

NUKLEARE ARCHÄOLOGIE

ODER: WIE FORSCHUNGSREAKTOREN ZUR NUKLEAREN ABRÜSTUNG BEITRAGEN KÖNNEN

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Program on Science and Global Security, Princeton University
Einstein Center Digital Future, Berlin

Helmholtz Zentrum Berlin, 17. November 2022

Revision 0

BACKGROUND

USA
5,500



U.S. Nuclear Weapon

Russia
6,000



United Kingdom
215



France
300



Israel
80



Pakistan
135



India
125



China
350

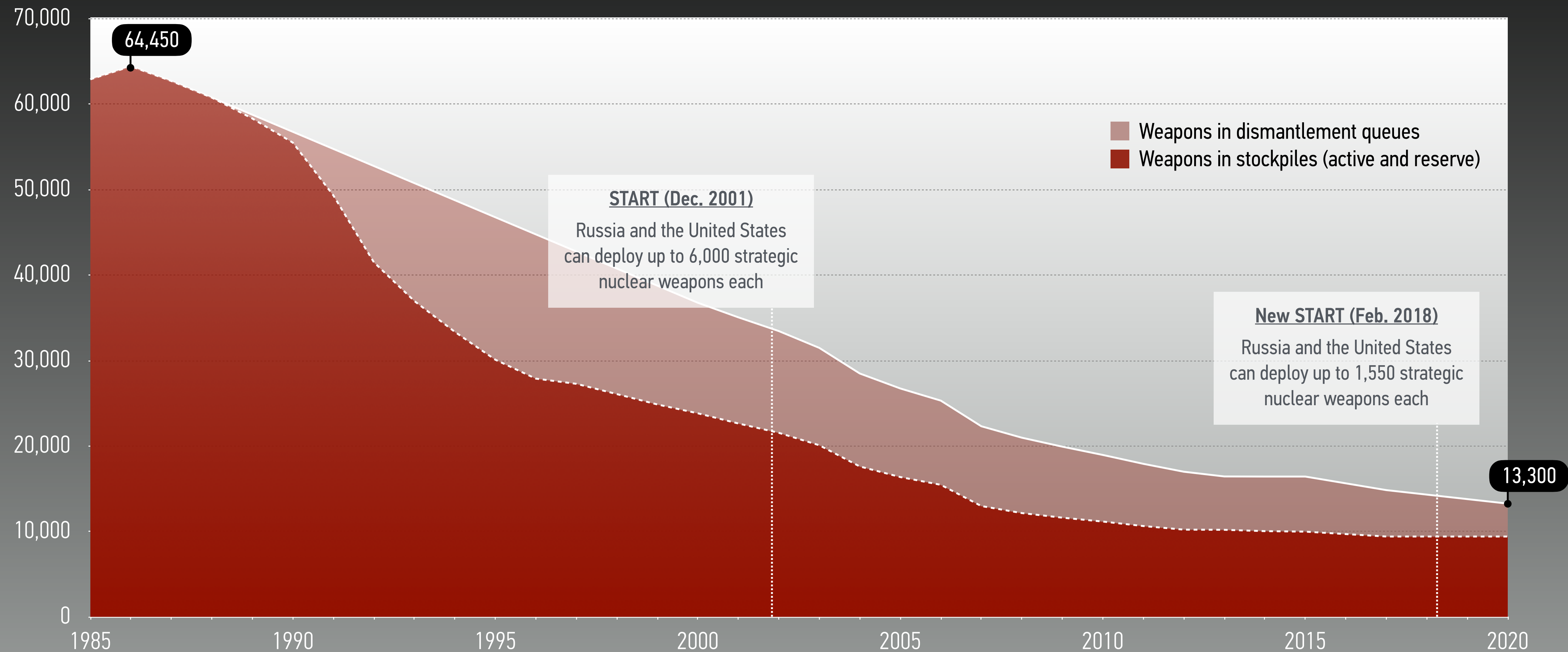


North Korean Nuclear Weapon

North Korea
15

***There remain almost
13,000 nuclear weapons
in the world today***

PROGRESS TOWARD NUCLEAR DISARMAMENT HAS BEEN REAL (BUT IT HAS SLOWED DOWN SIGNIFICANTLY OVER THE PAST DECADE)



Based on the Nuclear Notebook, maintained by Hans M. Kristensen and Matt Korda, thebulletin.org/nuclear-notebook/

“THE GRAND BARGAIN”

NUCLEAR NONPROLIFERATION, DISARMAMENT & PEACEFUL USE

NUCLEAR NON-PROLIFERATION TREATY (1970)



Existing nuclear weapon states agree not to transfer nuclear weapons to any other states

All other states agree to never acquire nuclear weapons

Nuclear weapon states (along with all others) undertake to pursue “good-faith negotiations” on effective measures relating to nuclear disarmament

Source: Zia Mian (August 2022)

PEACEFUL USE OF NUCLEAR ENERGY & IAEA SAFEGUARDS



The NPT acknowledges the right of all parties to develop nuclear energy for peaceful purposes

Non-nuclear-weapon states accept comprehensive IAEA safeguards to ensure peaceful use

As of November 2022, the NPT has 191 states parties
(5 weapon states, 186 non-weapon states)

