NEXT STEPS TOWARD VERIFIED NUCLEAR DISARMAMENT

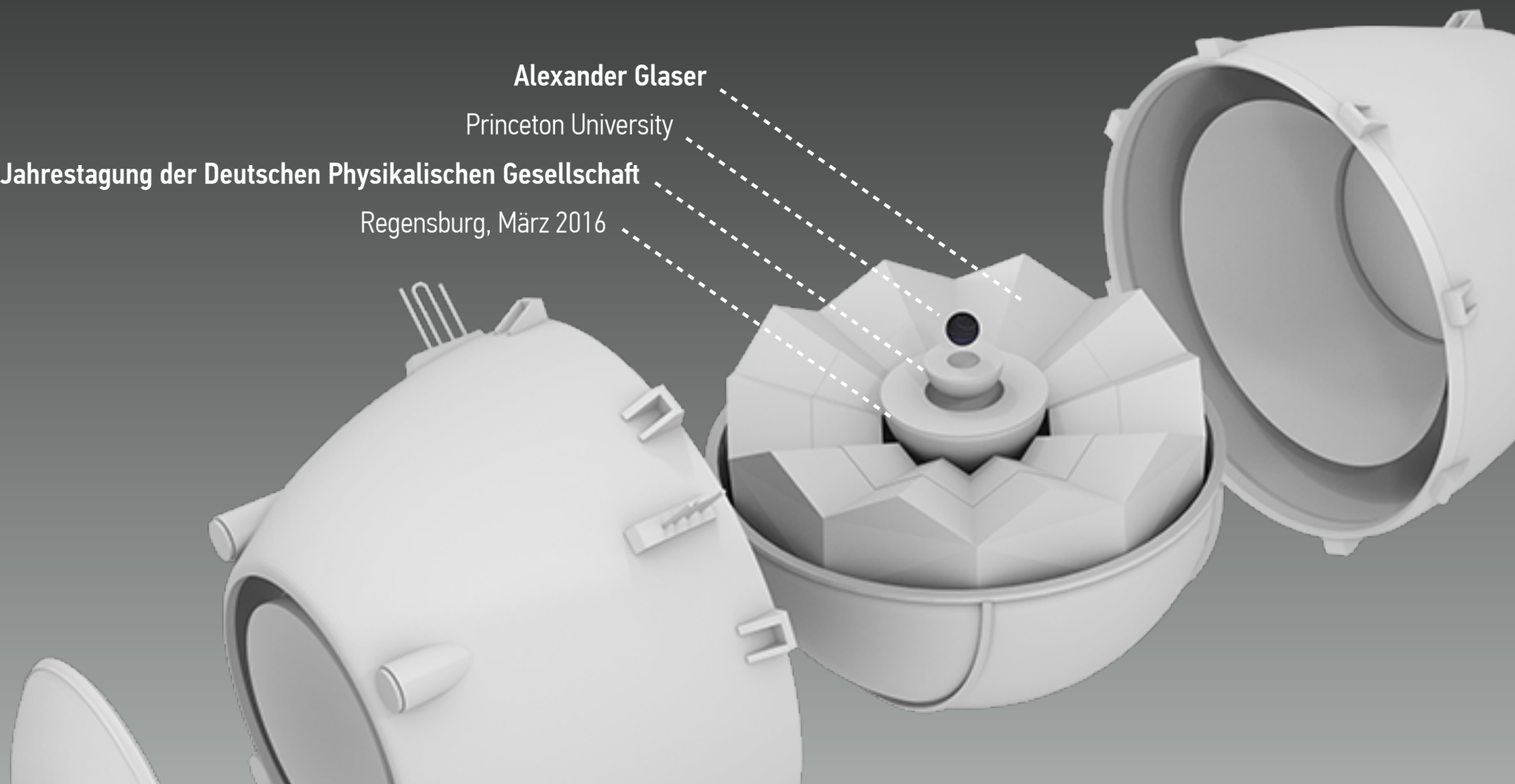
A RESEARCH AGENDA FOR PHYSICISTS WITHOUT SECURITY CLEARANCES

Alexander Glaser

Princeton University

Jahrestagung der Deutschen Physikalischen Gesellschaft

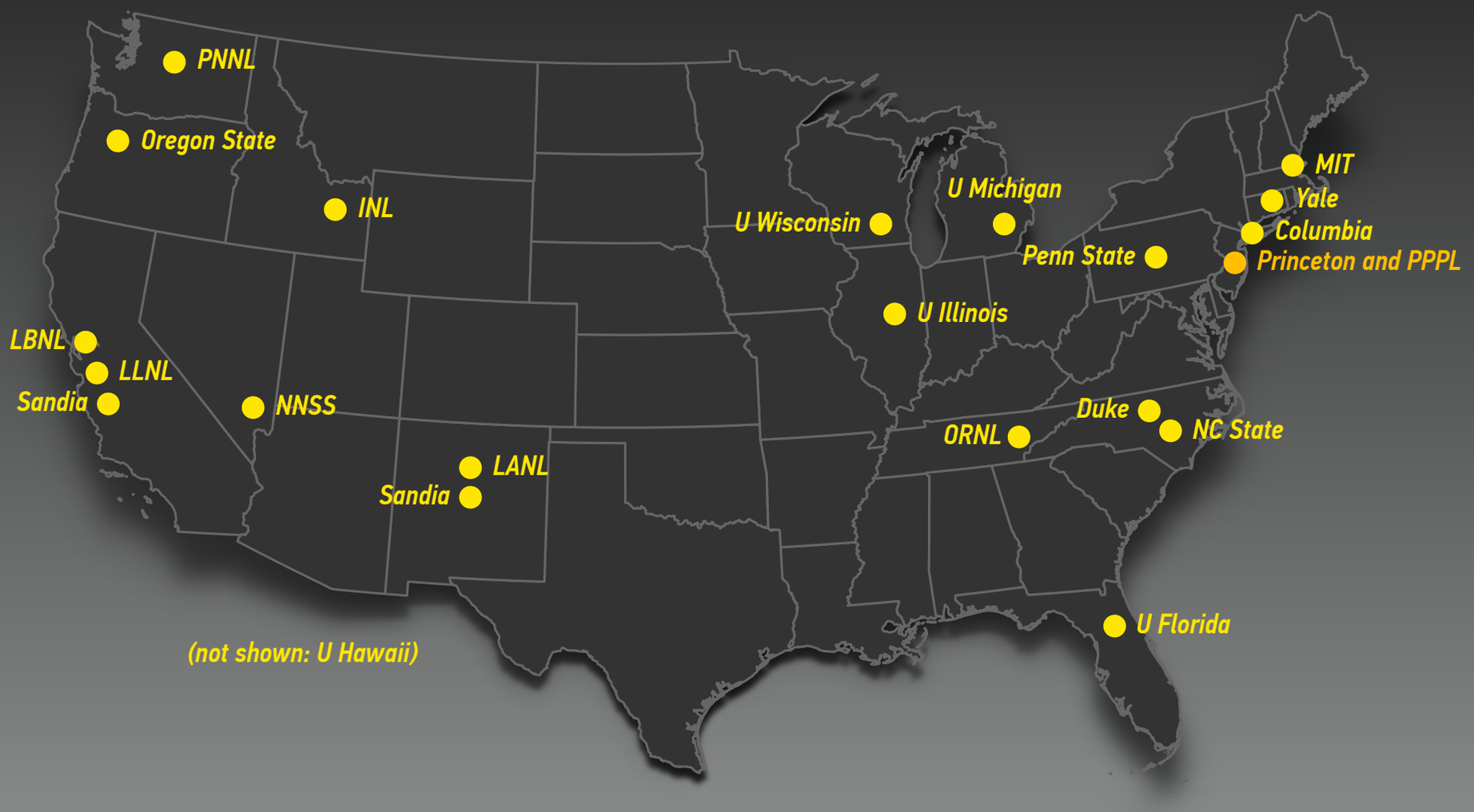
Regensburg, März 2016



Revision 3

CONSORTIUM FOR VERIFICATION TECHNOLOGY

A FIVE-YEAR PROJECT FUNDED BY THE U.S. DEPARTMENT OF ENERGY

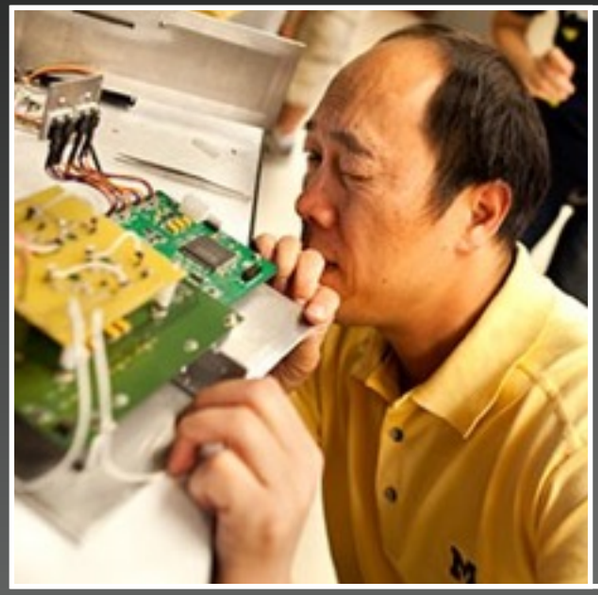


13 U.S. universities and 9 national labs, led by University of Michigan

Princeton participates in the research thrust on disarmament research
(and leads the research thrust of the consortium on policy)

CONSORTIUM FOR VERIFICATION TECHNOLOGY

BACKGROUND



TWO WAYS OF APPROACHING THE VERIFICATION PROBLEM

Technology-focused and mission-focused approach;

CVT seeks to combine both; unique opportunities for synergisms given diversity of 13 + 9 CVT partner institutions and groups

POLICY THRUST: A TREATY-ENABLING APPROACH

Emphasizes mission-focused dimension (as defined by existing and expected future treaties); support and guide CVT technology developments toward specific treaty applications; track emerging technologies

Source: www.engin.umich.edu (top) and news.kremlin.ru (bottom)

RELEVANT NUCLEAR ARMS CONTROL TREATIES

NUCLEAR NON-PROLIFERATION TREATY

Bans the acquisition of nuclear weapons by non-weapon states and commits the five weapon states to nuclear disarmament; verified by IAEA safeguards

COMPREHENSIVE TEST BAN TREATY

Bans all nuclear explosions in all environments and would be verified by extensive verification mechanisms (International Monitoring System, CTBTO)

FISSILE MATERIAL (CUTOFF) TREATY

At a minimum, treaty would ban fissile material production for weapons purposes;
Issue about treaty scope: Would it also cover existing stocks?

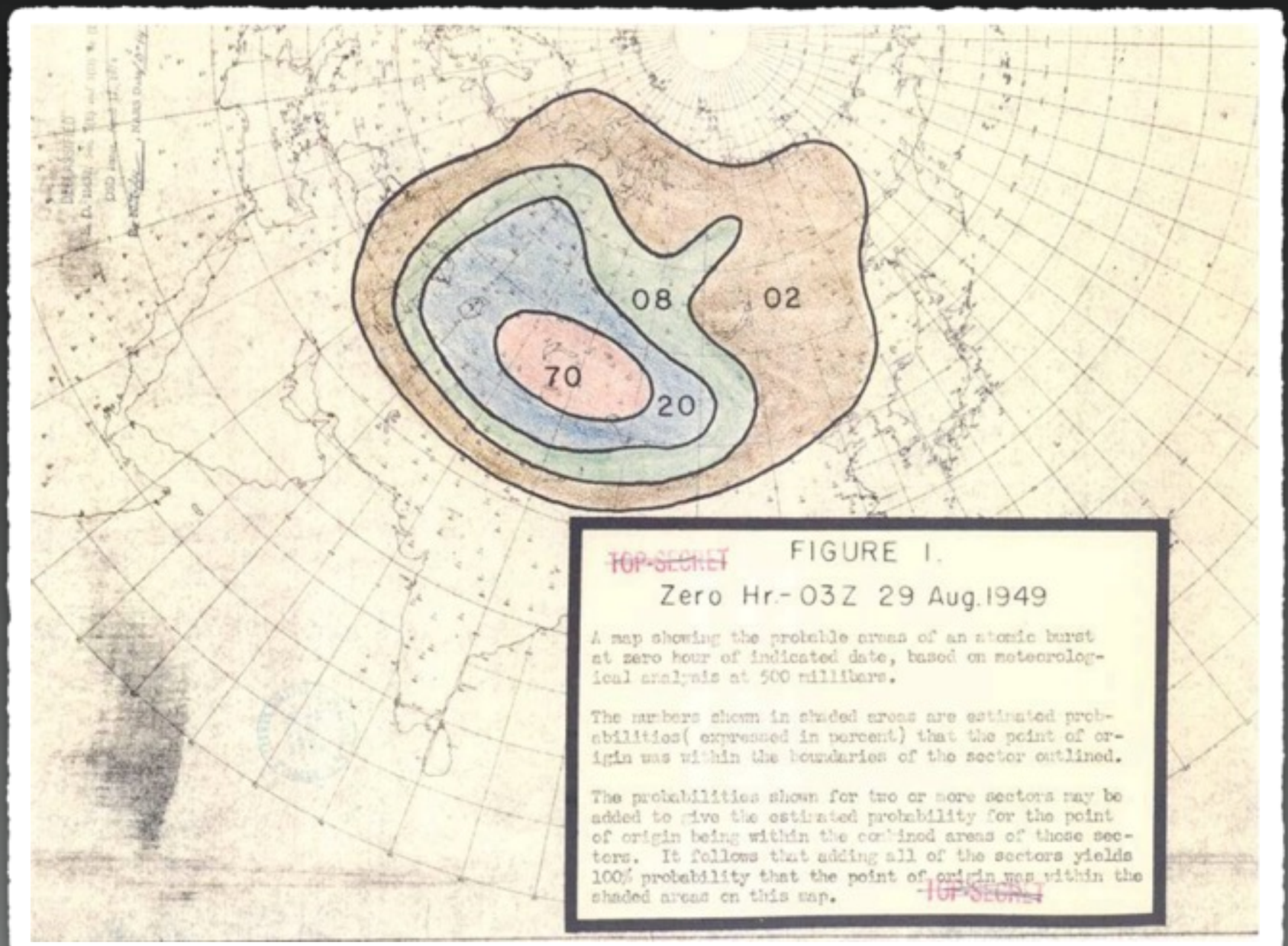
NEXT-GENERATION NUCLEAR DISARMAMENT TREATIES

