B boron concentration. In order to compute the boron content of the various combinations of graphite brands and fuel types, we have followed a two-step procedure.

First, we have run a series of TRIPOLI-4 simulations for the sigma pile models, adjusting the concentration of boron in the graphite to fit the experimental migration area. This determines the material compositions of all graphite types. Overall, a good agreement is found with respect to experimental data, although some slight discrepancies on the boron content of the various graphite brands are found. This might be related to a systematic bias in the early cross section measurements, as recently pointed out[23]. Then, keeping the moderator properties fixed, we have run a series of calculations with TRIPOLI-4 for the exponential pile models, using a critical-parameter search to adjust the concentration of ^{10}B in the fuel so that the computed infinite multiplication factor of the lattice matches the corresponding experimental value. This procedure determines the material compositions of all fuel types. In Sec. 1 of the Supplementary Information, we describe the material characterization in full detail and examine the limits of validity of our approach.

Building the full model of CP-1

Despite our best efforts, it was not possible to retrieve a complete description of the layers of CP-1 with the detailed positioning of the bricks and the fuel lumps. Only a small number of photos of the intermediate layers have survived (layers 3, 7, 10, 17, 25, and 29; see e.g. Fig. 2), and no photos are known of the fully built pile. A few horizontal and vertical plans of the pile are available in report CP-413[21] (layers 12 and 32, a vertical cut through the mid-plane, and a diagonal cut; see Supplementary Fig. 1 for an example). We have also resorted to an isometric view of the pile in three dimensions, drawn to build the mock-up of CP-1 exhibited for the tenth anniversary of the reactor divergence in 1952. This material was helpful in inferring the overall structure of CP-1, including the geometry of the graphite pier used to support the lower layers, and of the wood filler and casing. In view of building a full-scale Monte Carlo of CP-1, we have digitized all the plans, with a superposed mesh having the size of a single lattice cell; each element of the mesh has been attributed a material composition based on the brick type described in the CP-1 plans. A Python script has been then used in order to automatically convert the digitized schemes into a Monte Carlo model to be fed to TRIPOLI-4.

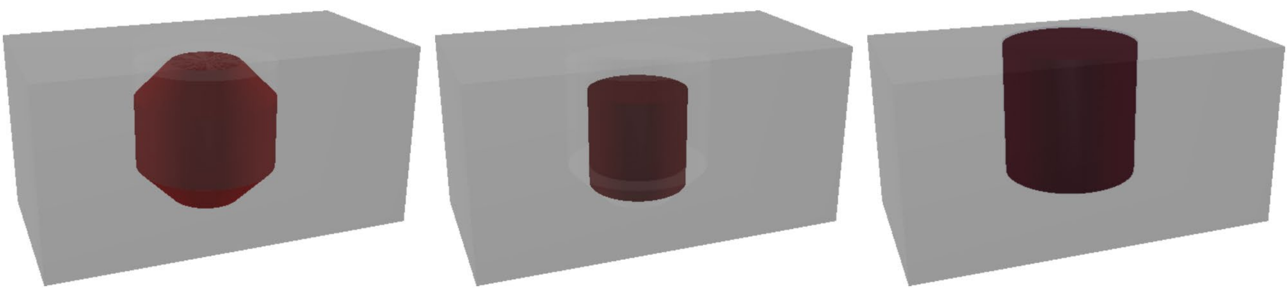

Fig. 1. TRIPOLI-4 models of three kinds of live bricks. Left: a half-brick containing a $3^1/4$ in uranium oxide pseudo-sphere; center: a half-brick containing a $2^1/4$ in uranium metal cylinder; right: a half-brick containing a 3 in uranium oxide cylinder. The drilled bases of the holes have been explicitly modeled.

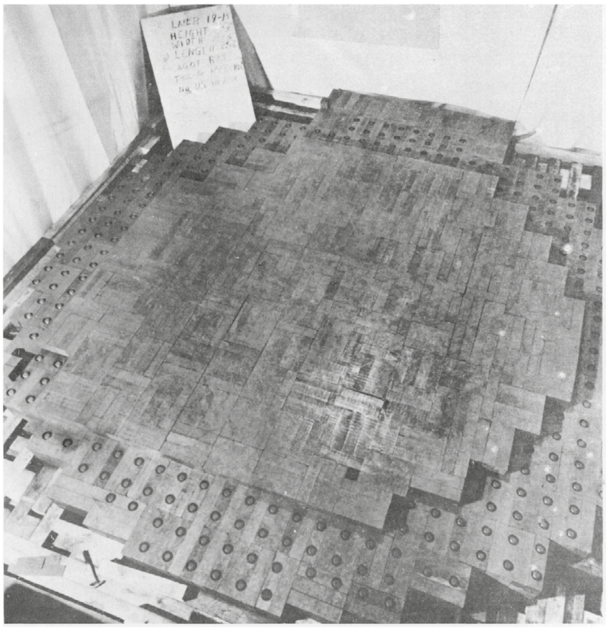

Fig. 2. A photo of the partially completed layer 17 of CP-1, from Ref. [21]. Layer 17 is entirely composed of dead bricks, whereas the underlying layer 16 is composed of alternating live and dead bricks, which preserve the lattice structure. The fuel lumps in the drilled holes are visible. This is one of the very few surviving photos of the CP-1 layers, taken during construction.