Source: IAEA

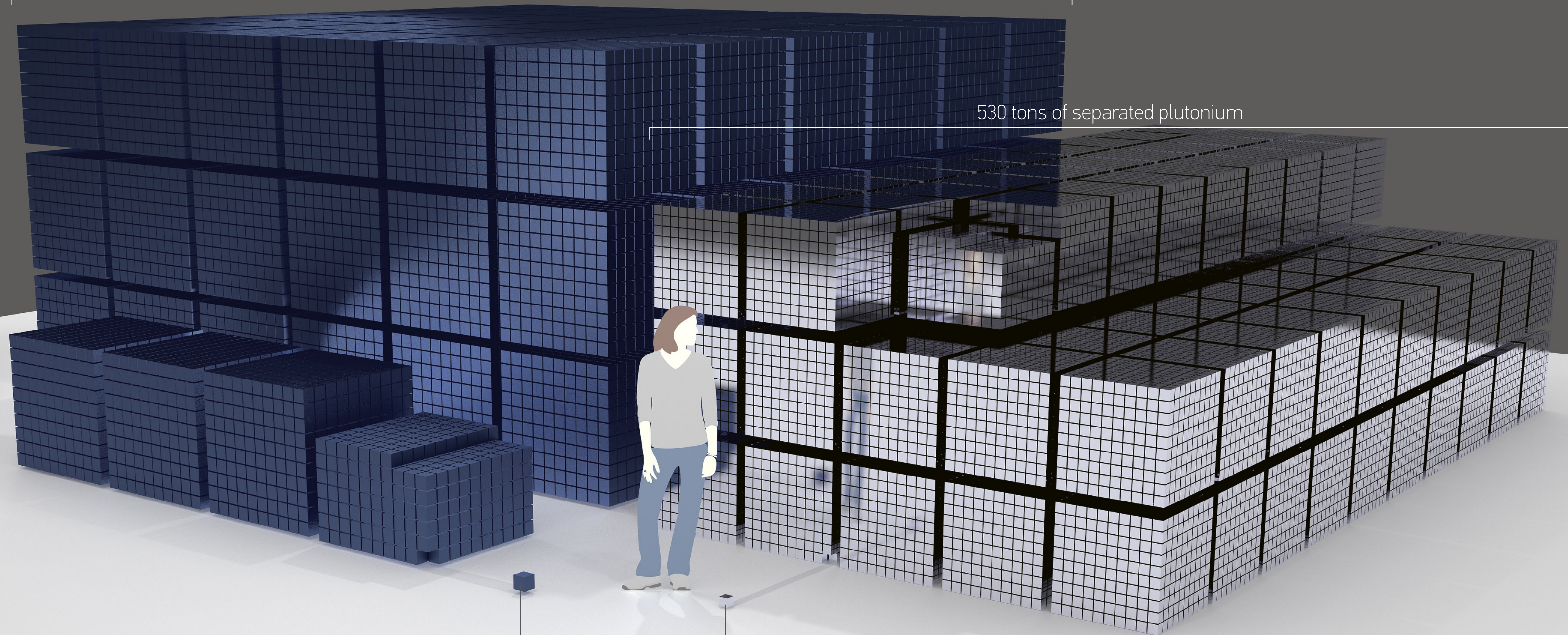
There is enough nuclear explosive material worldwide to make over 200,000 nuclear weapons

Graphic/concept by Alex Wellerstein and Tamara Patton

Status as of the beginning of 2019

1335 tons of highly enriched uranium (HEU)

530 tons of separated plutonium



*Each block corresponds to 12 kg of HEU,
the amount necessary to make a fission bomb;
about 111,670 bombs-worth total*

*Each block corresponds to 4 kg of plutonium,
the amount necessary to make a fission bomb;
about 130,000 bombs-worth total*

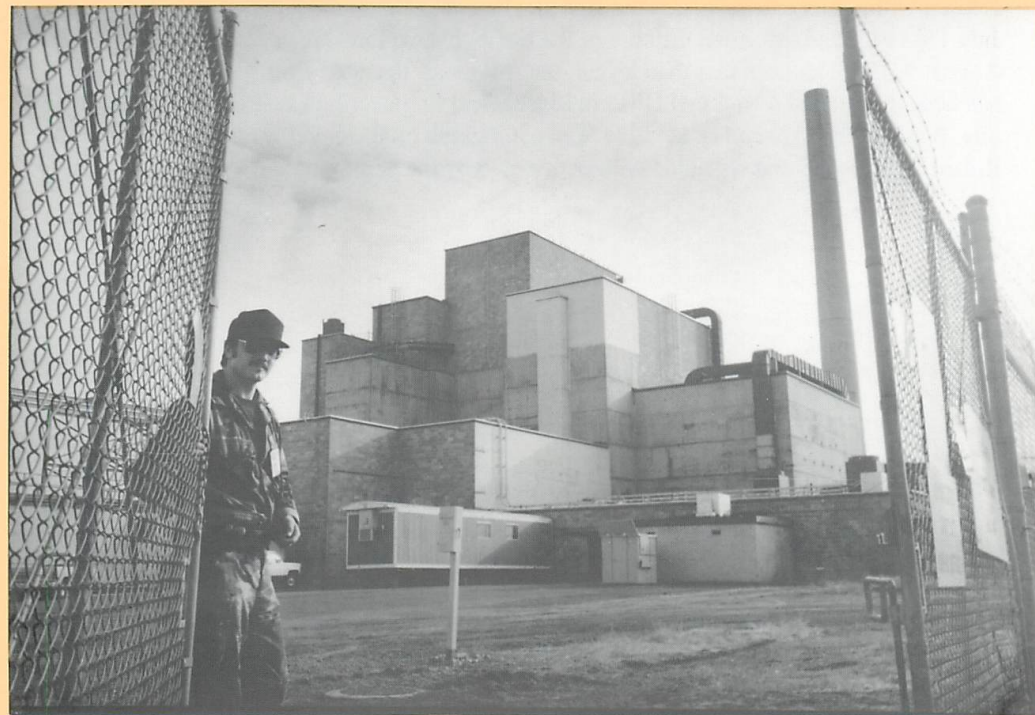
ESTIMATING INVENTORIES CAN BE HARD

(AN EXAMPLE FROM THE 1996 U.S. PLUTONIUM DECLARATION)