Agreements that place limits on total number of nuclear warheads in arsenals would pose qualitatively new verification challenges

BACKGROUND

SCIENCE AND TECHNOLOGY OF NUCLEAR VERIFICATION

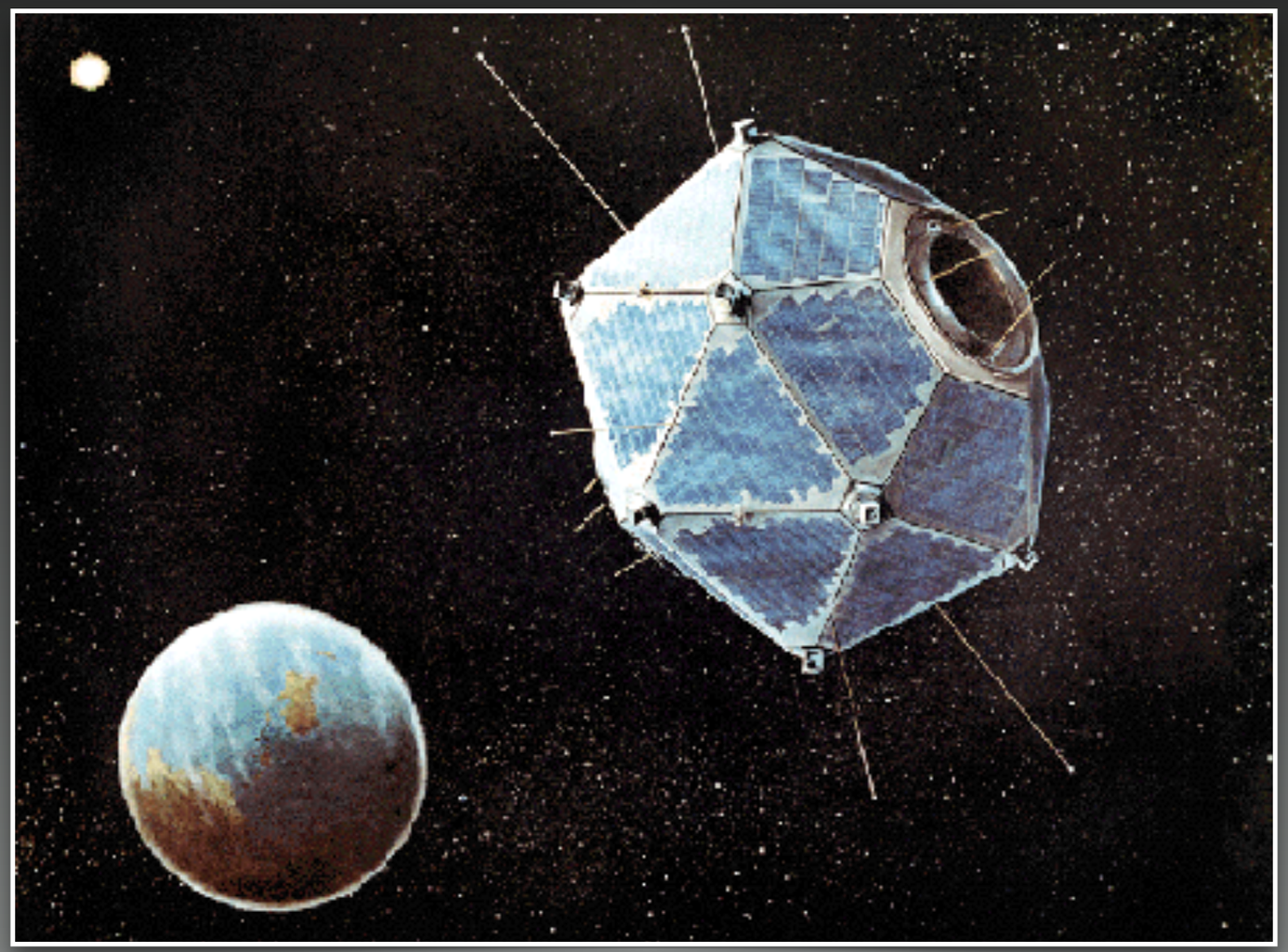
DETECTION OF "JOE-1" IN AUGUST 1949



Source: U.S. Weather Bureau Report on Alert Number 112 of the Atomic Detection System, 29 September 1949, PSF: Subject File 1940-1953, National Security Council – Atomic Files, Box 173, Folder: "Atomic Bomb: Reports," Harry S. Truman Presidential Library; Courtesy: Michael D. Gordin, Princeton University

THE VELA SATELLITE PROGRAM

1963–1984



Part of the system of “national technical means” to monitor compliance with the 1963 Limited Test Ban Treaty (Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space, and Under Water)

Satellites used non-imaging photodiodes to monitor light levels

GROUP OF SCIENTIFIC EXPERTS

1976–1996

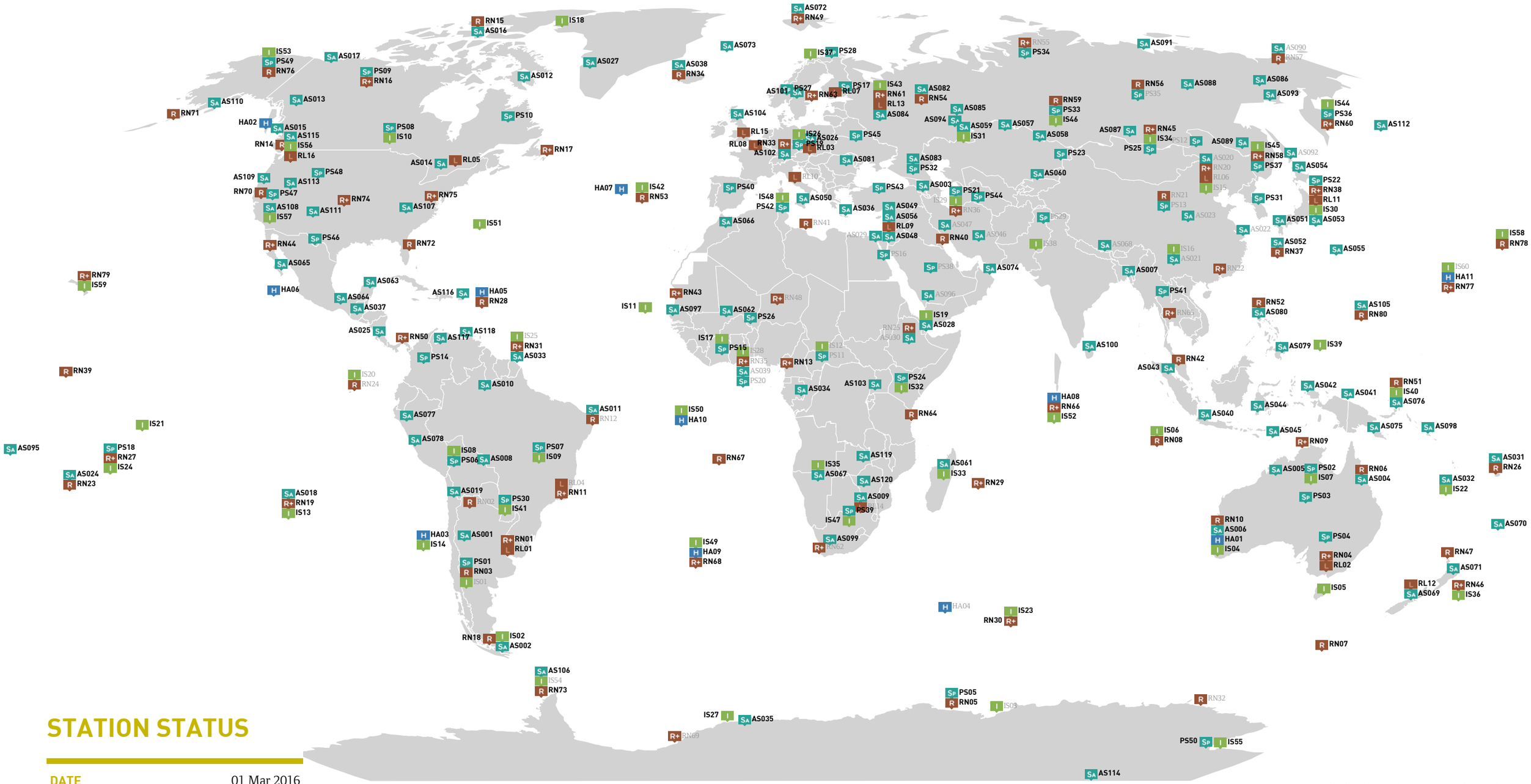
www.ctbto.org/the-treaty/1993-1996-treaty-negotiations/1993-95-prelude-and-formal-negotiations

INTERNATIONAL MONITORING SYSTEM

GLOBAL OVERVIEW - CERTIFIED STATIONS AND NON-CERTIFIED STATIONS

01 MARCH 2016

CTBTO PREPARATORY COMMISSION | preparatory commission for the comprehensive nuclear-test-ban treaty organization



STATION STATUS

DATE	01 Mar 2016
TOTAL STATIONS	337
PLANNING	18
UNDER CONSTRUCTION	18
INSTALLED	19
CERTIFIED	282

SP Primary Seismic | SA Auxiliary Seismic | I Infrasound | H Hydroacoustic | R Radionuclide | R+ Radionuclide w/ Noble Gas | L Radionuclide Lab

WWW.CTBTO.ORG

VERIFICATION CHALLENGES

OF NUCLEAR DISARMAMENT

WHAT IS TO BE VERIFIED?

VERIFICATION CHALLENGES OF NUCLEAR DISARMAMENT

1. VERIFYING NUMERICAL LIMITS OF DECLARED NUCLEAR WARHEADS

   Requires techniques to account for (and identify) nuclear warheads in storage

   for example, using (hashed) declarations, special tags, and/or unique identifiers (UIDs)

2. CONFIRMING THE AUTHENTICITY OF NUCLEAR WARHEADS

   Requires dedicated inspection systems

   for example, based on radiation-detection techniques (passive/active, neutron/gamma)

3. ESTABLISHING CONFIDENCE IN THE ABSENCE OF UNDECLARED STOCKS OR PRODUCTION

   How to make sure that no covert warheads / materials exist outside the verification regime?