This procedure has required a fair amount of guesswork, due to the high level of uncertainty concerning the geometry of CP-1 and material compositions. In particular, it has been necessary to infer the structure of the layers by applying reasonable assumptions on the existing rotational symmetries. Furthermore, the boundaries between regions having different material compositions are in some cases blurred on the plans, and we had again to guess where a given kind of bricks was superseded by another kind along a layer and between layers; this remark is particularly true for the reactor periphery, for which photos reveal rather chaotic arrangements of bricks. Finally, and most importantly, the total quantities of fuel and moderator are rather loosely specified in report CP-413[21]: the accuracy on the number of fuel lumps is of the order of ten, and the accuracy on the mass of graphite is of the order of 0.5 t. A complete analysis of the mass balance of the resulting Monte Carlo model is discussed in Sec. 2 of the Supplementary Information. The three-dimensional view of the TRIPOLI-4 model of CP-1 is shown in Fig. 3.

Monte Carlo simulation results for CP-1

Once the CP-1 model has been built, we have performed an extensive set of simulations with TRIPOLI-4 in order to estimate the main features of the pile and compare them to existing experimental measurements. Except where differently stated, all the calculations reported in this work were carried out using the ENDF/B-VIII.0 nuclear data library[24], at $T = 296\,\mathrm{K}$ and atmospheric pressure.

We begin our analysis by considering the sub-critical approach to criticality, whose data are reported in Ref. [21]. For a number of completed layers, starting from 15, indirect estimates of the neutron field were made by measuring the activation of an indium foil placed as close as possible to the center of the pile (in ARO condition). The inverse of the induced detector activity A_i, as a function of the number of layers *i*, crosses zero slightly above the 56$^{\text{th}}$ layer. No external source was used: the needed supply of neutrons was provided by the spontaneous fission of ^{238}U contained in the fuel lumps.

In the TRIPOLI-4 model, we have mimicked the sub-critical approach by estimating the source amplification with a series of criticality calculations. In particular, for each configuration, we have estimated the effective multiplication factor k_{eff}, which represents the average number of neutrons produced in a single fission-chain generation by one starting neutron. After *n* generations, the number of neutrons per initial neutron will be k_{eff}^n. Therefore, the total number of neutrons in the fission chain per starting neutron will be $1 + k_{\text{eff}} + k_{\text{eff}}^2 + \ldots = 1/(1 - k_{\text{eff}})$, if $k_{\text{eff}} < 1$ (sub-critical reactor), and diverges for $k_{\text{eff}} = 1$ (critical reactor). The simulation findings are shown in Fig. 4, where we compare $1 - k_{\text{eff}}$, i.e. the inverse of the amplification factor computed with TRIPOLI-4, with the quantity i/A_i; multiplication by the factor *i* takes into account the fact that the intensity of the spontaneous fission neutron source is roughly proportional to the number of completed layers. The TRIPOLI-4 curve is rescaled by a normalization factor so that the computed and measured values are equal at layer 54; this rescaling is mandatory in that the shape, position, and efficiency of the indium foil are not known. Based on the last two available values, the extrapolated number of layers for criticality reads 55.7 for TRIPOLI-4 and 55.8 for the experimental data. The computed amplification factor is in good agreement with the experimental values, although it should be noted that the use of the normalization might hide part of the

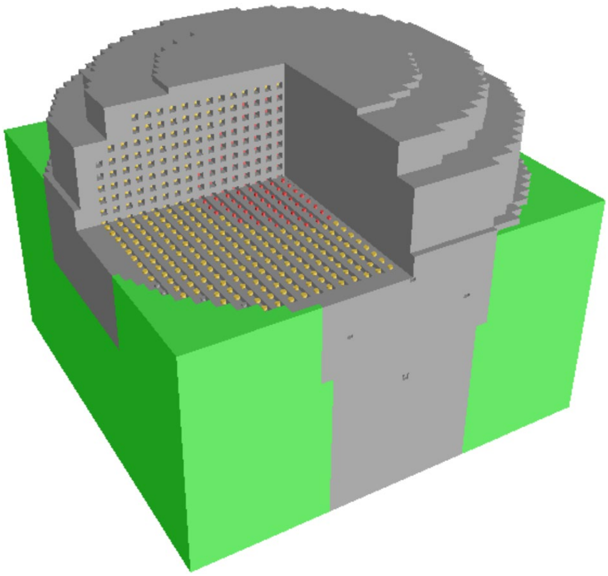

Fig. 3. Three-dimensional view of the CP-1 model built with TRIPOLI-4. The graphite pier (grey) and the wooden scaffold (green) are visible.