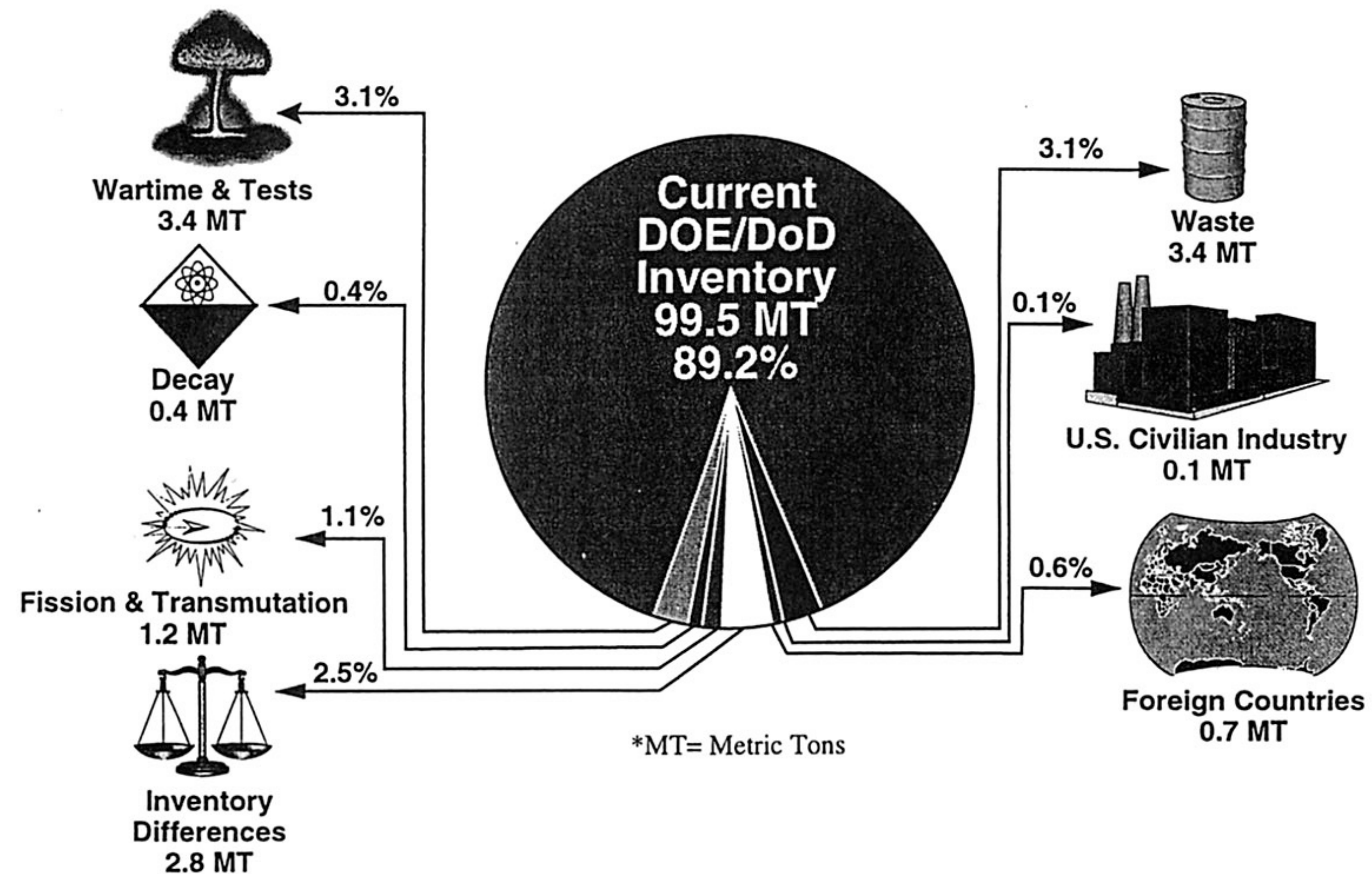
Plutonium: The First 50 Years



DOE/DP-0137
U.S. Department of Energy
February 1996



United States plutonium production, acquisition,
and utilization from 1944 through 1994



Plutonium: The First 50 Years, DOE/DP-0137, U.S. Department of Energy, Washington, DC, February 1996, www.ipfmlibrary.org/doe96.pdf



K Reactor, Savannah River Site, i.imgur.com/CPrBoCK.jpg

NUCLEAR ARCHAEOLOGY

UNDERSTANDING THE OPERATIONAL HISTORY OF NUCLEAR FACILITIES

Science & Global Security, 1993, Volume 3, pp.237–259
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Printed in the United States of America

Nuclear Archaeology: Verifying Declarations of Fissile-Material Production

Steve Fetter^a

Controlling the production of fissile material is a key element of nonproliferation policy. Similarly, accounting for an important component of nuclear production techniques that make use of plutonium to verify the past production of plutonium, the concentrations of long-lived isotopes in the reactor core are used to estimate the plutonium production and thereby verify declaration. In this technique, the ratio of the concentration of enriched uranium, which is determined by the use of nuclear techniques, can be used in nuclear archaeology, in which the ratios and thereby lay a firm foundation for the verification of nuclear production.

INTRODUCTION

For the first time, the tide of nuclear proliferation—is ebbing. The combined nuclear arsenals of the world are expected to be reduced by the turn of the century by the turn of the century. South Africa, the only country to have voluntarily dismantled its nuclear weapons, has set a precedent. The threshold for nuclear disarmament is being reached.

Science & Global Security, 21:70–92, 2013
ISSN: 0892-9882 print / 1547-7800 online
DOI: 10.1080/08929882.2013.755028

Applications and of Nuclear Archaeology in Uranium Enrichment

Matthew Sharp

Bureau of European and Eurasian Affairs,
Washington, DC, USA

The uranium-235 content of a uranium sample is determined by the ratio of the uranium-234 content of its waste, allowing for the determination of the plant's declared past production. The uranium-235 content of a sample may still be distinguished based on the ratio of the uranium-234 content of its waste, allowing for the determination of the plant's declared past production.

Science & Global Security, 22:4–26, 2014
Copyright © Pacific Northwest National Laboratory
ISSN: 0892-9882 print / 1547-7800 online
DOI: 10.1080/08929882.2014.874217

 Routledge
Taylor & Francis Group

The Future of Nuclear Archaeology: Reducing Legacy Risks of Weapons Fissile Material

Thomas W. Wood, Bruce D. Reid, Christopher M. Toomey,
Kannan Krishnaswami, Kimberly A. Burns, Larry O. Casazza,
Don S. Daly, and Leesa L. Duckworth

Pacific Northwest National Laboratory, Richland, WA, USA

This report describes the value proposition for a “nuclear archaeological” technical capability and applications program, targeted at resolving uncertainties regarding weapons fissile materials production and use. Central to this proposition is the notion that one can never be sure that all fissile material is adequately secure without a clear idea of what “all” means, and that uncertainty in this matter carries risk. We argue that this proposition is as valid today, under emerging state and possible non-state nuclear threats, as it was in an immediate post-Cold-War context, and describe how nuclear archaeological methods can be used to verify fissile materials declarations, or estimate and characterize historical fissile materials production independent of declarations. Methods for accurately estimating plutonium production from graphite reactors have been demonstrated and could be extended to other reactor types. Proposed methods for accurately estimating uranium production from gas centrifuge reactors have been demonstrated and could be extended to other reactor types. Proposed methods for accurately estimating plutonium production from gas centrifuge reactors have been demonstrated and could be extended to other reactor types.

Science & Global Security, 19:223–233, 2011
Copyright © Taylor & Francis Group, LLC
ISSN: 0892-9882 print / 1547-7800 online
DOI: 10.1080/08929882.2011.616124

 Routledge
Taylor & Francis Group

Nuclear Archaeology for Gas-Water-Moderated Plutonium Production Reactors

Thomas W. Wood and Alexander Glaser

Department of Mechanical and Aerospace Engineering, Princeton University Engineering, Princeton, NJ 08544

Interest in a set of methods and tools that can be used to characterize nuclear material production activities, using measurements and sampling at storage sites. This field has been dubbed “nuclear archaeology.” The example of nuclear archaeology relies on measurements of the isotope ratios of elements in the graphite of graphite-moderated plutonium production reactors. The Graphite Isotope-Ratio Method (GIRM) determines the cumulative plutonium production through the graphite and thereby estimates the cumulative plutonium production. The great limitation of this particular method is that it can only be used for graphite-moderated reactors, which represent only one class of reactor. This method to non-graphite moderated reactors by analyzing relevant isotope ratios in the support structures and other core components of heavy-moderated reactors. We present results of neutronics calculations for a heavy-moderated reactor evaluating the robustness of the method of nuclear archaeology for applications in arms-control treaty verification.