   No silver bullet, but many different techniques and approaches

Source: Paul Shambroom (top), U.S. Department of Energy (middle), and Google Earth (bottom)

VERIFICATION CHALLENGE 1

CONFIRMING NUMERICAL LIMITS

ON TREATY ACCOUNTABLE ITEMS

THOUSANDS OF NUCLEAR WEAPONS

ARE CURRENTLY IN RESERVE OR AWAITING DISMANTLEMENT

W87/Mk-21 Reentry Vehicles in storage, Warren Air Force Base, Cheyenne, Wyoming

Photo courtesy of Paul Shambroom, www.paulshambroom.com

TAGGING

TRANSFORMING A “NUMERICAL LIMIT” INTO A “BAN ON UNTAGGED ITEMS”

Source: www.automoblog.net

Steve Fetter and Thomas Garwin, “Using Tags to Monitor Numerical Limits in Arms Control Agreements” in Barry M. Blechman, ed., Technology and the Limitation of International Conflict, Washington, DC, 1989, pp. 33–54

VERIFYING NUMERICAL LIMITS OF DECLARED NUCLEAR WARHEADS

WARHEAD TAGGING OPTIONS

1

Serial number on warhead

Non-intrusiveness

Robustness

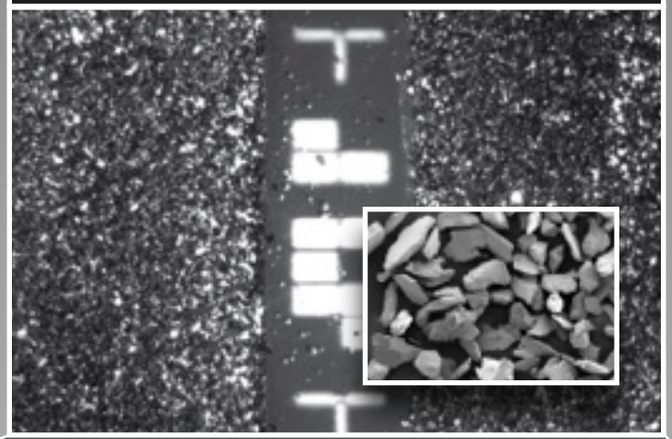
2

Unique ID on warhead

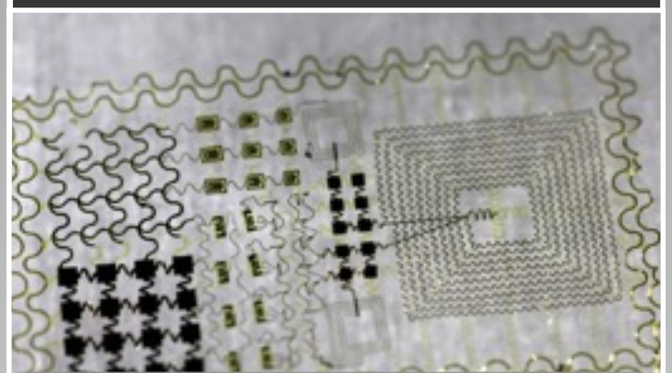
Non-intrusiveness

Robustness

Reflective Particle Tags



"Electronic Tattoos"



Source: John Rogers, University of Illinois

3

Simple Buddy Tag

Non-intrusiveness

Robustness

4

Buddy Tag with serial number

Non-intrusiveness

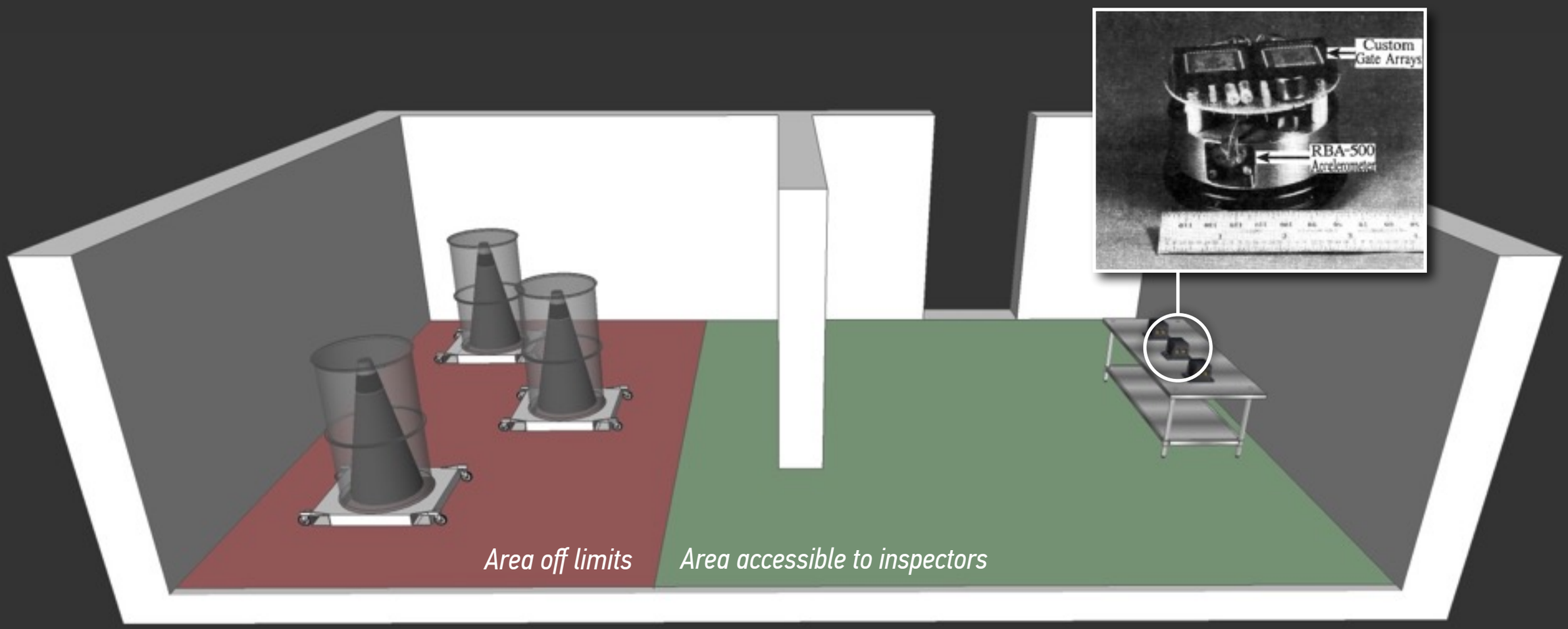
Robustness

Reflective particle tag concept: A. Gonzales, *Reflective Particle Tag for Arms Control and Safeguards Authentication,* Sandia National Laboratories, 2004

Original buddy tag concept: S. E. Jordan, *Buddy Tag's Motion Sensing and Analysis Subsystem,* Sandia National Laboratories, 1991

MINIMALLY INTRUSIVE VERIFICATION APPROACHES

Unique identifiers (UIDs) don't necessarily have to be directly attached to treaty accountable items



Project on advanced buddy tags, launched in Oct. 2015, U.S. Department of State, Bureau of Arms Control, Verification and Compliance, SNL/Princeton
Original buddy tag concept: S. E. Jordan, Buddy Tag's Motion Sensing and Analysis Subsystem, Sandia National Laboratories, 1991

FULL-MOTION VIRTUAL REALITY

FOR EXPLORING MANAGED-ACCESS AND WARHEAD-DISMANTLEMENT PROCEDURES

(WITH REAL-TIME VIRTUAL RADIATION FIELDS)

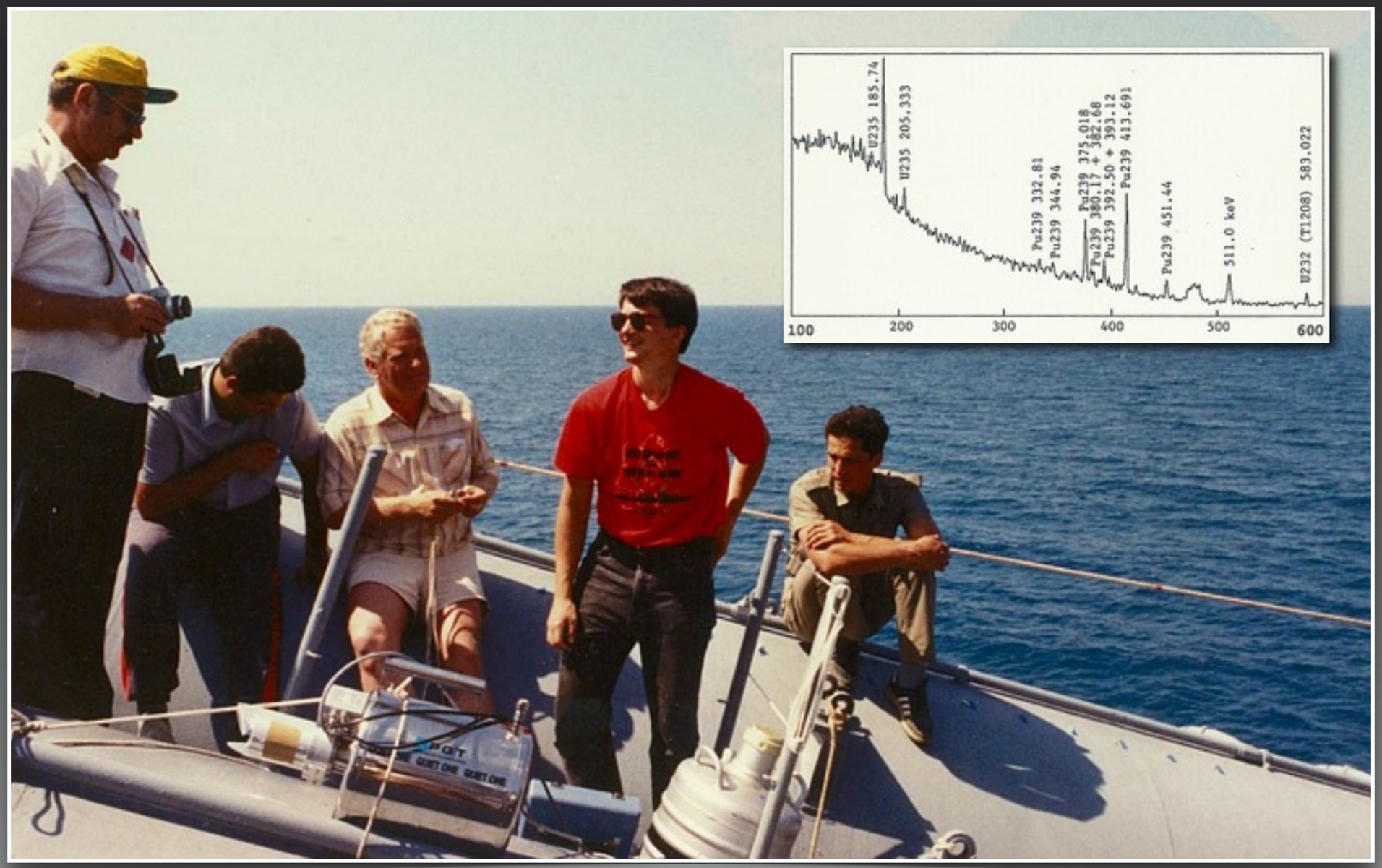
VERIFICATION CHALLENGE 2

CONFIRMING THE AUTHENTICITY OF A NUCLEAR WARHEAD

(WHILE LEARNING NOTHING ABOUT IT)