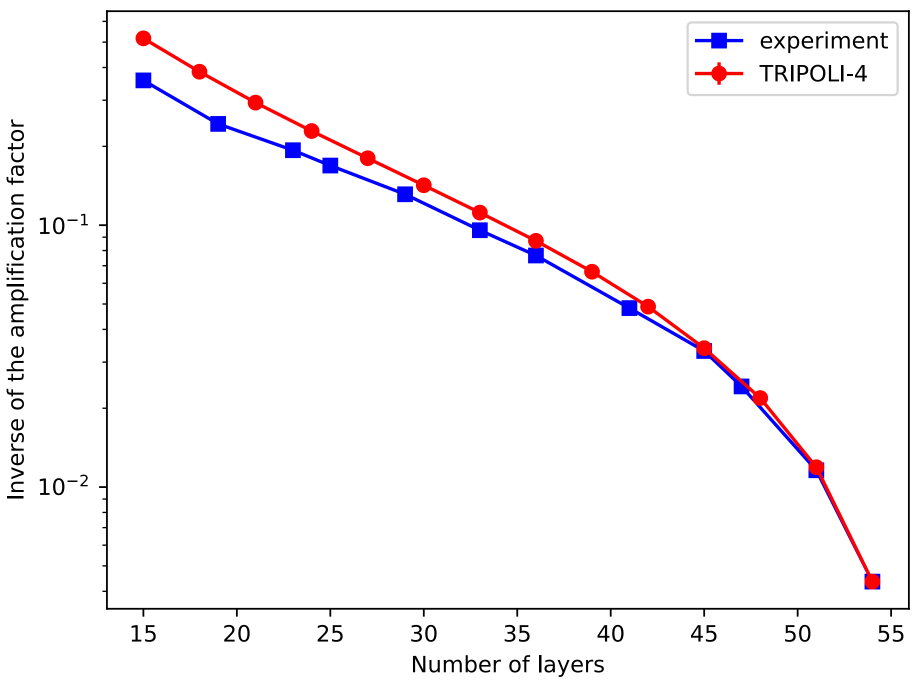

Fig. 4. Sub-critical approach to the divergence of CP-1. We display the inverse of the amplification factor as a function of the number *i* of completed layers: experimental data (blue squares) correspond to the quantity i/A_i, where A_i is the detector response reported in Ref. [21], Table 1 (the value $A_{41} = 350$ in the report was clearly a typo and should read $A_{41} = 846$, or possibly $A_{41} = 850$, based on the available data). The values computed with TRIPOLI-4 (red circles) correspond to $1 - k_{\text{eff}}$. The TRIPOLI-4 curve has been normalized to match the experimental values at layer 54. Values for layers beyond 54 were not provided in Ref. [21]; CP-1 went slightly supercritical at layer 57.

discrepancies. Note, however, that the simulated values could be refined by replacing the criticality calculations with fixed-source calculations for ^{238}U spontaneous fission: this is left for future work.

Next, we consider the behavior of CP-1 close to the critical configuration. In these conditions, the neutron population is known to evolve in time as $\exp(t/T)$, where T is the so-called *reactor period*, which can also be related to the effective multiplication factor k_{eff}; in the critical configuration ($k_{\mathrm{eff}} = 1$), the period is infinite. Otherwise, the value of the period depends on the position of the control rods.

In Fermi's report, the reactor period and the critical position are provided for the manual rod 21 (a cadmium sheet nailed to a fiber support) and for the control rod 38 (boron steel over a steel support)[21]. The rod number refers to the layer through which a slot was drilled for their insertion. Based on the description in Refs. [21] and [22], we have built fully detailed models of the control rods, including the safety rods 32 (one of them being the famous 'Zip' rod that was used to terminate the first divergence of CP-1 on December 2nd, 1942). The boron content of rod 38 is first reported as 1.5% in mass, and then as 15%[21]: we made the assumption that 15% was a typo, since it appears to be inconsistent with typical technological specifications for boron steel.

The estimated critical positions of the two rods are in good agreement with the values reported in Ref. [21]: CP-1 was reported to be critical with control rod 21 inserted by slightly more than $8^1/_2\ ft$ (based on the divergence diagram, the pile went super-critical at $8^1/_2\ ft$), or with control rod 38 inserted by about 7 ft. In both cases, all the other rods were out of the pile. A detailed analysis of the kinetics of the pile is provided in Secs. 2.3 and 2.4 of the Supplementary Information.