NUCLEAR ARCHAEOLOGY

DOCUMENTING THE PAST TO ENABLE A NUCLEAR-WEAPON-FREE FUTURE



THE CHALLENGE

Future progress toward verified nuclear disarmament will require a much better understanding of the stockpile of fissile materials that have been produced in unsafeguarded facilities; “nuclear archaeology” seeks to provide the tools to do so



THE IDEA

Develop of a framework that can provide a basis for preserving the history of relevant nuclear facilities; examine, in particular, the potential role of operating records to do so

Such a framework would complement other nuclear archaeology techniques, which rely on physical samples taken from structural components or waste materials for forensic analysis to draw conclusions about past activities

Source: IAEA (top), asian-defence-news.blogspot.com (bottom)

WHY GERMANY?

(and/or other non-nuclear-weapon states)

ONGOING VERIFICATION INITIATIVES

(AS OF 2022, ALL WITH GERMAN PARTICIPATION)

INTERNATIONAL PARTNERSHIP FOR DISARMAMENT VERIFICATION



Established in 2015; currently 29 participating countries

IPNDV seeks to identify challenges associated with nuclear disarmament verification and to develop potential procedures and technologies to address those challenges

Phase III began in Spring/Summer 2021

Germany is co-chairing two (out of three) working groups

www.ipndv.org

Source: ipndv.org

GROUP OF GOVERNMENTAL EXPERTS ON DISARMAMENT VERIFICATION



Group of Governmental Experts (GGE) considers “the role of verification in advancing nuclear disarmament”

Established by the UN Secretary General following a resolution of the UN General Assembly (A/RES/71/67, Dec. 2016), the first GGE delivered its final report in May 2019 (A/71/67)

The second GGE has been convening in Geneva since 2021

25 members, including Germany

Source: www.flickr.com/photos/gruban/336920038

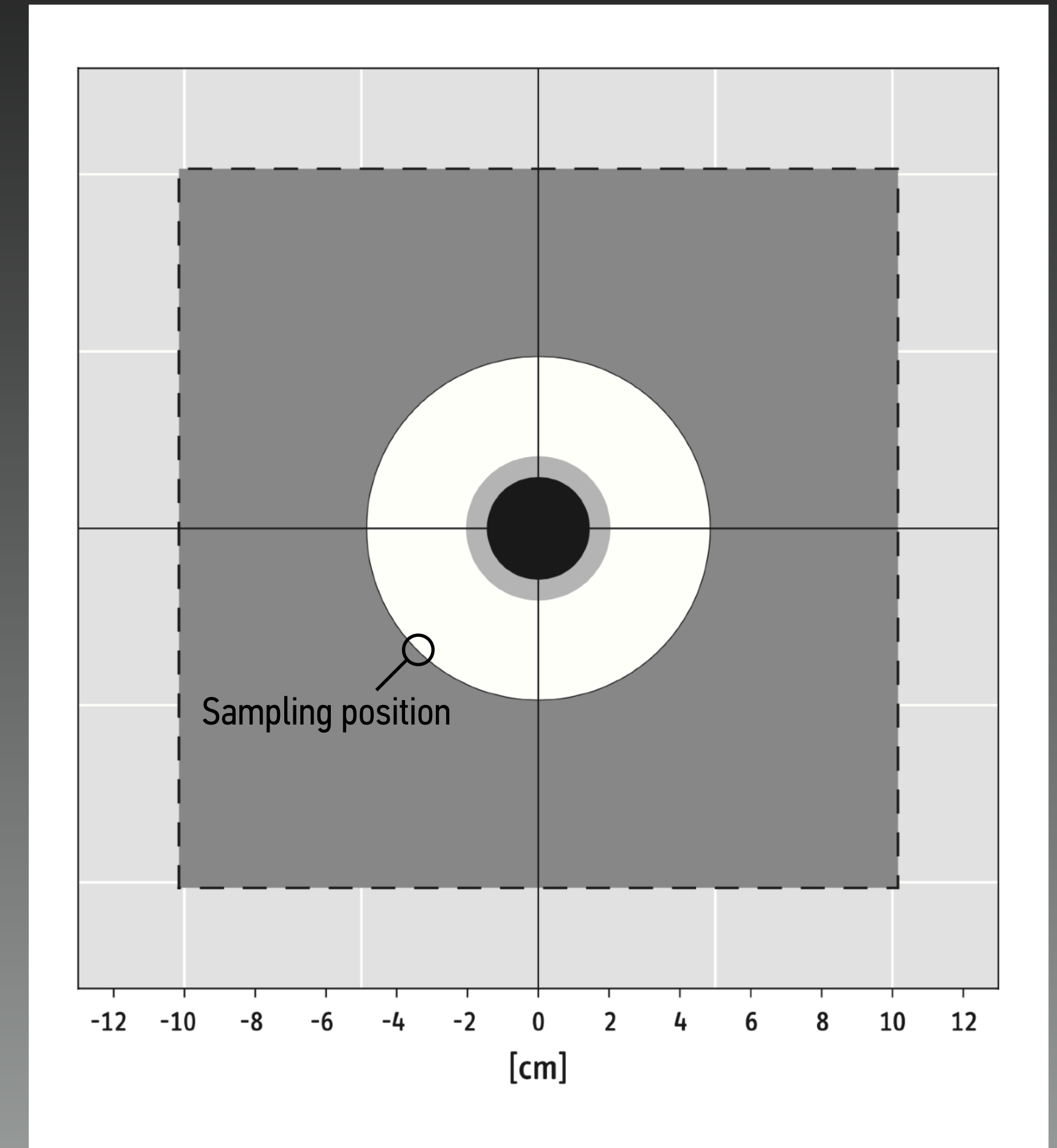
SAMPLE-BASED NUCLEAR ARCHAEOLOGY

(A possible use case)