NUCLEAR WEAPONS HAVE UNIQUE SIGNATURES

BUT THEY ARE SENSITIVE AND CANNOT BE REVEALED TO INSPECTORS



U.S. Scientists on a Soviet Cruiser in the Black Sea, 1989

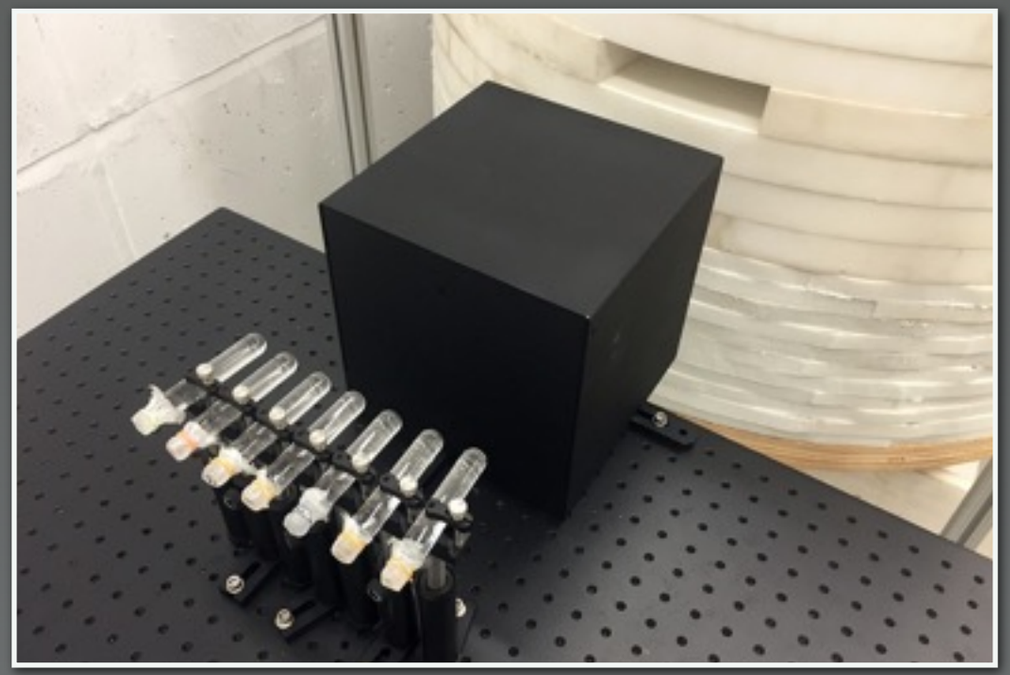
PREVENTING THE EXCHANGE OF SENSITIVE INFORMATION DURING A RADIATION MEASUREMENT

TRUSTED INFORMATION BARRIER

Measure (but sanitize) sensitive information

"Hard" to authenticate and certify

Single-bit observation



INTERACTIVE ZERO-KNOWLEDGE PROOF

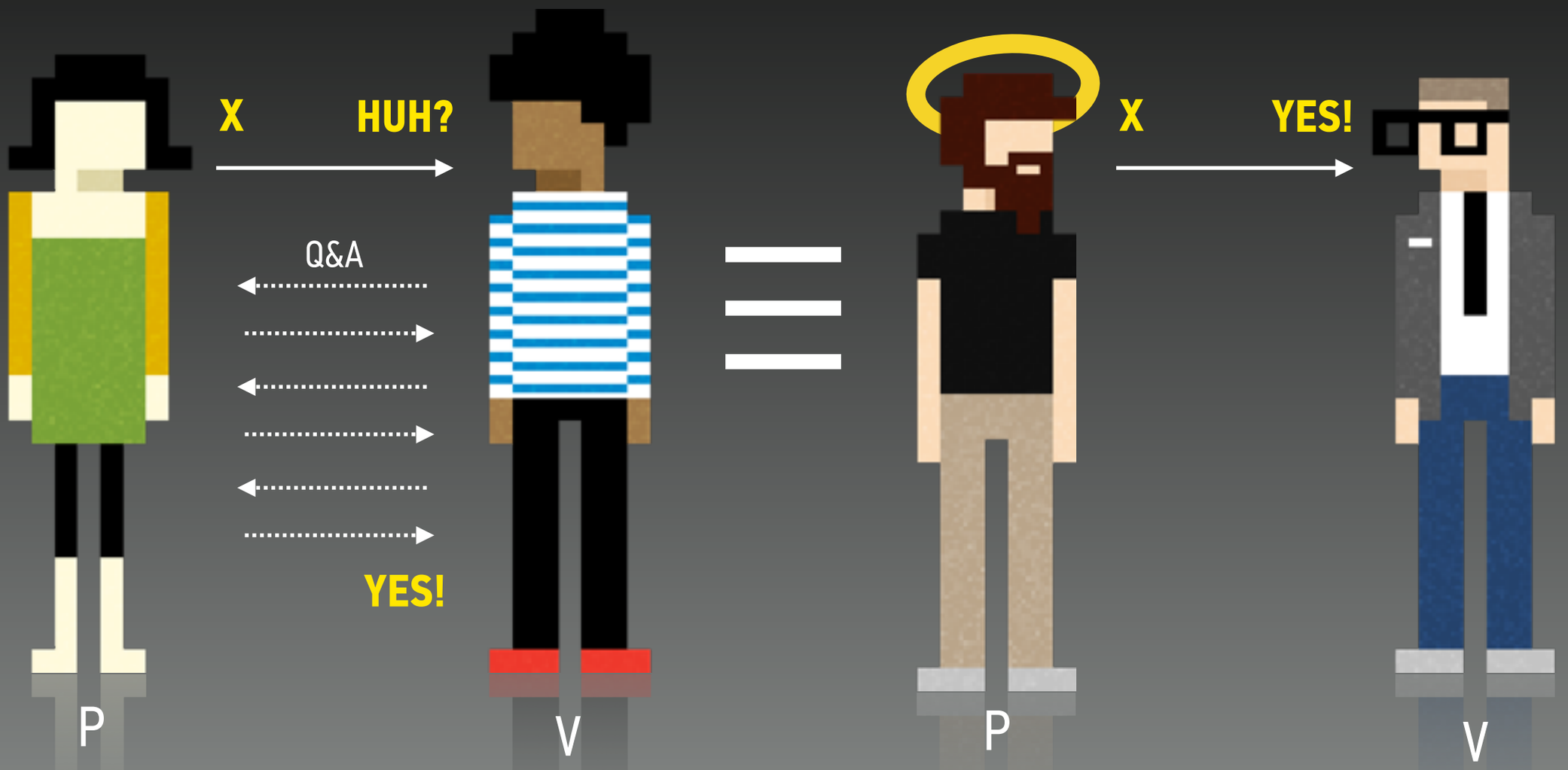
Never measure sensitive information

"Easy" to authenticate and certify

More complex observation

S. Philippe, B. Barak, and A. Glaser, "Designing Protocols for Nuclear Warhead Verification"
56th Annual INMM Meeting, July 12-16, 2015, Indian Wells, California

INTERACTIVE ZERO-KNOWLEDGE PROOFS



Zero-Knowledge Proofs: The prover (P) convinces the verifier (V)
that s/he knows a secret without giving anything about the secret itself away

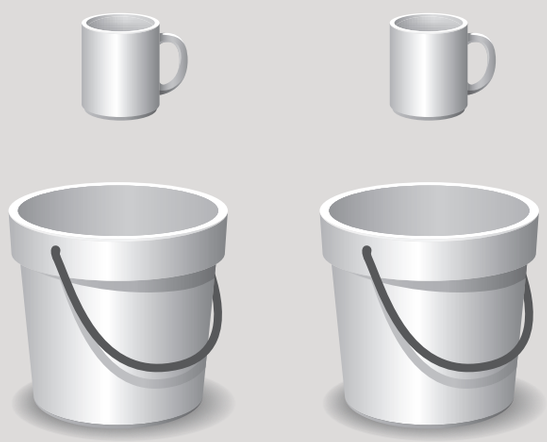
O. Goldreich, S. Micali, A. Wigderson, "How to Play ANY Mental Game," 19th Annual ACM Conference on Theory of Computing, 1987
Graphics adapted from O. Goldreich, *Foundations of Cryptography,* Cambridge University Press, 2001; and eightbit.me

PHYSICAL ZERO-KNOWLEDGE PROOF

"NUMBER OF MARBLES IN A CUP"

1

Alice claims that
two cups contain the same
number of marbles



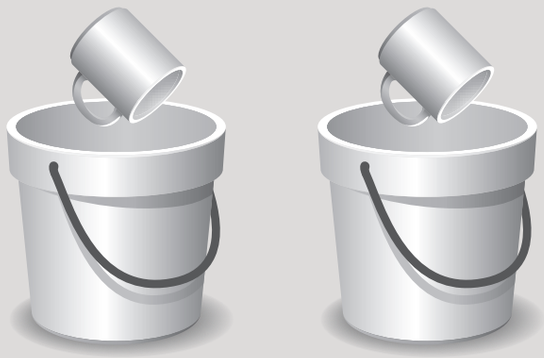
She then also offers
two buckets of marbles

She claims these buckets also contain
an identical number of marbles

2

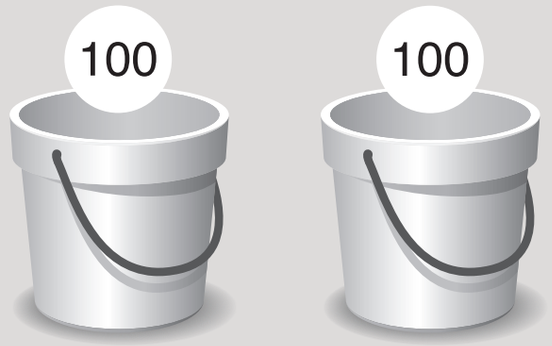
Bob chooses randomly
into which bucket
which cup is poured

(L,L) and (R,R) or (L,R) and (R,L)



3

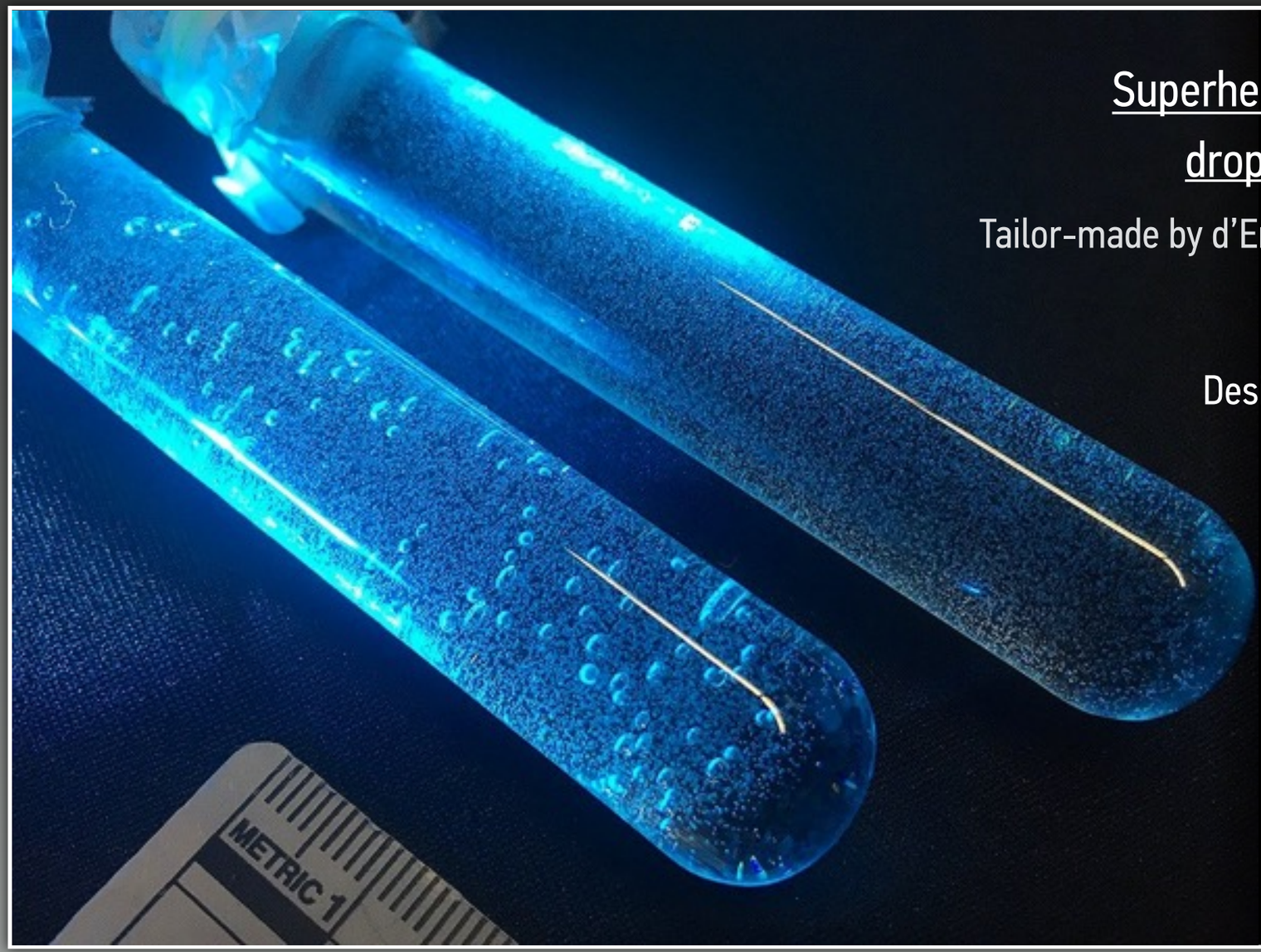
Bob now counts the marbles
in each bucket and should
find the same number in both



50% confidence after 1st game
75% confidence after 2nd game
95% confidence after 5th game