During the three months between the divergence and the end of operations, Fermi's collaborators measured the impact of a series of physical parameters on the multiplication factor of the pile[1]. For a few of them, the experimental procedures described in Ref.[1] were sufficiently detailed to build the corresponding Monte Carlo model for TRIPOLI-4, and the simulation results are reported in the following. One of the most important quantities that the Chicago team needed to measure was the temperature reactivity coefficient, i.e. the variation of k_{eff} with temperature, for which data obtained from the exponential piles prior to the construction of CP-1 were not reliable[1]. The isothermal temperature coefficient of CP-1 was experimentally determined by cooling the pile by about 9 K by opening some windows, and then heating it back to room temperature, over a period of three weeks, which yielded a reactivity coefficient of about $C_{\mathrm{exp}}^{T_{\mathrm{iso}}}$=$-3.8\,\mathrm{pcm\,K^{-1}}$ ($1\,\mathrm{pcm} = 10^{-5}$); with TRIPOLI-4 we obtain $C_{\mathrm{T4}}^{T_{\mathrm{iso}}} = -(4.20 \pm 0.12)\,\mathrm{pcm\,K^{-1}}$. The temperature coefficient of metal uranium was experimentally determined by insulating the uranium lumps from graphite and raising their temperature up to $500^{\circ}\mathrm{C}$ with heaters, which yielded a reactivity coefficient of about $C_{\mathrm{exp}}^{T_{\mathrm{met}}} = -1\,\mathrm{pcm\,K^{-1}}$; with TRIPOLI-4 we obtain $C_{\mathrm{T4}}^{T_{\mathrm{met}}} = (-1.0 \pm 0.2)\,\mathrm{pcm\,K^{-1}}$. For the sake of completeness, we have also computed the *Doppler coefficient*, which is defined as the variation of k_{eff} due to a variation of temperature of all the fuel (metal and oxide) in the pile: $C_{\mathrm{T4}}^{T_{\mathrm{fuel}}} = -(2.2 \pm 0.3)\,\mathrm{pcm\,K^{-1}}$.

The effect of atmospheric pressure on the pile multiplication factor was also experimentally determined by correlating the displacements of the control rod needed to keep the reactor critical with the variation of a barometer. Fluctuations of pressure are mirrored in fluctuations of $^{14}\mathrm{N}$ contained in the air and in the graphite (open spaces such as the fuel-bearing holes, cracks and pores). $^{14}\mathrm{N}$ is a neutron absorber, and CP-1 was highly sensitive to its variations. The total amount of air per fuel cell was reported to be about $2240\,\mathrm{cm^3}$ for CP-1[1], for a cell volume of about $9170\,\mathrm{cm^3}$, and the experimental pressure coefficient was found to be $C_{\mathrm{exp}}^{P} = -6.9\,\mathrm{pcm\,cm_{Hg}^{-1}}$. Assuming that all the air content in the graphite can be displaced by barometric variations, the pressure coefficient computed with TRIPOLI-4 reads $C_{\mathrm{T4}}^{P} = -(7.76 \pm 0.18)\,\mathrm{pcm\,cm_{Hg}^{-1}}$, which is in good agreement with the measurement. The slight discrepancy can be attributed to technological uncertainties in the Monte Carlo model; however, it might also suggests that the total amount of 'accessible' air in the graphite is rather of the order of $2000\,\mathrm{cm^3}$ per fuel cell, i.e. about 89% of the total amount.

During the operation of CP-1 at a nominal power of 200 W, the radiation field intensity was recorded at various locations within the West Stand hall and in the street outside, using standard R-meters, with $\mathrm{BF_3}$ counters and indium foils[21]. We have used TRIPOLI-4 to compute the ambient dose equivalent $H^*(10)$ field[25] in the CP-1 model. The obtained results have been normalized so that the power deposited by neutrons and photons in the Monte Carlo model of CP-1 corresponds to the nominal value of 200 W. At an unspecified location close to the pile, the instruments read $50\,\mathrm{mSv\,min^{-1}}$; for TRIPOLI-4, the dose equivalent computed in a volume of $10 \times 10 \times 10\,\mathrm{cm^3}$ at half-height near the external surface of CP-1 yields $0.85\,\mathrm{mSv\,min^{-1}}$ for the neutron contribution and $0.045\,\mathrm{mSv\,min^{-1}}$ for the photon contribution. Although exposure (roentgens) and dose equivalent (sieverts) are not immediately comparable, we can perform a rough conversion from one to the other by assuming that 1 R corresponds to about $1\,\mathrm{rem} = 0.01\,Gy$ in soft biological tissue; furthermore, for the conversion of dose equivalent into dose, we assume a quality factor of 1 for the photons, as customary, and a quality factor ranging between 2 (thermal) and 10 (fast) for the neutrons. The TRIPOLI-4 estimates for the dose equivalent rates then correspond to about $11.5\,\mathrm{mR\,min^{-1}}$ if we assume that all of the dose comes from fast neutrons, or to about $45.5\,\mathrm{mR\,min^{-1}}$ if we assume that it comes from thermal neutrons. This argument is not rigorous, but serves the purpose of showing that the order of magnitude of the TRIPOLI-4 simulations seem to be coherent with the measured radiation fields. Far from the pile, within the room, the measurements yielded $6mR\,min^{-1}$[21]; the corresponding estimate for the TRIPOLI-4 model is about $0.3\,\mathrm{mSv\,min^{-1}}$ for the neutron contribution and $0.03\,\mathrm{mSv\,min^{-1}}$ for the photon contribution. Applying the same argument as before, we would have roughly $4\,\mathrm{mR\,min^{-1}}$ if we assume that all of the dose comes from fast neutrons, or $16\,\mathrm{mR\,min^{-1}}$ if we assume that it comes from thermal neutrons. For reference, the allowed exposure limit according to the recommendations of the health physics group of the Metallurgical Laboratory was $0.1\,\mathrm{Rd^{-1}}$[26].