NUCLEAR ARCHAEOLOGY COULD BE USED TO VERIFY A NORTH KOREAN PLUTONIUM DECLARATION

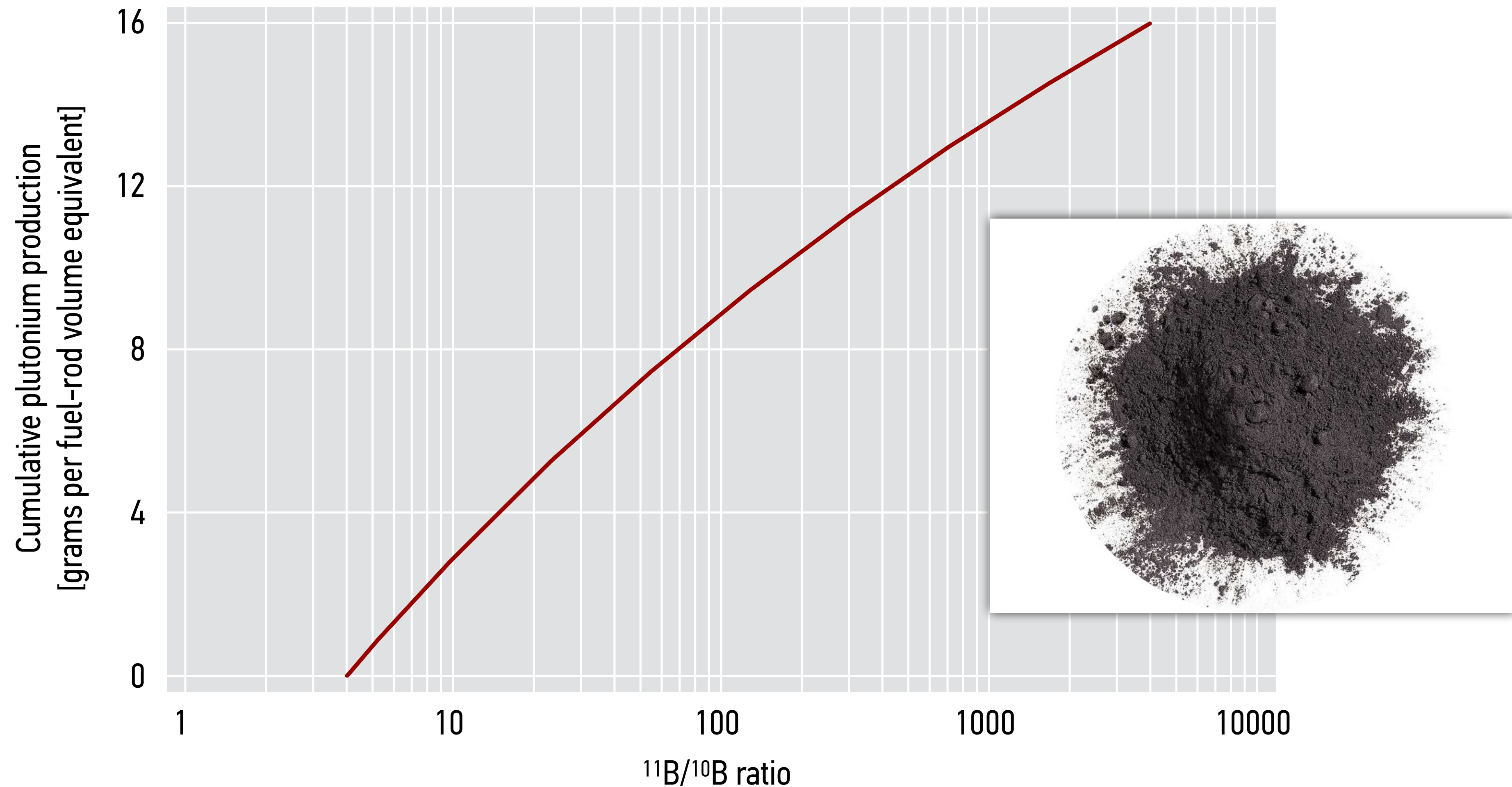


Credit: CNN/Brian Rokus, 2008



Unit cell of the North Korea's Yongbyon reactor

GRAPHITE ISOTOPE RATIO METHOD (GIRM)



Based on data from Jungmin Kang, "Using the GIRM to Verify the DPRK's Plutonium-Production Declaration," *Science & Global Security*, 19 (2), 2011

DOCUMENT-BASED NUCLEAR ARCHAEOLOGY

(A first case study)



Indiana Jones: Raiders of the Lost Ark
Paramount Pictures, 1981



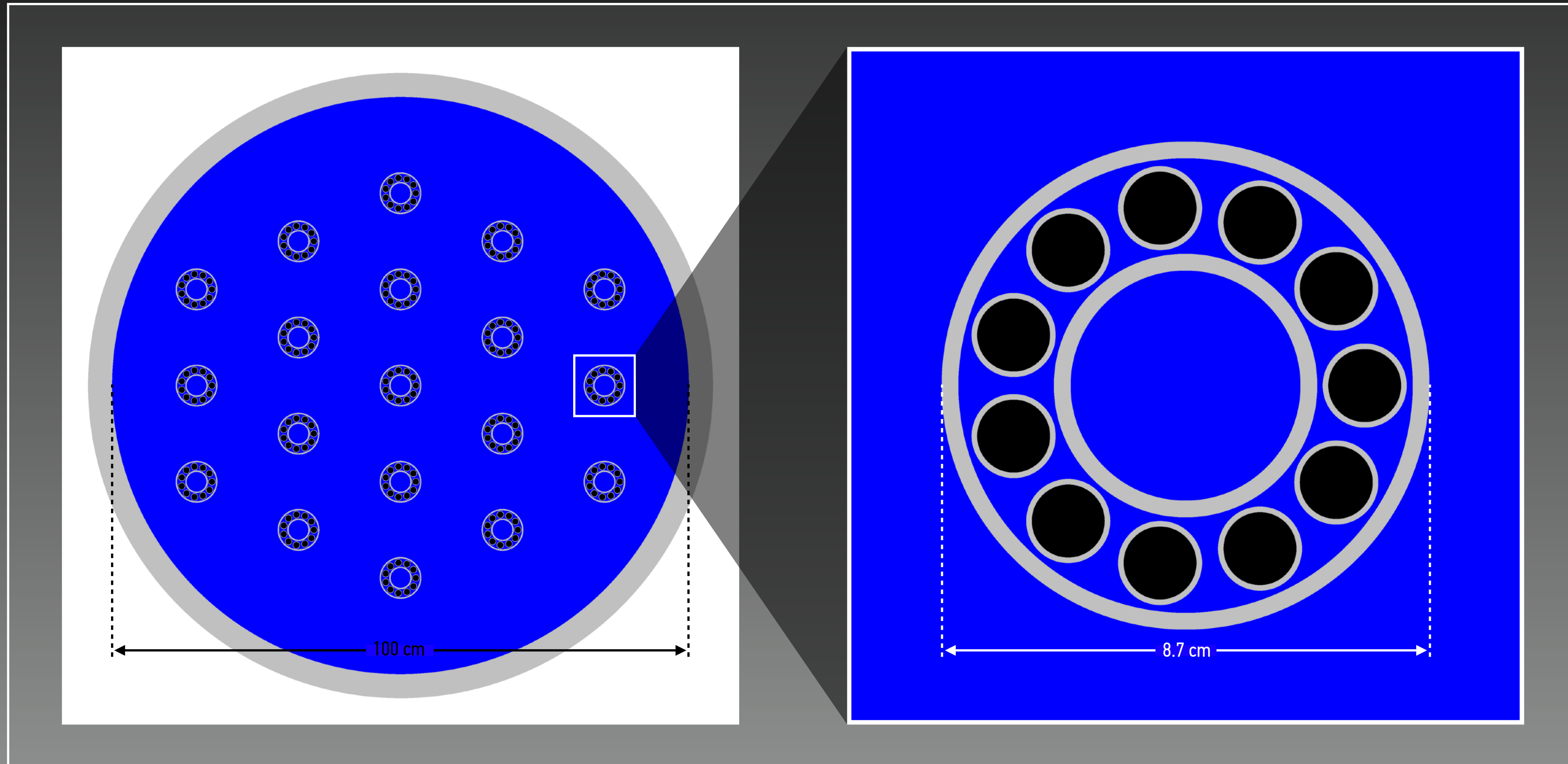
A large, cylindrical, silver-colored metal building with vertical corrugations, identified as the JEEP II Reactor. It stands on a green lawn under a clear blue sky. To the left, there are green trees. To the right, there are other buildings, including a multi-story orange one and a smaller white one with a dark roof. A paved path runs across the foreground grass.