SUPERHEATED DROPLET DETECTORS OFFER A WAY TO IMPLEMENT THIS PROTOCOL

AND AVOID DETECTOR-SIDE ELECTRONICS



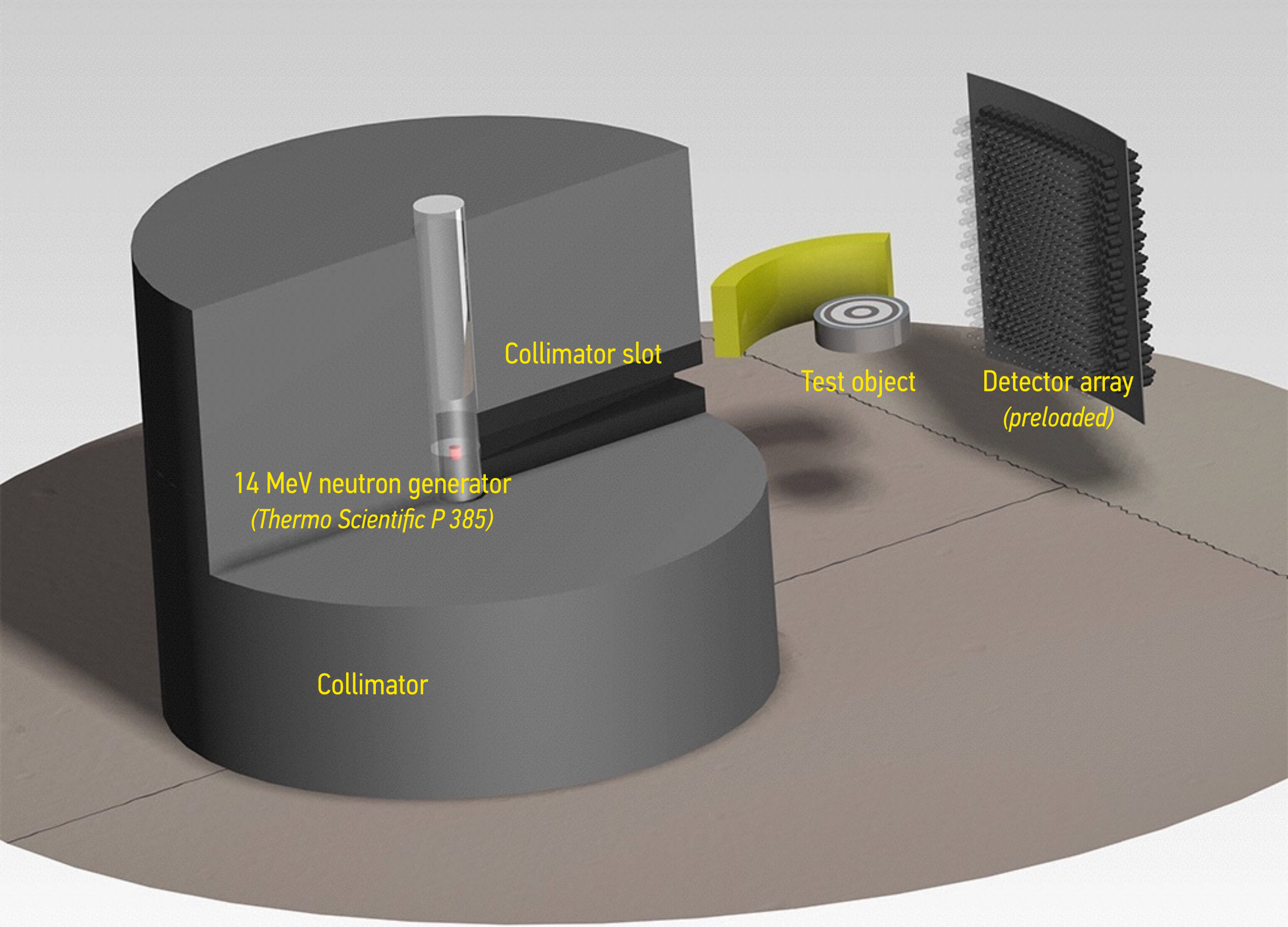
Superheated C-318 fluorocarbon (C_4F_8)
droplets suspended in aqueous gel

Tailor-made by d'Errico Research Group, Yale University

Sensitive to neutrons with $E_n > E_{min}$

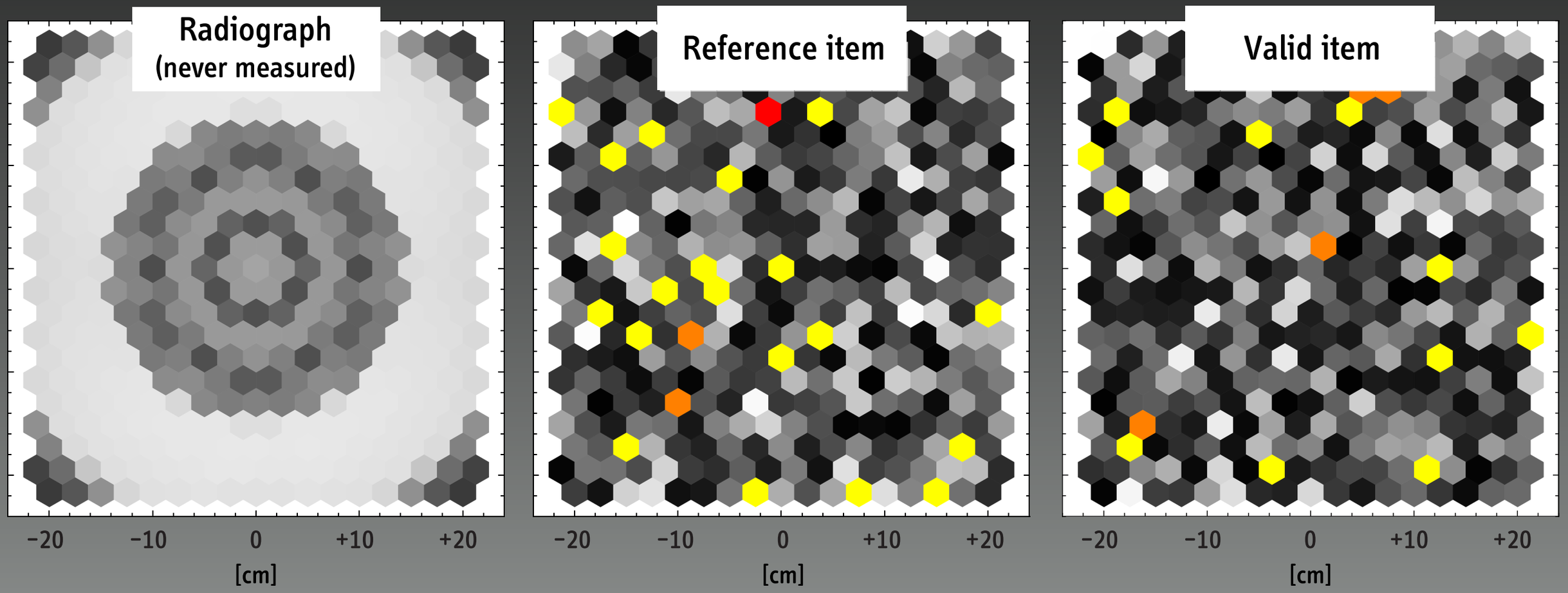
Designed to be insensitive to γ-radiation

Active volume ..... : 6.0 cm^3
Droplet density ..... : 3500 cm^{-3}
Droplet diameter ..... : ~100 μm
Absolute Efficiency ... : 4 x 10^{-4}


Collimator slot
Test object
Detector array
(preloaded)
14 MeV neutron generator
(Thermo Scientific P 385)
Collimator

ZERO-KNOWLEDGE VERIFICATION

RADIOGRAPHY WITH 14 MEV NEUTRONS

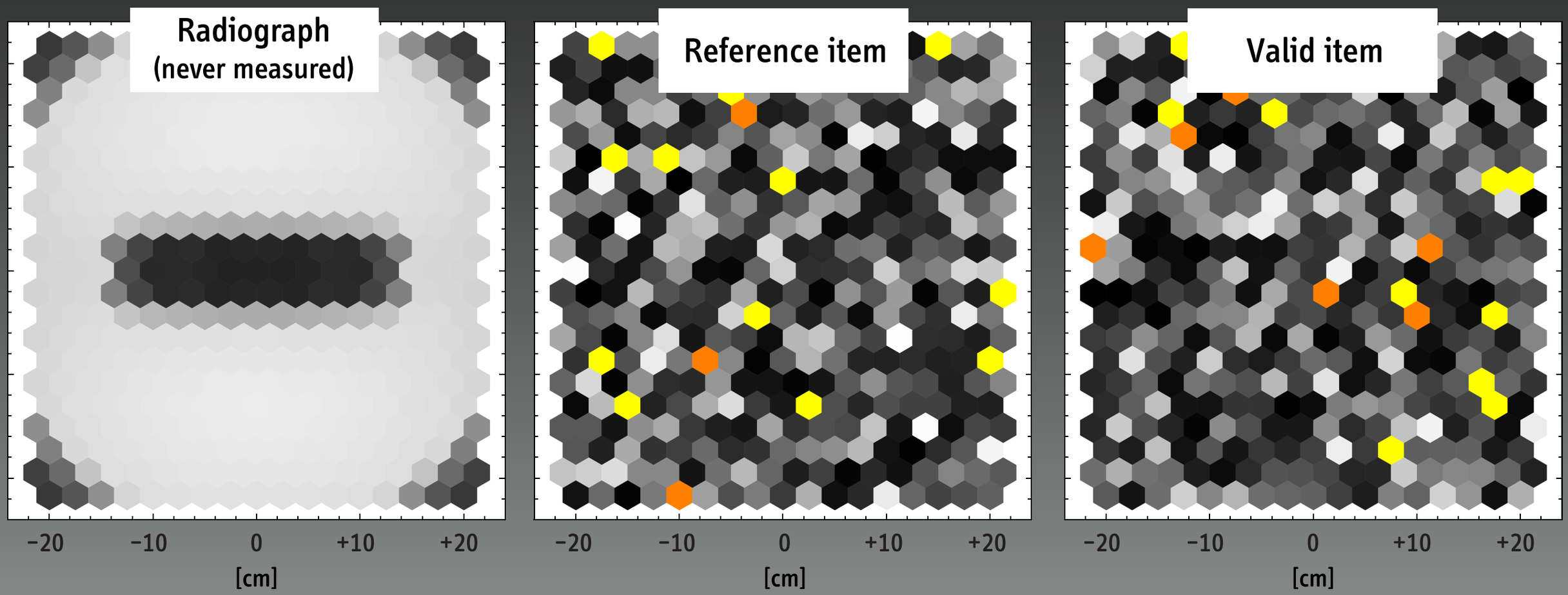


Simulated data from MCNP calculations; neutron detection energies > 10 MeV; N(max) = 5,000

A. Glaser, B. Barak, R. J. Goldston, "A Zero-knowledge Protocol for Nuclear Warhead Verification," *Nature,* 510, 26 June 2014, 497–502

ZERO-KNOWLEDGE VERIFICATION

RADIOGRAPHY WITH 14 MEV NEUTRONS



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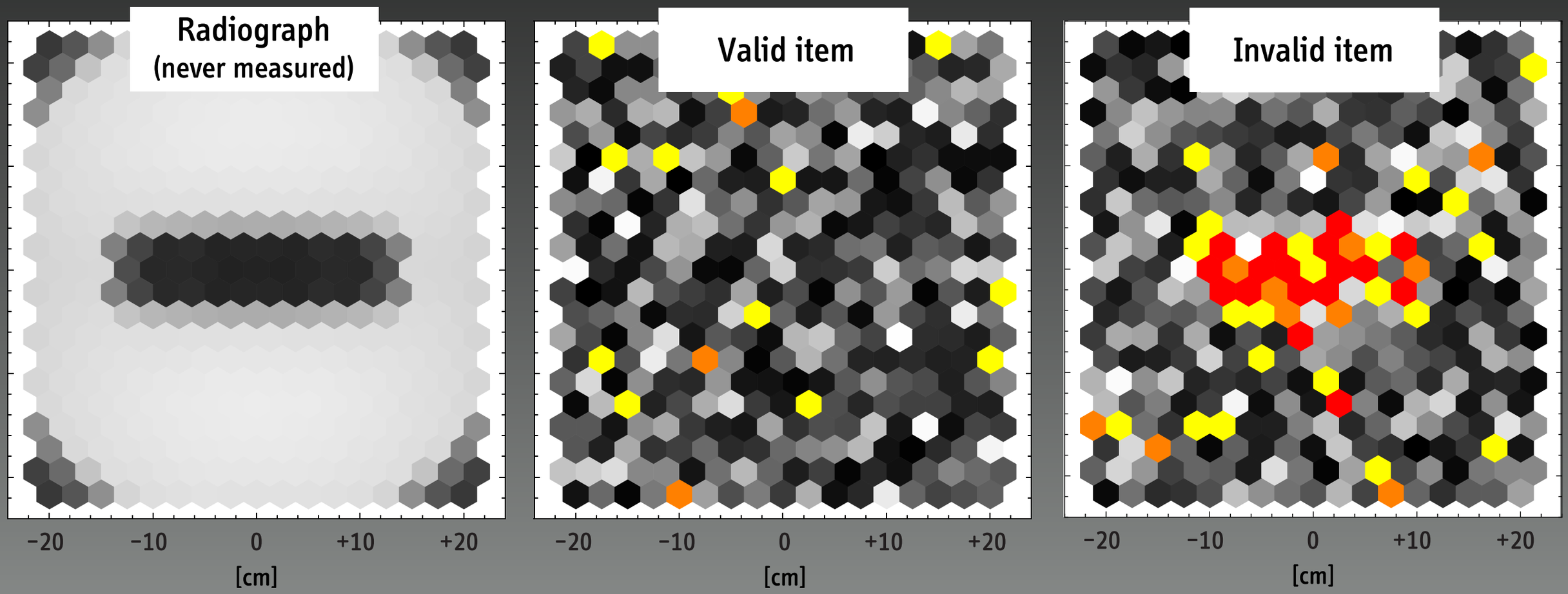
A. Glaser, B. Barak, R. J. Goldston, "A Zero-knowledge Protocol for Nuclear Warhead Verification," *Nature,* 510, 26 June 2014, 497–502