CP-2: Monte Carlo model and simulation results

The Chicago Pile number 2, or CP-2, was the reincarnation of CP-1 at the Argonne site, taking the approximately cubical shape (20 feet wide, 22 feet deep, and about 19 feet high) that had being originally proposed in October 1942, before physicists were forced to switch to a spherical shape due to the lack of sufficient amounts of fuel and graphite. A few photos have survived: for an illustration, see Fig. 5. An overview of the material compositions and the geometry of CP-2 can be found in Ref. [3], with useful complements from Ref. [22]. Additional details

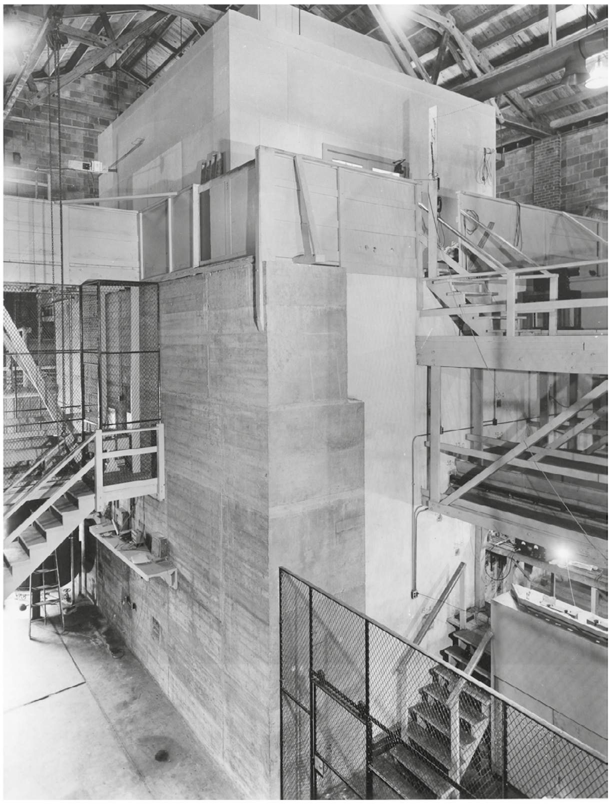

Fig. 5. A photo of the completed Chicago Pile 2 (CP-2), in the reactor hall at the Argonne Site A. The concrete shielding is visible, with penetrations corresponding to the safety rods (on the left) and the shim and control rods (on the right). On top of the pile lies the experimental facility used to extract the neutron flux from the thermal column. Photo credits: Argonne National Laboratory, USA.

concerning the pile operation, including kinetics parameters, reactor period and material testing experiments, can be retrieved from Refs. [27–29] and the technical reports in Ref. [1].

The materials used in CP-2 were mostly reused from those of CP-1. The main differences were related to the delivery of larger amounts of metal uranium lumps (in several sizes and masses) and high-purity AGOT graphite, which were thus added to CP-2 in place of lower-quality materials present in CP-1. The lattice pitch of CP-2 was the same as in CP-1. Since not enough metal uranium was available to fill the lattice of the entire pile, CP-2 again adopted a two-core architecture, with an inner metal uranium core (a stepped structure having a roughly spherical shape) and an outer uranium oxide core. In the periphery of the pile, a shell of dead graphite acted as neutron reflector.

For the material compositions of the CP-2 Monte Carlo model, the only required modification was the addition of a set of fuel cells with metal uranium lump sizes weighting 4 lb, 7 lb or 8 lb (in the central and upper layers of the pile), or metal scraps weighing 5 lb on average. The specific geometrical dimensions of the lumps were not given: we assumed for the sake of simplicity that all the metal lumps had a cylindrical shape, with diameter equal to the one of the CP-1 lumps and height scaled proportionally to their weight. Since metal uranium in AGOT graphite had been already calibrated for the CP-1 model, no further adjustment procedures were needed for the CP-2 model.

We were able to access the unpublished drawings of the 54 layers of CP-2, which have been preserved at the National Archives at Chicago. The plans encompass the exact positioning of the single fuel lumps and graphite bricks, layer by layer, the dimensions and orientation of the control, shim and safety rods, the slots devoted to instrumentation, and the removable stringers. A few example plans are shown in Supplementary Fig. 9. Specifications for the 1.5 m-thick concrete shield surrounding CP-2 are not provided in the drawings, but can be inferred from Refs.[22,29]. The same holds for the top shield (composed of about 40 in of wood and 6 in of lead), laid on top of the 54th layer of the pile. Unfortunately, we were not able to retrieve the exact dimensions of the reactor hall within the Argonne Site A and of the experimental facilities built above the pile, except for the thermal column, whose shape is described in Ref.[1].