JEEP II Reactor

*Institute for Energy Technology (IFE)
Kjeller, Norway, 12/1966–12/2018*

*2 MW
Heavy-water moderated and cooled
3.5%-enriched uranium fuel*

OPENMC/ONIX MODEL OF JEEP II



Paul K. Romano et al., "OpenMC: A State-of-the-Art Monte Carlo Code for Research and Development," *Annals of Nuclear Energy*, 82, 2015

Julien de Troullioud de Lanversin, Moritz Kütt, and Alexander Glaser, "ONIX: An Open-source Depletion Code," *Annals of Nuclear Energy*, 151, 2021

[View from the JEEP II Archive](#)

*Institute for Energy Technology (IFE)
Kjeller, Norway, July 2021*

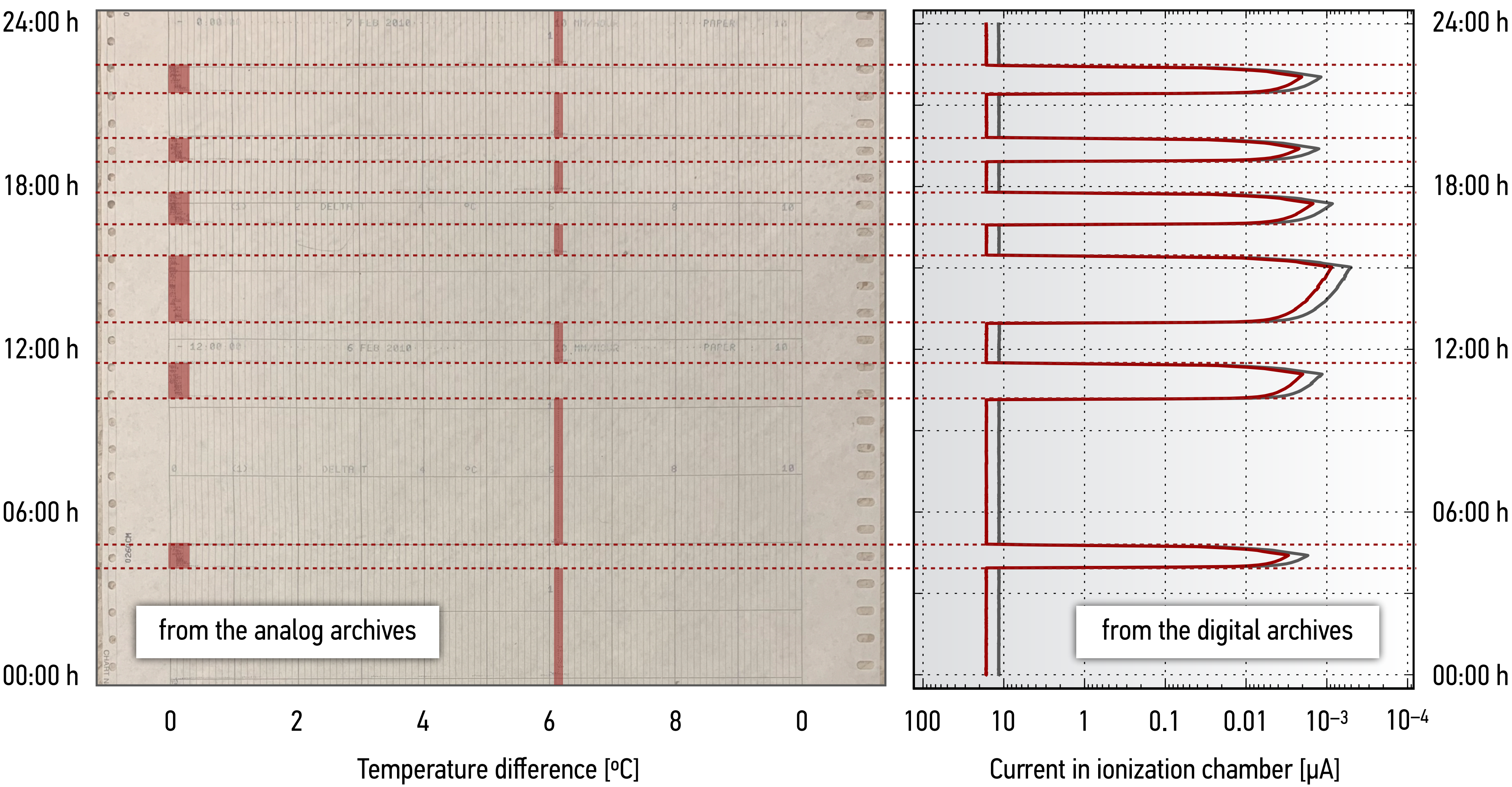
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T 5					58,1	60,6	60,6	60,6		
T 6					61,1	63,6	63,6	63,6		
T 9					64,1	66,6	66,6	66,6		
T 10					67,1	69,6	69,6	69,6		