ZERO-KNOWLEDGE VERIFICATION

RADIOGRAPHY WITH 14 MEV NEUTRONS

(Tungsten rings replaced by lead rings)

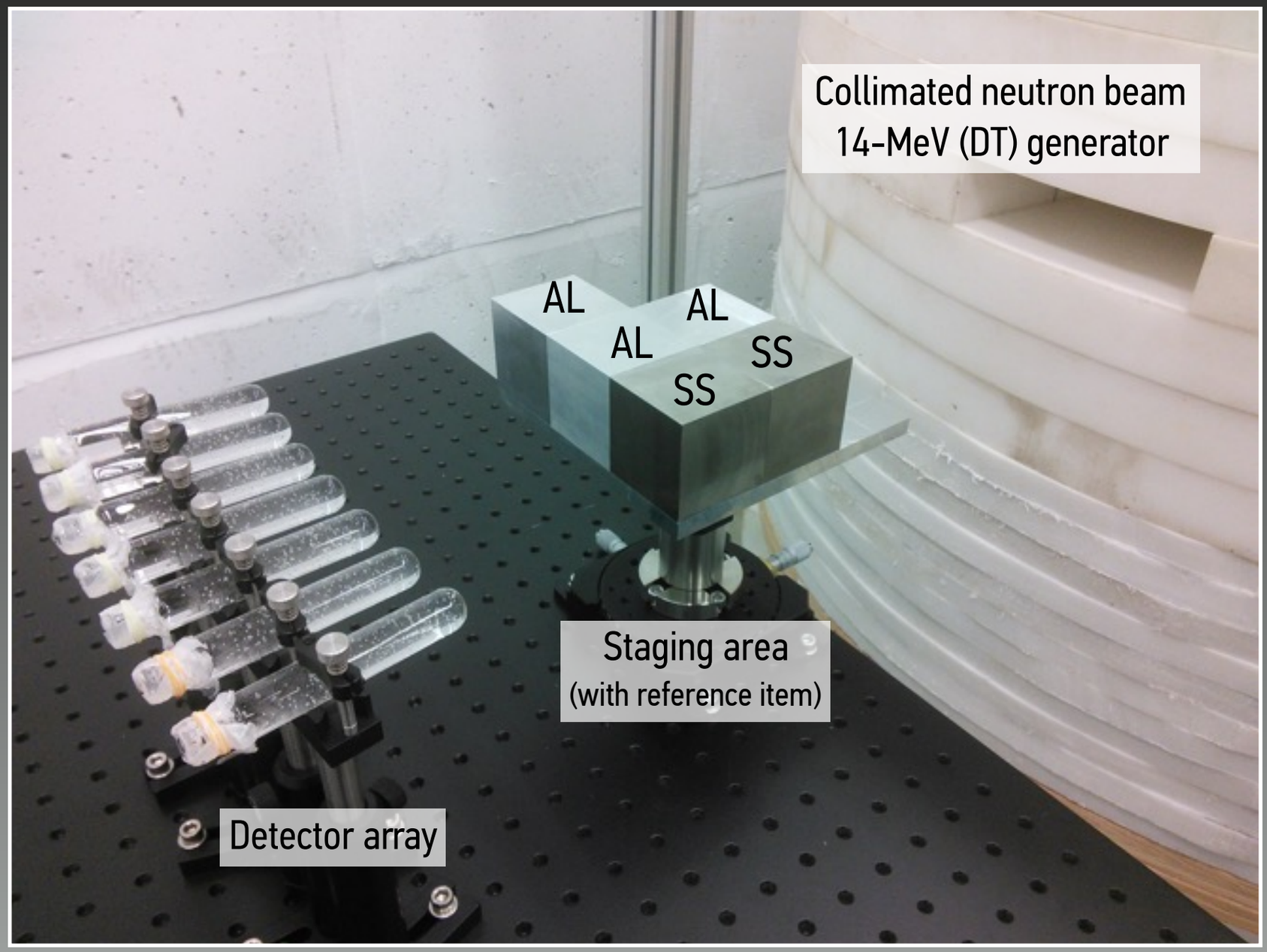


Simulated data from MCNP calculations; neutron detection energies > 10 MeV; N(max) = 5,000

A. Glaser, B. Barak, R. J. Goldston, "A Zero-knowledge Protocol for Nuclear Warhead Verification," *Nature,* 510, 26 June 2014, 497–502

EXPERIMENTAL SETUP AND SCENARIO

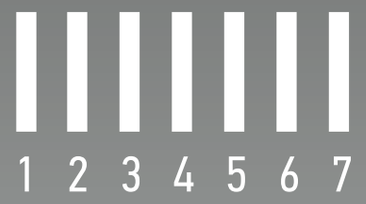
WE WISH TO IDENTIFY CASES IN WHICH THE CUBE PATTERN HAS BEEN ALTERED WITHOUT GAINING ANY INFORMATION ABOUT THE CONFIGURATION IN CASES WHERE IT HAS NOT



Reference item consists of a combination of 2-inch cubes (aluminum and stainless steel)

Reference item

X	X	X
X	AL	SS
AL	AL	SS



Detector positions


CRAFTSMAN
SanDisk
Programming the Raspberry Pi


ACQUIRE TEMPLATE
STATUS
POWER
MATCH
READY
BUSY
TEMPLATE
MISMATCH
INSPECT ITEM
PRESENT
CLEAR

VERIFICATION CHALLENGE 3

CONFIRMING COMPLETENESS

OF NUCLEAR WEAPON AND FISSILE MATERIAL STOCKPILES

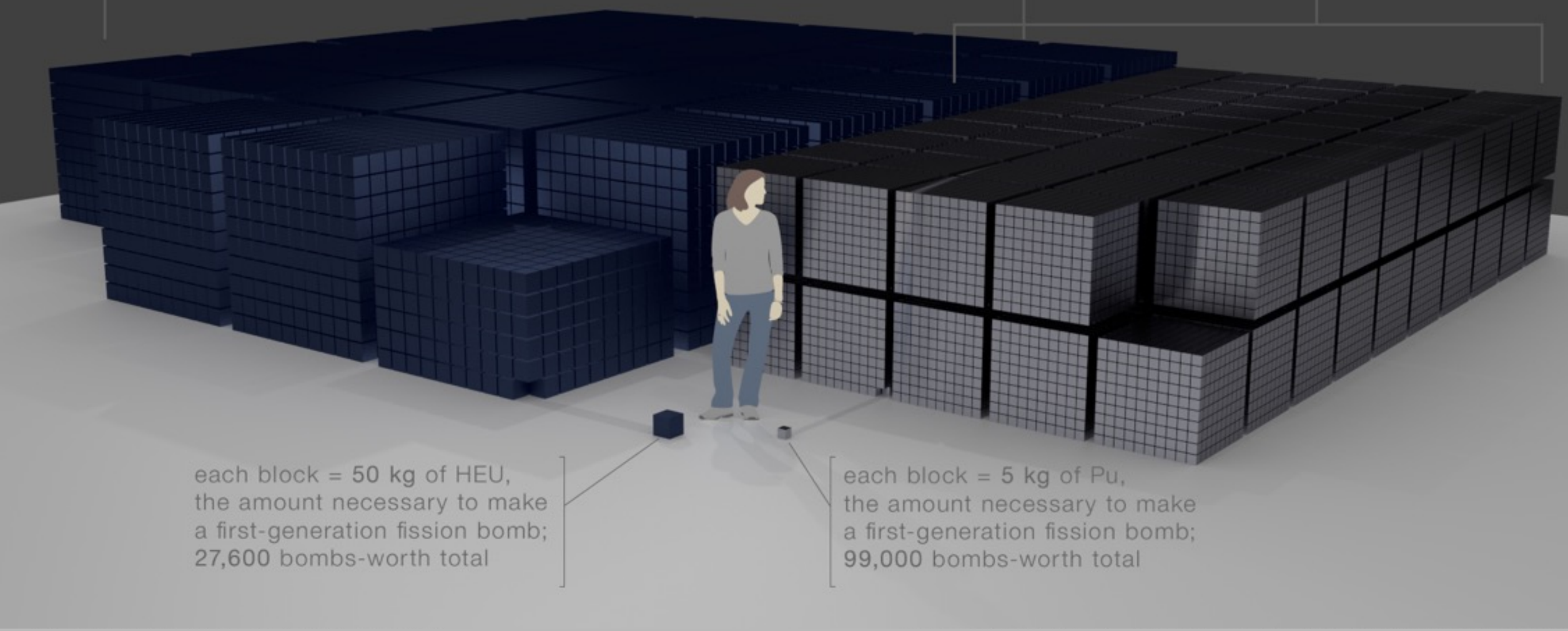
World Stockpiles of Fissile Materials

1345

1380 tons of highly-enriched uranium

499

495 tons of separated plutonium

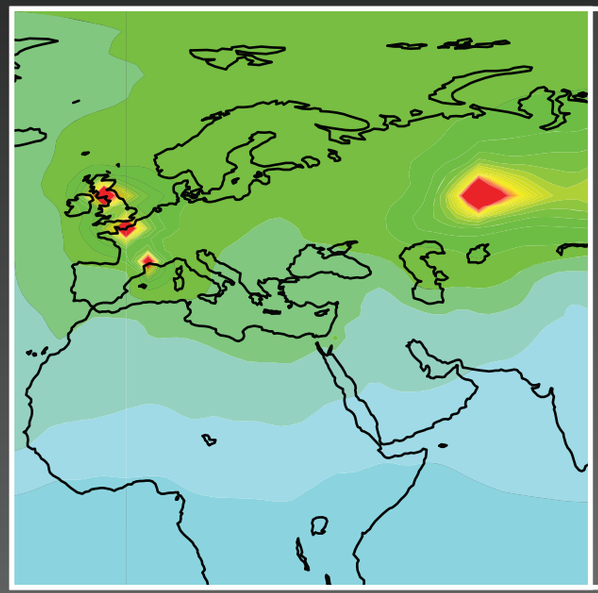


each block = **50 kg** of HEU,
the amount necessary to make
a first-generation fission bomb;
27,600 bombs-worth total

each block = **5 kg** of Pu,
the amount necessary to make
a first-generation fission bomb;
99,000 bombs-worth total

Graphic by Alex Wellerstein, nuclearsecrecy.com

WILL WE EVER KNOW HOW MUCH FISSILE MATERIAL EXISTS WORLDWIDE?



RECONSTRUCTING HISTORIC FISSILE MATERIAL PRODUCTION

Many aspects of declared production histories can be reviewed for consistency even without verification

(for example, by comparison with historic krypton emissions)

DATA EXCHANGE AND NUCLEAR ARCHAEOLOGY

Verification could begin with data exchanges (e.g. sharing of available operating records) and, eventually, envision onsite inspections

Nuclear archaeology is based on nuclear forensic analysis of samples taken at former production facilities

Source: Ole Ross and www.francetnp2010.fr

Science & Global Security, 1993, Volume 3, pp.237–259
Photocopying permitted by license only
Reprints available directly from the publisher

Nuclear Archaeology: Verifying Declarations of Fissile-Material Production

Steve Fetter[a]

Controlling the production of fissile material is an essential element of nonproliferation policy. Similarly, accounting for the past production of fissile material should be an important component of nuclear disarmament. This paper describes two promising techniques that make use of physical evidence at reactors and enrichment facilities to verify the past production of plutonium and highly enriched uranium. In the first technique, the concentrations of long-lived radionuclides in permanent components of the reactor core are used to estimate the neutron fluence in various regions of the reactor and thereby verify declar... of plutonium production in the reactor. In the secon... technique, the ratio of th... U-235 to that of U-234 in the tails is used ... in the production of l... determine whether a g... enriched uranium, whi... which can be used in ... "nuclear archaeology," ... ties and thereby lay a ...

INTRODUCTION

For the first time, ... tal proliferation– ... reduce their com... than 10,000 by t... South Africa, Ir... nuclear thresho...

It is impor... capabilities a...

a. School o...

Science and Global Security, 19:223–233, 2011

ISSN: 0892-9882 print / 1547-7800 online
DOI: 10.1080/08929882.2011.616124

Routledge
Taylor & Francis Group

Nuclear Archaeology for Heavy-Water-Moderated Plutonium Production Reactors

Alex Gasner and Alexander Glaser

Department of Mechanical and Aerospace Engineering, Princeton University Engineering Quadrangle, Olden Street, Princeton, NJ 08544

There is growing interest in a set of methods and tools that can be used to characterize past fissile material production activities, using measurements and sampling at production and stora... ...as been dubbed "nuclear archaeology." The ...ology relies on measurements of the isotope ... of graphite-moderated plutonium produc... Method (GIRM) determines the cumulative ...hereby estimates the cumulative plutonium ...ion of this particular method is that it can ...tors, which represent only one class of re...led plutonium production. In this article, ...raphite moderated reactors by analyzing ...e support structures and other core com... We present results of neutronics calcula... evaluating the robustness of the method ... for applications in arms-control treaty

...1.
...ted at the 51st INMM Annual Meeting, ...ltimore, MD, July 11–15, 2010. ...Department of Geosciences, for advic... ...Matos from Argonne Nati... ...trace anal...