For the full-scale CP-2 model, the plans and the complementary specifications provide a detailed description of the pile, including geometry and material compositions. Similarly as done for CP-1, the geometry has been converted with a Python script into a Monte Carlo model for TRIPOLI-4. For the sake of simplicity, we assume that the Monte Carlo model of CP-2 is limited to the reactor, the concrete shielding (including the concrete floor), and the top lead and wood shield: we neglect the reactor building and the structures on top of the biological shield. The resulting TRIPOLI-4 model of CP-2 is shown in Fig. 6.

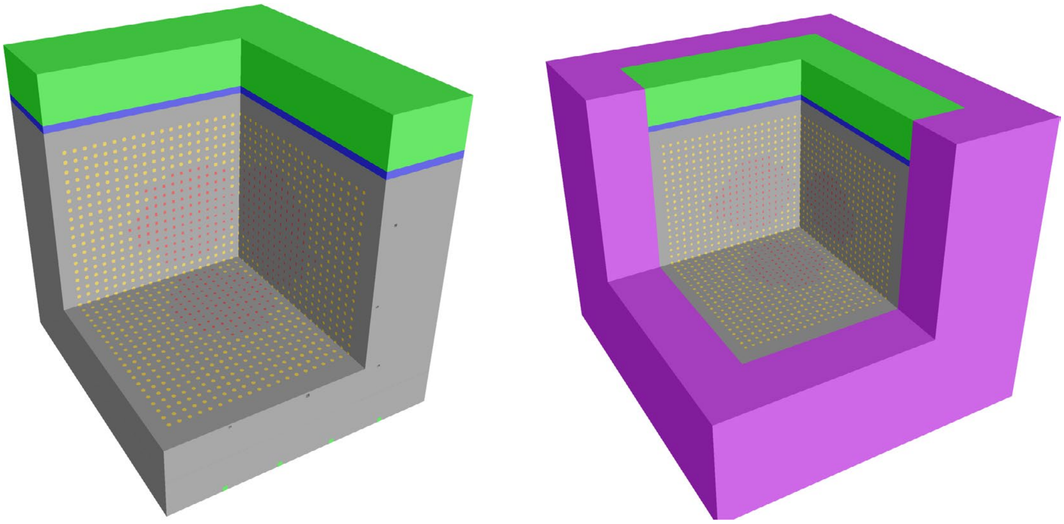

Fig. 6. Three-dimensional views of the CP-2 model built with TRIPOLI-4, without (left) and with (right) the concrete shield. The inner metal uranium core and the outer uranium oxide core are visible, together with the graphite reflector and the top shield.

We used the CP-2 model to estimated the main parameters of the pile using TRIPOLI-4. Except where differently stated, all the calculations were again carried out using the ENDF/B-VIII.0 nuclear data library, at $T = 296\,\mathrm{K}$ and atmospheric pressure. We illustrate now the key simulation results for the CP-2 model, using available experimental data as a reference, whenever possible.

According to Refs.[3,22], the concrete for the foundations and the shield was first poured, and the layers of CP-2 were then stacked in the open vault surrounded by the shield. Only three sides of the concrete shield were present during the construction of the uranium-graphite lattice of CP-2 and until a few weeks after the first divergence in March 1942. The south wall was left open, to enable the access to the vault, and the top of the pile was open. Criticality was reached above the 50th layer. When the 51th layer was added, the experimental doubling time was determined to be $T_2 = T \ln 2 = 90\,s$[3]; the associated uncertainty was not provided.

Similarly as for CP-1, the source amplification of CP-2 in the sub-critical condition has been recorded as a function of the number of built layers, until divergence was achieved[3,22]. The comparison between the TRIPOLI-4 findings and the experimental values is shown in Fig. 7. For the sake of coherence, the simulations have been conducted using the same procedure as for CP-1: we estimate the source amplification factor as $1/(1 - k_{\mathrm{eff}})$. The normalization of the experimental values was imposed by scaling the inverse of the amplification computed by TRIPOLI-4 to match the experimental value at layer 48. Contrary to the case of CP-1, where the measured values were provided as a table, for CP-2 the measurement values had to be digitized from the points of a curve in the corresponding figure of Ref. [22]. The procedure was repeated several times, in order to provide a rough estimate of the accuracy of data extraction. Overall, the agreement between simulated and experimental values is satisfactory, with the same caveats about normalization as for the case of CP-1. Based on the last two available values, the extrapolated number of layers for criticality reads 51.0 for TRIPOLI-4 and 50.3 for the experimental data.

Several experiments were conducted to characterize the kinetics of the pile close to criticality, including the calibration of the control rods. The TRIPOLI-4 analysis of these measurements is presented in Sec. 3 of the Supplementary Information.