T 12					70,1	72,6	72,6	72,6		
T 13					73,1	75,6	75,6	75,6		
T 15					76,1	78,6	78,6	78,6		
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T 51					109,1	111,6	111,6	111,6		
T 52					110,1	112,6	112,6	112,6		
T 53					111,1	113,6	113,6	113,6		
T 54					112,1	114,6	114,6	114,6		
T 56					113,1	115,6	115,6	115,6		
T 57					114,1	116,6	116,6	116,6		
T 62					115,1	117,6	117,6	117,6		
T 63					116,1	118,6	118,6	118,6		
T 64					117,1	119,6	119,6	119,6		
T 65					118,1	120,6	120,6	120,6		
T 66					119,1	121,6	121,6	121,6		
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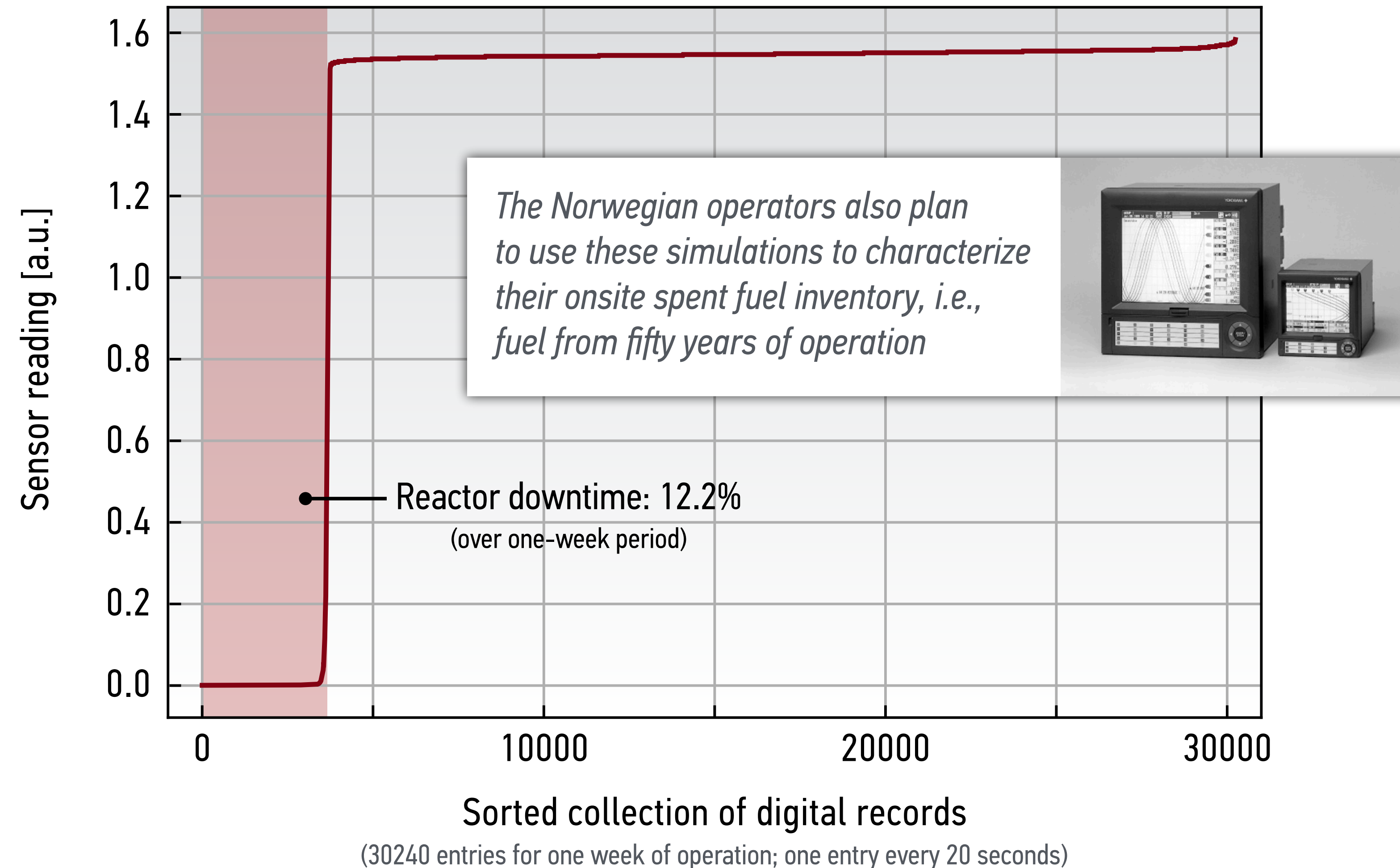
RECONCILING ANALOG AND DIGITAL RECORDS

SATURDAY, FEBRUARY 6, 2010



DETERMINING A CAPACITY FACTOR

FROM DIGITAL DATA AVAILABLE IN THE ARCHIVE



WHAT'S NEXT?