Science & Global Security, 22:27–49, 2014

ISSN: 0892-9882 print / 1547-7800 online
DOI: 10.1080/08929882.2014.871881

Routledge
Taylor & Francis Group

Nuclear Archaeology for Gaseous Diffusion Enrichment Plants

Sébastien Philippe and Alexander Glaser

Nuclear Futures Laboratory, Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ, USA

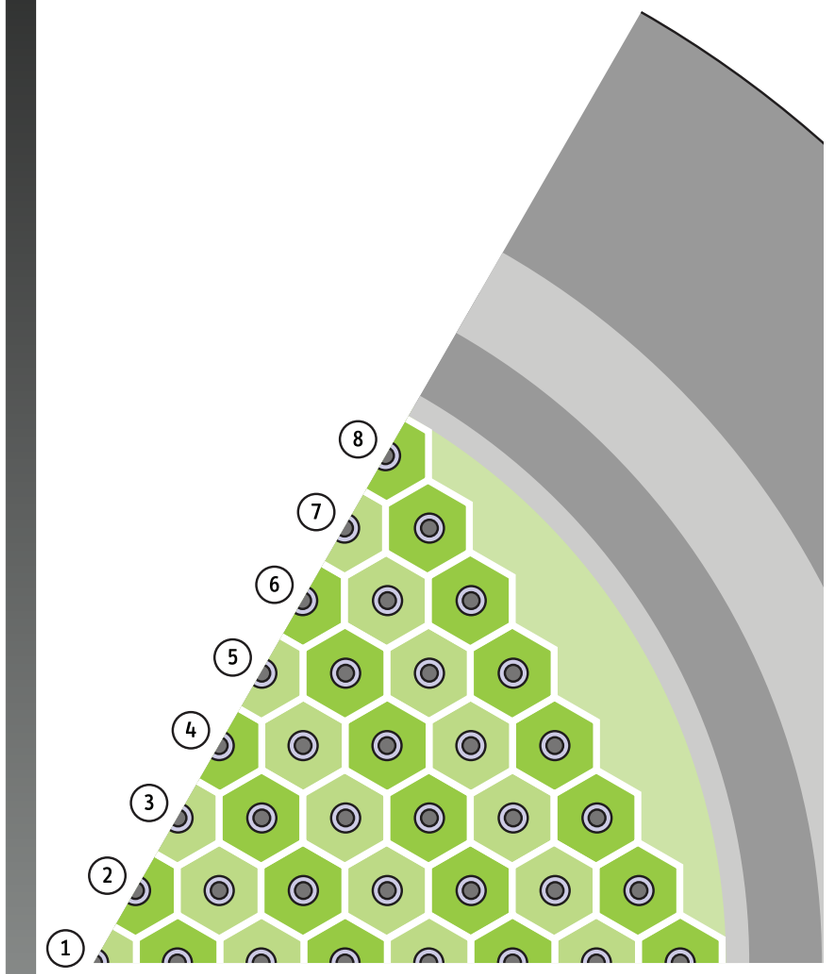
Gaseous diffusion was historically the most widely used technology for military production of highly enriched uranium. Since June 2013, all gaseous diffusion enrichment plants worldwide are permanently shut down. The experience with decommissioning some of these plants has shown that they contain large amounts of uranium particles deposited in the cascade equipment. This article evaluates the ... uranium particle deposition to unde... gaseous diffus...

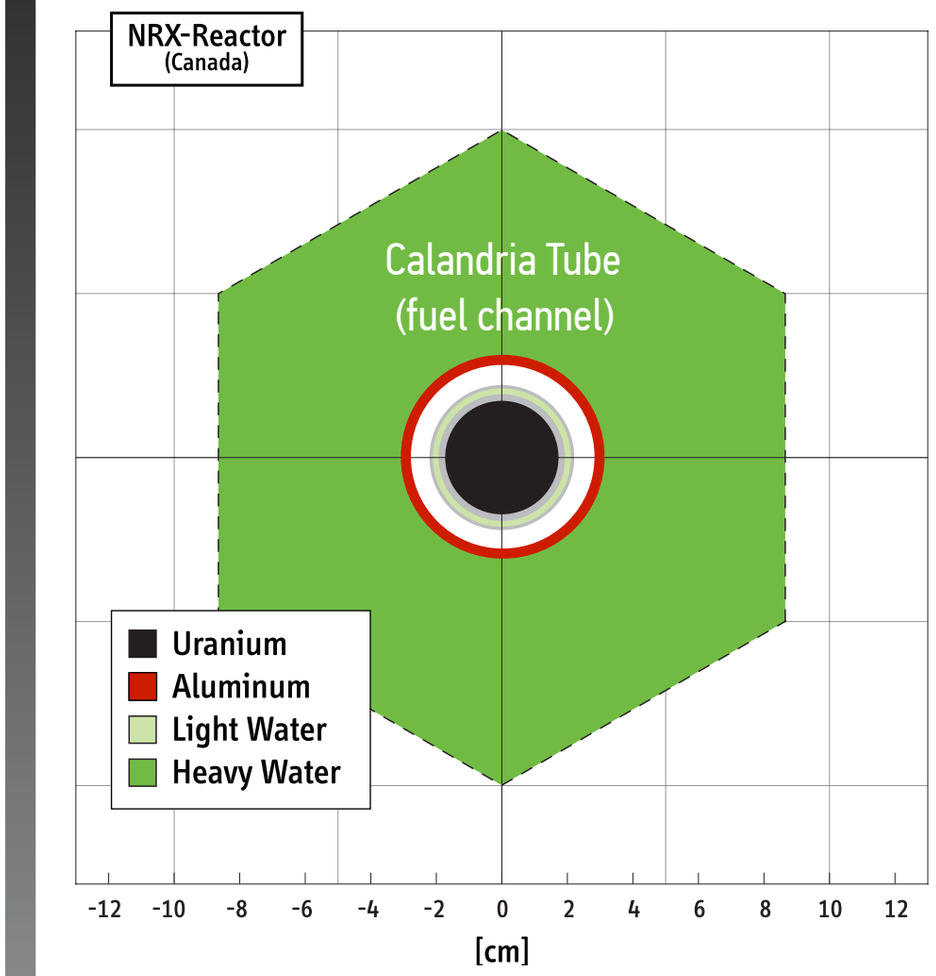
NUCLEAR ARCHAEOLOGY

THE CASE OF PLUTONIUM PRODUCTION

COMPUTER MODEL OF NRX/CIRUS

(40–50 MW, HEAVY-WATER MODERATED, NATURAL-URANIUM FUELED)

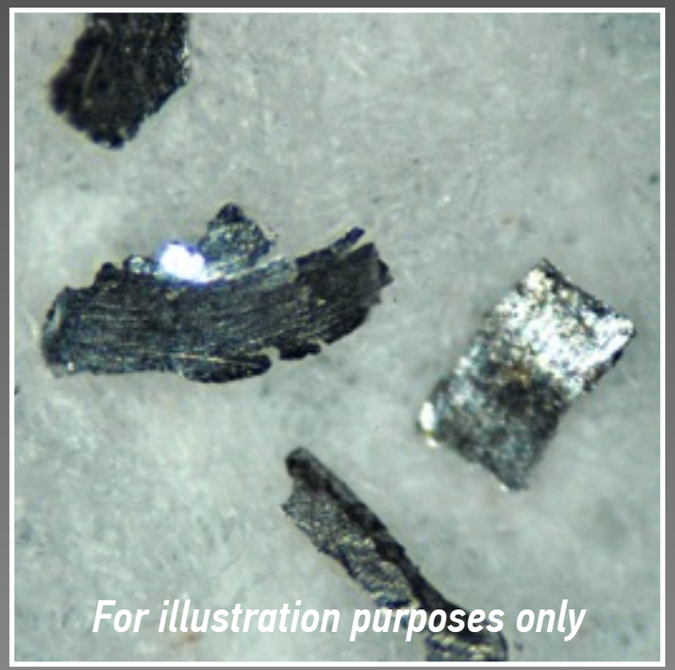




A. Gasner and A. Glaser, "Nuclear Archaeology for Heavy-Water-Moderated Plutonium Production Reactors," *Science & Global Security,* 19, 2011

MANY ELEMENTS ARE PRESENT AS IMPURITIES IN ALUMINUM

RESULTS FROM ANALYSIS OF HISTORIC ALUMINUM SAMPLE FROM MANHATTAN COLLEGE ZERO POWER REACTOR (MCZPR)



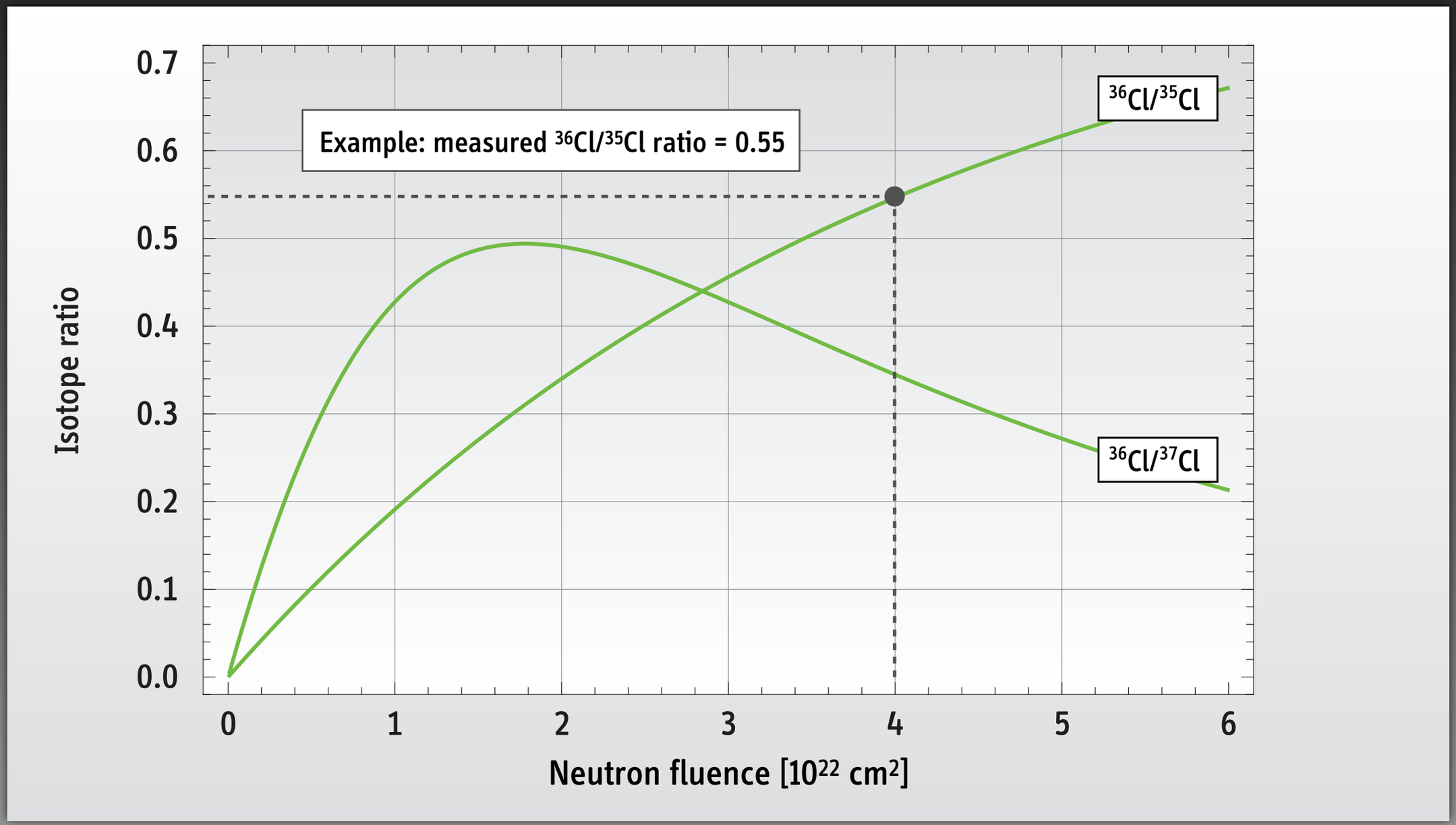
Element	Content
5 Boron	2 ppm
12 Magnesium	<100 ppm
14 Silicon	1900 ppm
22 Titanium	200 ppm
23 Vanadium	<100 ppm
24 Chromium	<100 ppm