The dependence of the CP-2 multiplication factor on the physical parameters is discussed in Refs.[1,28]. The sensitivity to temperature was variously reported to be $-2.5\,\mathrm{pcm\,K^{-1}}$[1] or $-1\,\mathrm{pcm\,K^{-1}}$[28]; we were unable to retrieve the details of the experimental procedure, and in particular whether these values correspond to variations in the temperature of the entire pile or of the fuel alone. Simulation results obtained with TRIPOLI-4 yield a temperature coefficient of $C^{T_{\mathrm{iso}}} = -(3.46 \pm 0.07)\,\mathrm{pcm\,K^{-1}}$ for isothermal conditions (i.e. the temperature of the fuel, the moderator and the other structures of the pile is simultaneously modified), $C^{T_{\mathrm{fuel}}} = -(1.89 \pm 0.07)\,\mathrm{pcm\,K^{-1}}$ when only the temperature of the fuel is modified, and finally $C^{T_{\mathrm{met}}} = -(1.08 \pm 0.07)\,\mathrm{pcm\,K^{-1}}$ when only the temperature of the metal fuel is modified. These findings for CP-2 are consistent with those for CP-1.

The sensitivity coefficient to barometric pressure was variously reported to be $-9.8\,\mathrm{pcm\,cm_{Hg}^{-1}}$[1], $-8.7\,\mathrm{pcm\,cm_{Hg}^{-1}}$, or $-8.2\,\mathrm{pcm\,cm_{Hg}^{-1}}$[28], which are very close to the values measured for CP-1. This is not surprising, since the material compositions and the geometry of the fuel cells are basically the same for the two Chicago piles. In the TRIPOLI-4 model, assuming that all the air in the graphite can be displaced by variations in the atmospheric pressure, we obtain a pressure coefficient $C^{P}_{\mathrm{T4}} = (-7.9 \pm 0.2)\,\mathrm{pcm\,cm_{Hg}^{-1}}$, in good agreement with experimental data. Observe however that the total amount of displaceable air per fuel cell for CP-2 was reported to be about $450\,\mathrm{cm}^3$[28], which is much smaller than the estimate of $2240\,\mathrm{cm}^3$ for CP-1[1]. No details are

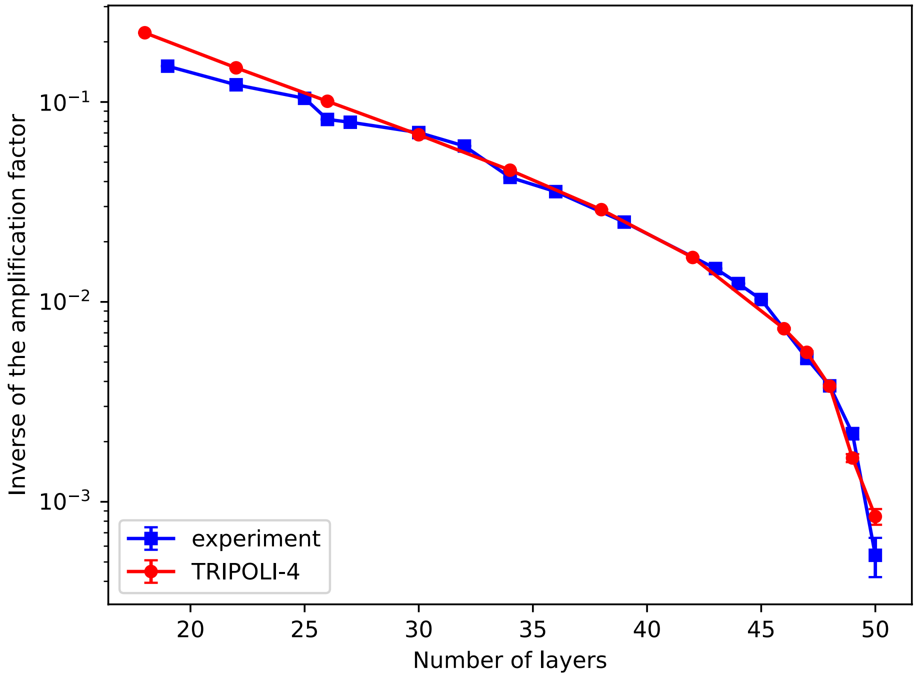

Fig. 7. Sub-critical approach to the divergence of CP-2. We display the inverse of the amplification factor as a function of the number *i* of completed layers: experimental data (blue squares) correspond to the quantity i/A_i, where A_i is the detector response reported in Refs.[3,22]; the values computed with TRIPOLI-4 (red circles) correspond to $1 - k_{\text{eff}}$. The error bars on the experimental values were estimated by assessing the accuracy of the data series digitization from the corresponding figure in Ref. [22]: in practice, only the point at layer 50 is concerned. The TRIPOLI-4 curve has been normalized to match the experimental values at layer 48.

provided concerning how this value was inferred; we conjecture that this surprisingly low estimate might be due to a typo in the report.

The neutron flux within CP-2 was measured using activated copper foils in the removable graphite stringer T23, running through layer 23 (along the north-south axis of the pile). Simultaneously, the flux was also measured by activation in the positions of the metal lumps in an adjacent slot[28]. The precise location of the stringer carrying the metal lumps was not specified in Ref. [28], and we assumed that these measurements were taken in the layer above the graphite stringer, since the report mentions a possible difficulty with positioning the two sets of activation foils close to each other. The experimental data available in Ref. [28] for both graphite and metal fuel were normalized so that the maximum flux is equal to one. We have computed the corresponding spatial profile of the thermal neutron flux with TRIPOLI-4 over a spatial mesh for the CP-2 configuration, with the control rod inserted at the critical position: simulation findings are shown in Fig. 8 and show a very good agreement with the experimental data.