TEST BEDS FOR NUCLEAR ARCHAEOLOGY



Ågesta Reactor, Sweden



NRX, Canada



G2/G3, France

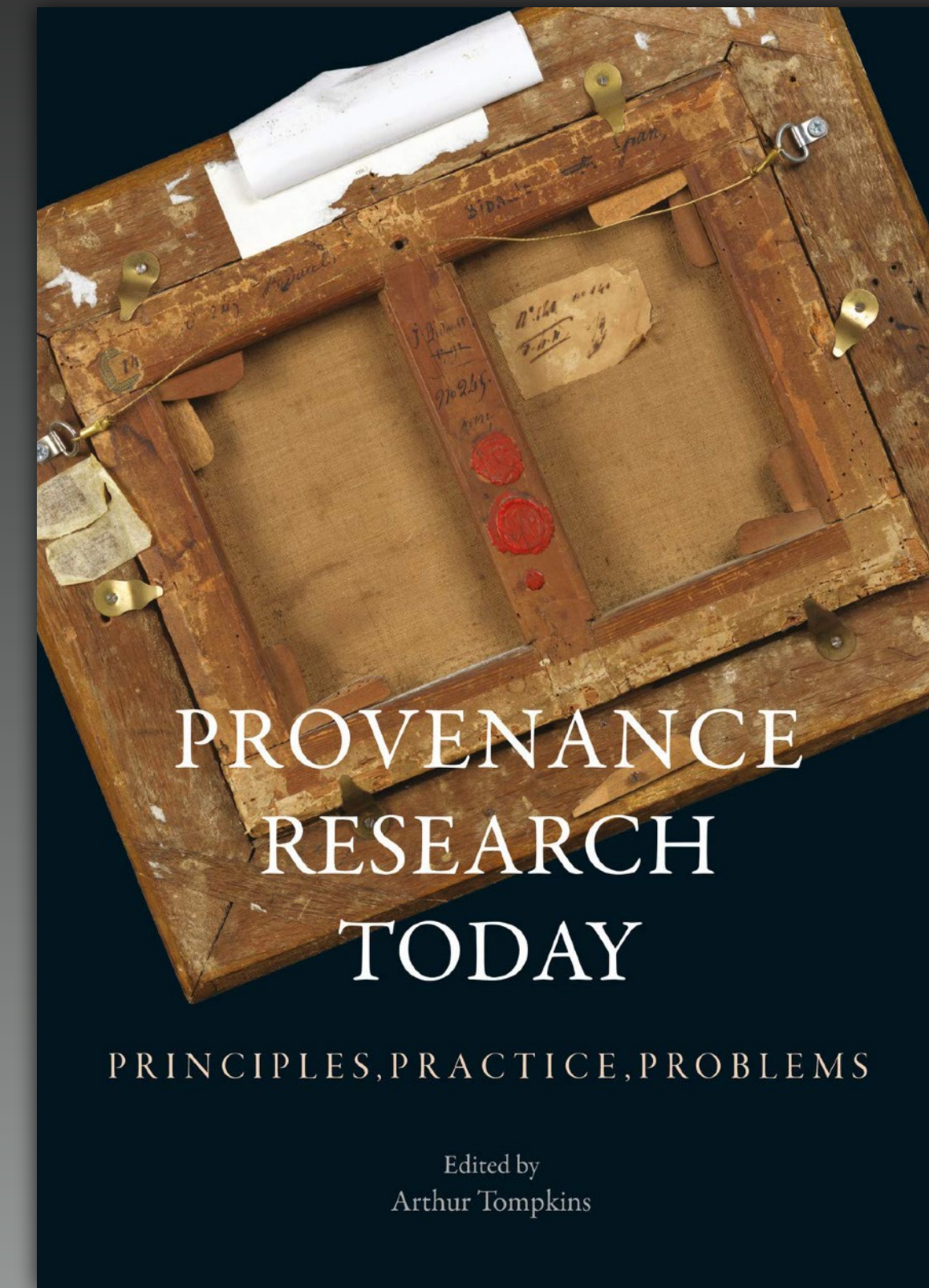
A MULTIDISCIPLINARY EFFORT

HOW TO CURATE AND PRESERVE ANALOG & DIGITAL DATA

HOW TO CONFIRM INTEGRITY, AUTHENTICITY, AND PROVENANCE OF RECORDS

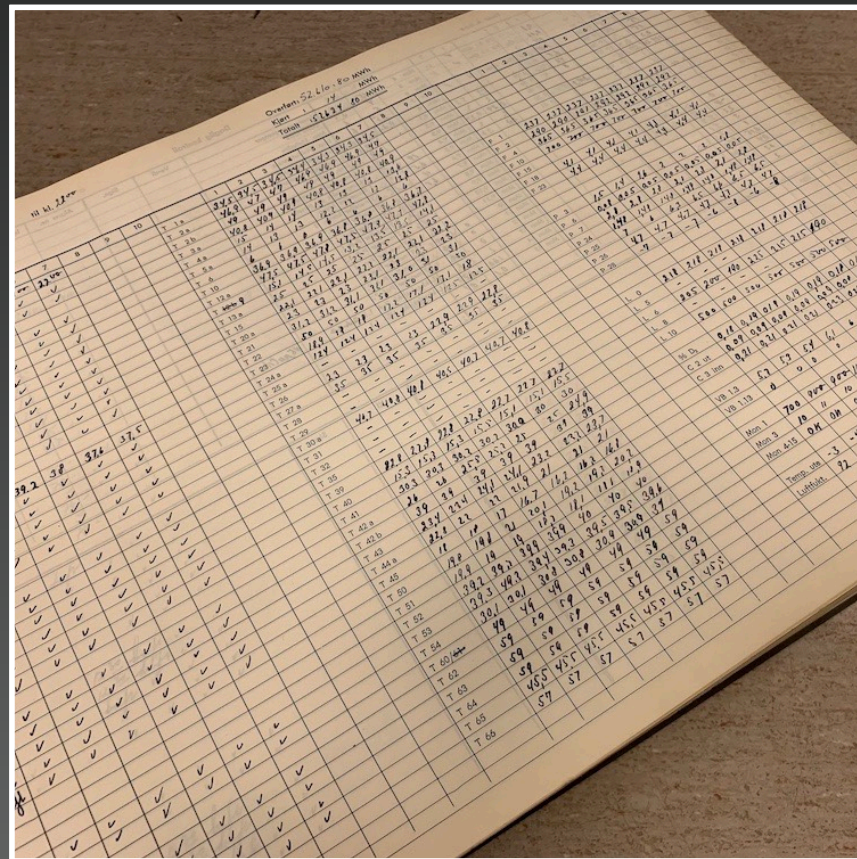


Source: asian-defence-news.blogspot.com



DEVELOPING A FIRST SET OF GUIDELINES

FOR DOCUMENT-BASED ARCHAEOLOGY



ANALOG RECORDS

Analog records can survive for decades, but require significant amounts of storage space

- Assess each type of a record's suitability for digitization
- Determine what properties of the physical records should be preserved in the digital surrogates
- Seek non-destructive digitization of logbooks and other physical records



DIGITAL OBJECTS

Digital records are more difficult to maintain than their analog counterparts

Requires decisions about file formats, metadata standards, and data management systems

Storage in repository that follows the Open Archival Information System (OAIS, www.oais.info) reference model and meets the criteria of established repository certification systems

Ole Reistad, Rebecca D. Frank, Alex Glaser, and Sindre H. Kaald, Document-based Nuclear Archaeology, *Science & Global Security*, 30 (2), 2022

CONCLUSION & WAY FORWARD



DEVELOP BEST PRACTICES FOR DOCUMENTING AND ARCHIVAL

No systematic efforts currently exist to archive and preserve the historical records of nuclear facilities at a level required for potential nuclear archaeology applications

Develop recommendations for data collection and storage at operational and future plants

This is a time critical effort (as facilities are being demolished, records destroyed, and staff retires)



A TIME FOR ACTION

Lead by example with regard to openness and transparency

Document-based archaeology can help support ongoing or planned decommissioning efforts

JEEP II case study has provided first insights ... but other participants are urgently needed

Source: www.flickr.com/photos/iaea_imagebank (top) and IFE (bottom)

SCIENCE & GLOBAL SECURITY

 PRINCETON UNIVERSITY

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Digital Future