Element	Content
26 Iron	5100 ppm
28 Nickel	<100 ppm
29 Copper	1400 ppm
30 Zinc	200 ppm
40 Zirconium	<100 ppm
82 Lead	<100 ppm

Need to identify isotope ratios that correlate well with neutron fluence

ARCHAEOLOGY FOR CANADA'S NRX REACTOR

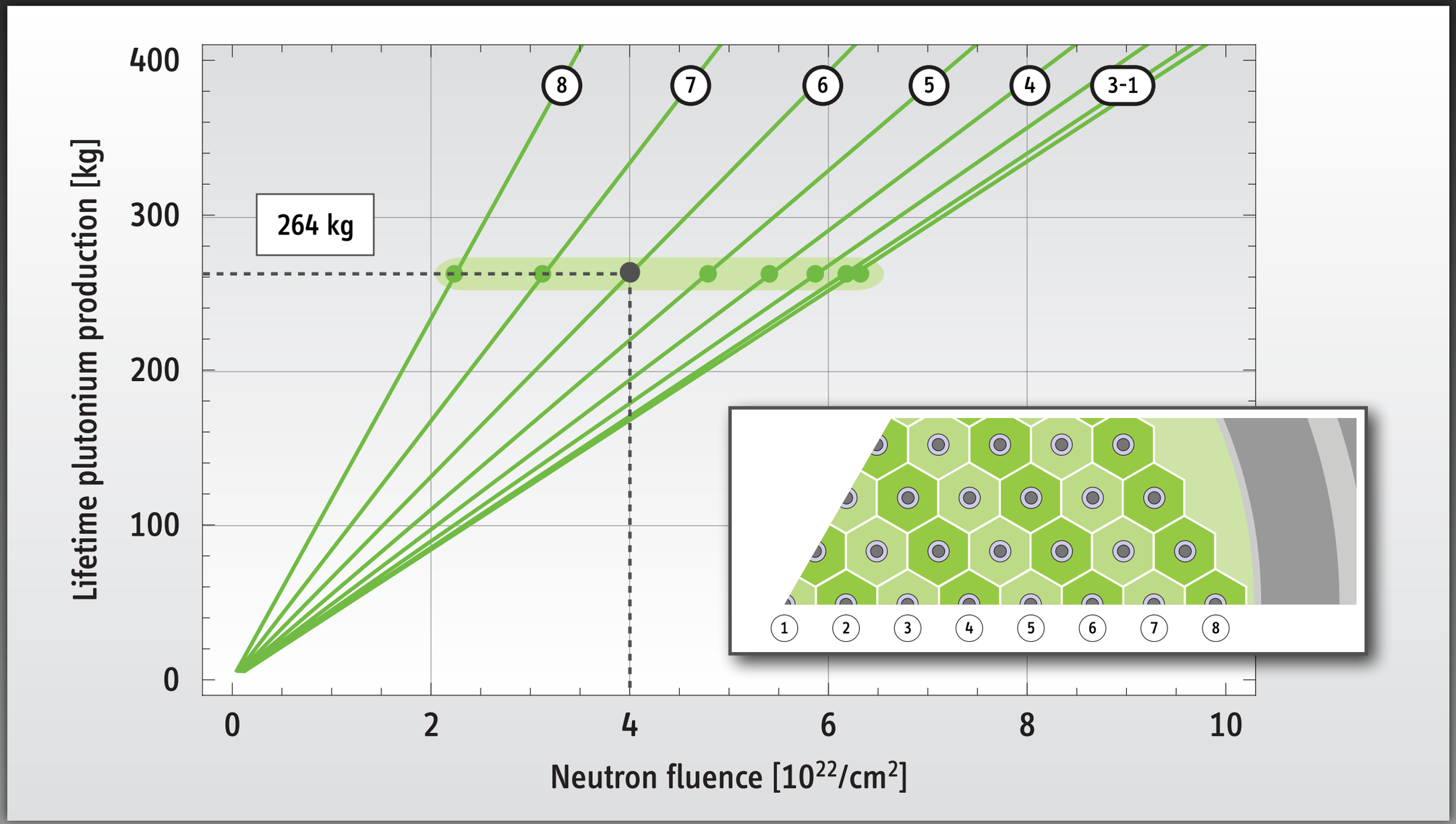
EVOLUTION OF SELECTED CHLORINE RATIOS, SIMULATED DATA



A. Gasner and A. Glaser, "Nuclear Archaeology for Heavy-Water-Moderated Plutonium Production Reactors," *Science & Global Security,* 19, 2011

ARCHAEOLOGY FOR CANADA'S NRX REACTOR

"LOOKUP TABLES" CAN BE USED TO MAP FLUENCE VALUE (IN FUEL CHANNEL) TO LIFETIME PLUTONIUM PRODUCTION OF REACTOR

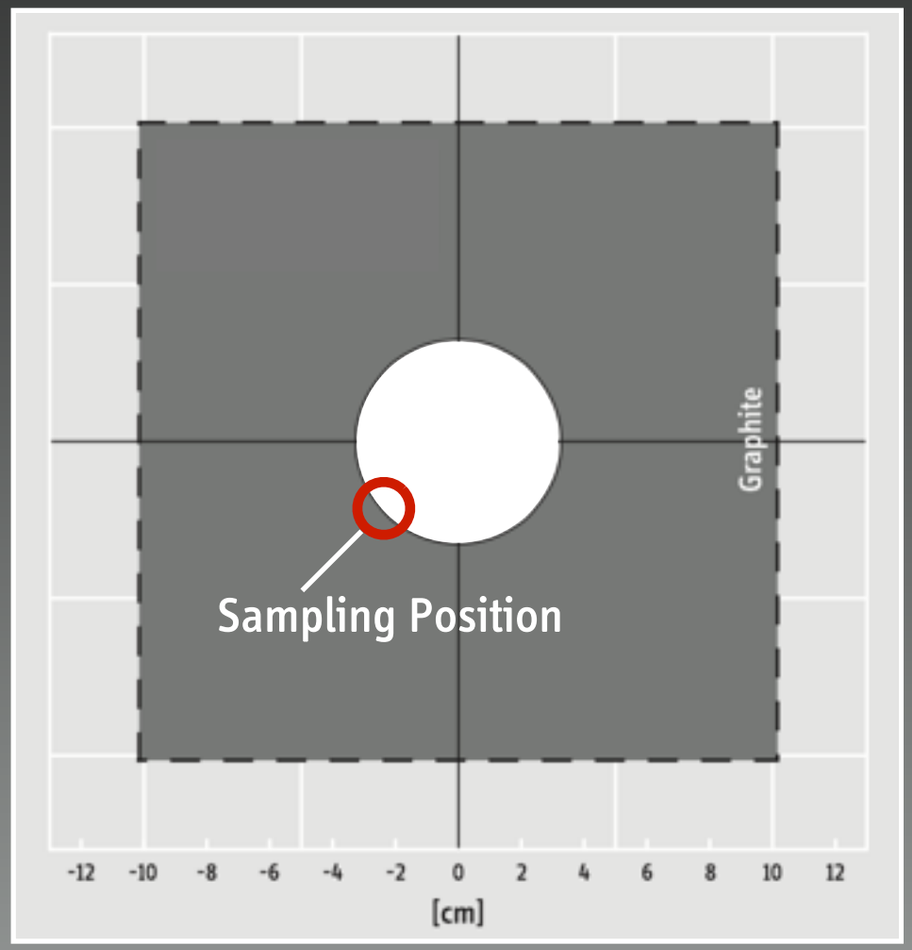


A. Gasner and A. Glaser, "Nuclear Archaeology for Heavy-Water-Moderated Plutonium Production Reactors," *Science & Global Security,* 19, 2011

NUCLEAR ARCHAEOLOGY WOULD HAVE BEEN USED TO VERIFY NORTH KOREA'S PLUTONIUM DECLARATION

FORENSIC ANALYSIS OF GRAPHITE SAMPLES COULD CONFIRM TOTAL PLUTONIUM PRODUCTION IN NORTH KOREA WITHIN AN UNCERTAINTY OF ±2 KG

The banner reads: "Let's protect Dear General Kim Jong Il desperately!"
Credit: CNN/Brian Rokus, 2008



Unit cell of the DPRK Yongbyon reactor

PLUTONIUM PRODUCTION REACTORS

BY TYPE AND COUNTRY

	Graphite moderated		Heavy-water moderated	
	H_2O cooled	CO_2 cooled	H_2O cooled	D_2O cooled
United States	Hanford			Savannah River
Russia	“Tomsk-7”			
United Kingdom		Calder Hall		
France		G-Series		Célestin
China	“Jiuquan”			
Israel				Dimona
India			Cirus/NRX	Dhruva
Pakistan			Khushab	
DPRK		Yongbyon		

A. Glaser, “Isotopic Signatures of Weapon-grade Plutonium from Dedicated Natural-uranium-fueled Production Reactors and Their Relevance for Nuclear Forensic Analysis,” *Nuclear Science & Engineering,* September 2009

TEST BEDS FOR NUCLEAR ARCHAEOLOGY

To begin countries could offer single sites or facilities as test beds and invite partners with similar production facilities to engage in “site-to-site exercises” to jointly demonstrate verification approaches and measurement techniques

Left: Windscale Piles, www.sellafieldsites.com
Right: G2/G3, Marcoule, www.francetnp.fr

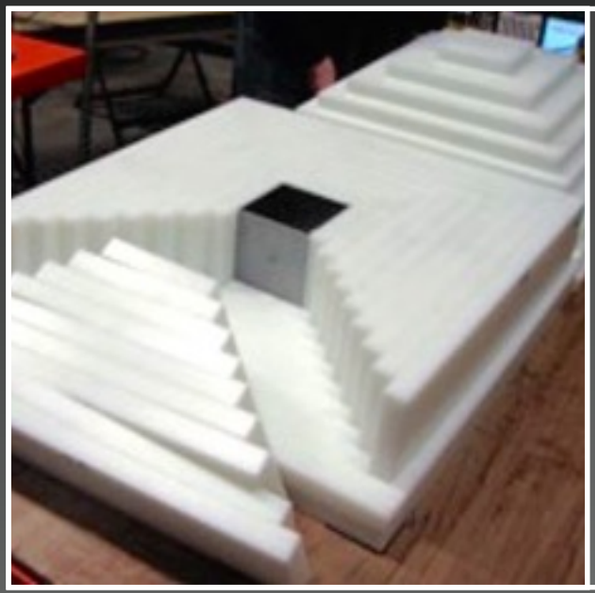
MANY NON-NUCLEAR WEAPON STATES HAVE CANDIDATE FACILITIES THAT COULD BE USED TO DEMONSTRATE METHODS REQUIRED FOR NUCLEAR ARCHAEOLOGY

FR-2 (44 MW), Karlsruhe (shut down since 1981)

MZFR (200 MW), Karlsruhe (now decommissioned)

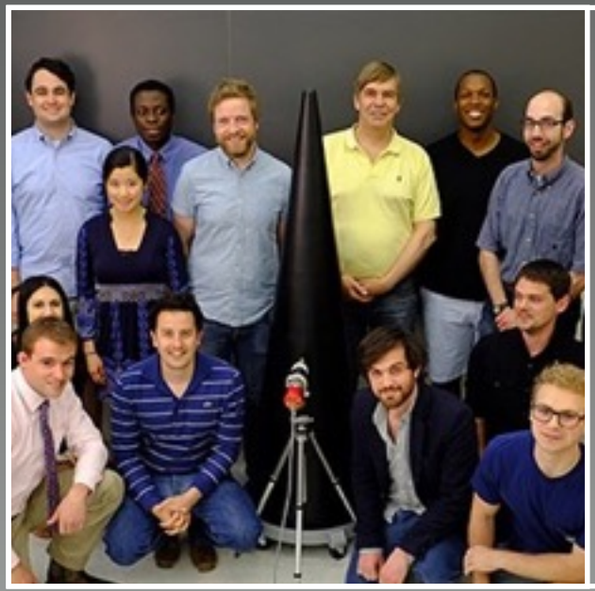
um.baden-wuerttemberg.de/de/umwelt/kernenergie-und-radioaktivitaet/kerntechnische-anlagen/sonstige-kerntechnische-anlagen/wiederaufarbeitungsanlage-karlsruhe-wak-gmbh

SUMMARY AND NEXT STEPS



REFRAMING THE RESEARCH QUESTIONS

- Agree on “Universal Test Objects” and define benchmarks
- Begin with minimally intrusive verification approaches and techniques
- Offer test beds for joint development and demonstration



ENGAGING THE LARGER SCIENTIFIC COMMUNITY

- So far, mostly top-down initiatives
  for example, International Partnership on Nuclear Disarmament Verification
- Need also bottom-up
- Highlight connections to non-nuclear sciences (e.g. cryptography)

Source: U.S. Department of Energy (top)

Photo: Mikhail Klimentyev/AP (September 2015)

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