Discussion

We have explored the features of the first nuclear reactors, the Chicago Piles CP-1 and CP-2, using state-of-the art numerical simulation tools and nuclear data libraries. In building the Monte Carlo models for the piles, we have been confronted with several outstanding difficulties due to the lack of knowledge about the geometry (especially in the case of CP-1) and material compositions. Overall, the comparisons between simulation findings and experimental data were satisfactory.

Our findings provide a stepping stone towards a more comprehensive understanding of the technological features and of the neutronic behavior of the Chicago Piles. We feel that new insights on CP-1 and CP-2 might emerge in the future: the rediscovery of unpublished reports could lead to a more accurate description of the pile geometry, which is an especially acute need for CP-1. Further advances may be achieved by pursuing investigations in two directions. First, a few dead and live bricks of CP-1 and CP-2 have survived and are preserved in several museums: a spectral analysis, combined with some assumptions on the fuel irradiation history, could shed some light on the material composition (with special emphasis on the presence of impurities) of the fuel lumps. This approach has been explored by Dr. Willis at the University of New Mexico[30], and it could be naturally extended to the characterization of graphite. Second, comparing our results with those obtained with independently developed Monte Carlo models (such as the MCNP model of CP-1 that has been conceived by Dr. Willis) could help in inferring the sensitivity of the simulation results to the several hypotheses used to build those models.

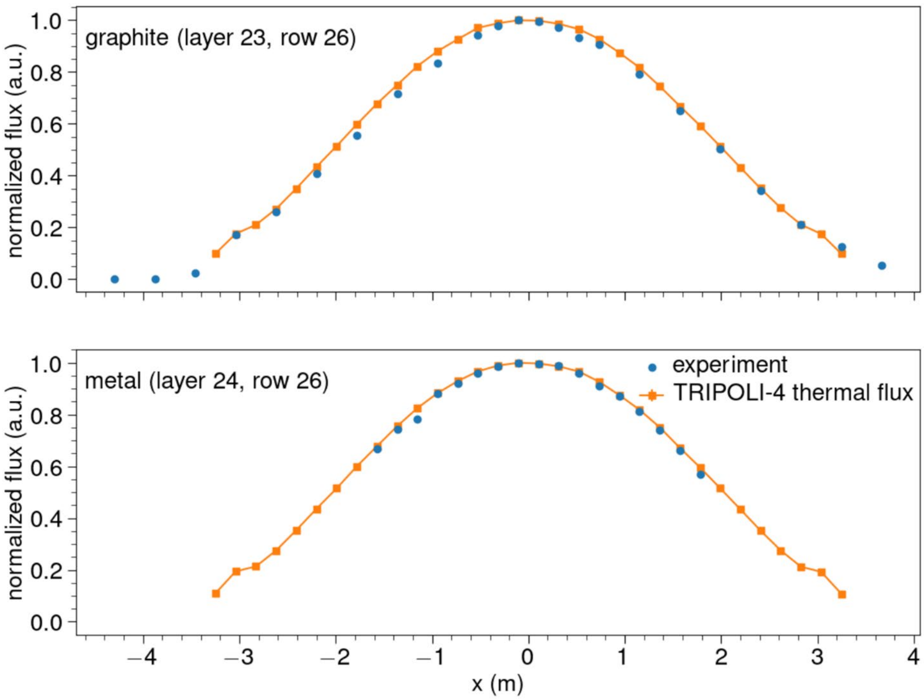

Fig. 8. Spatial shape of the thermal neutron flux within CP-2, along the north-south axis of the pile. Experimental data from Ref. [28] are shown as blue circles; TRIPOLI-4 results are shown as orange squares. Top: thermal flux in the graphite stringer located at layer 23, along row 26 (position provided in Ref. [28]); bottom: thermal flux in the metal lumps of the stringer located at layer 24, along row 26 (position guessed from hints in Ref. [28]).

Methods

All the simulations performed for this work have been carried out using TRIPOLI-4®, a general-purpose Monte Carlo particle-transport code for nuclear reactor analysis[20]. Specific details of the simulations are discussed in the Supplementary Information.

Data availibility

The datasets generated and/or analysed during the current study are not publicly available due to them being generated using export-controlled codes, but are available from the corresponding author on reasonable request.

Accession codes TRIPOLI-4® is a registered trademark of CEA. A license can be obtained from CEA, upon request. The code is distributed under export control rules.

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Author contributions
A.Z. and D.M. designed research; A.Z., A.G., and D.M. performed research; A.Z., A.G., and D.M. analyzed data; and A.Z. and D.M. wrote the paper.

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Declarations

Competing interests
The authors declare no competing interests.

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