
# WARHEAD MONITORING & VERIFICATION

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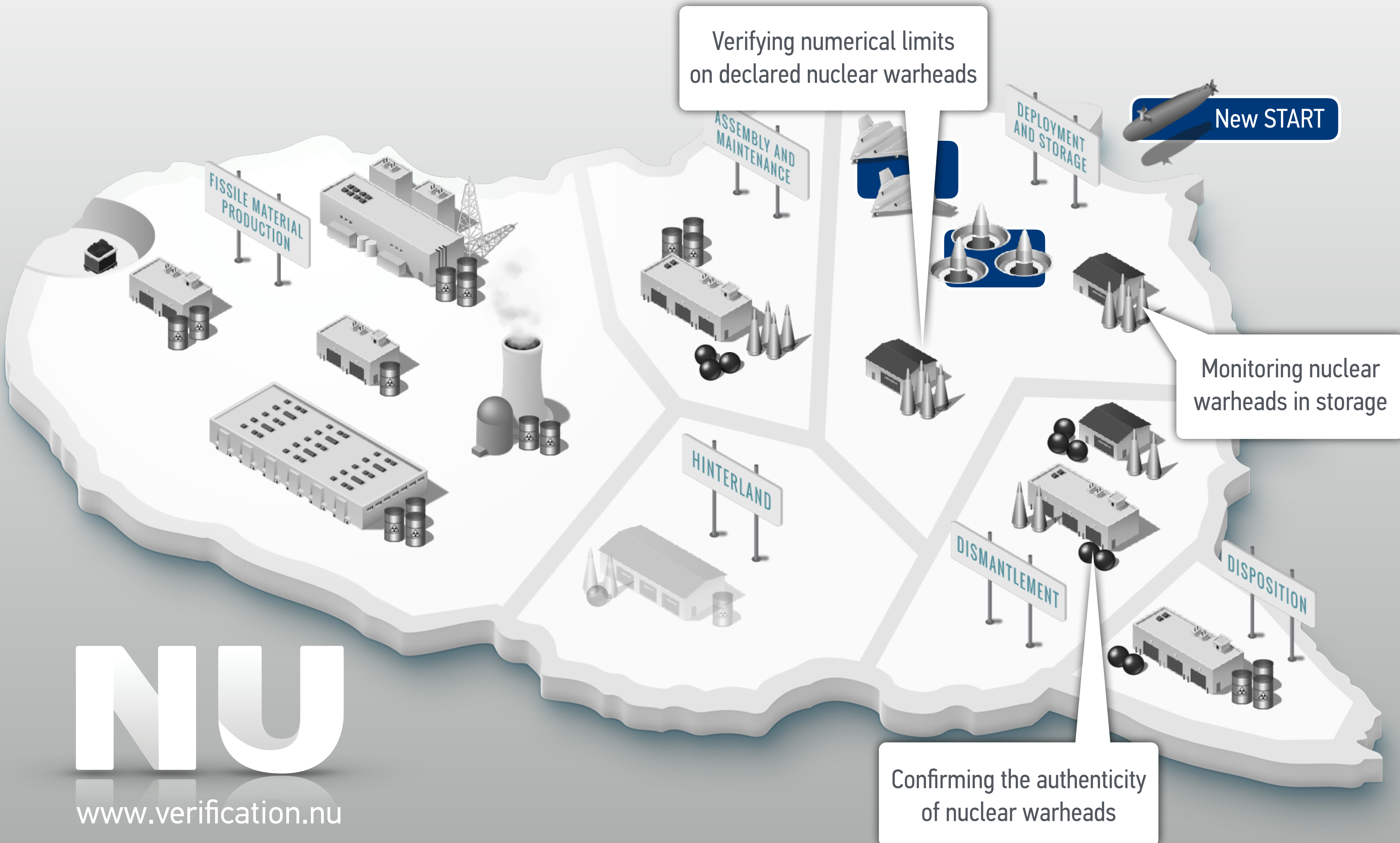
*Committee on International Security and Arms Control, June 2, 2020*

Painting by Helen Audrey Schrayer, Acrylic on Canvas, 2017

# VERIFICATION CHALLENGES

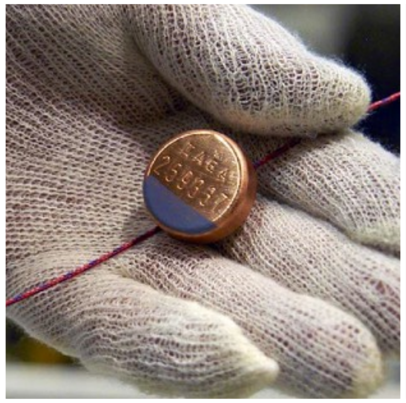
## FOR NUCLEAR ARMS CONTROL AND DISARMAMENT




Revision 4

# REQUIREMENTS

## FOR RELEVANT MONITORING AND VERIFICATION TECHNOLOGIES



### ROBUSTNESS

How difficult is it to defeat or circumvent the technology?

### NON-INTRUSIVENESS

How intrusive are deployment and use of the technology?

*for example, does it interfere with operations; is sensitive information put at risk?*


### SIMPLICITY

How easy is it to deploy and use the technology?

*for example, passive systems are generally (much) preferable to active ones*

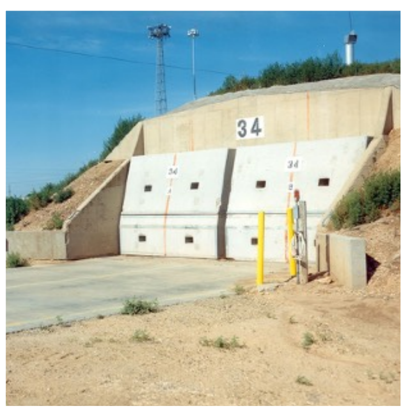
*Source: IAEA (top) and defenseimagery.mil (middle)*

# DEALING WITH SECRETS

# HOW NOT TO GIVE AWAY A SECRET

## CONTINUE IMPROVING TECHNOLOGIES AND APPROACHES

Work on information barriers with a particular focus on certification and authentication; in particular, identify joint hardware and software development platforms




## REINVENT THE PROBLEM: NEVER ACQUIRE SENSITIVE INFORMATION TO BEGIN WITH

Explore new verification technologies and approaches;
for example, develop alternatives to onsite inspections at certain sensitive facilities

## REVEAL THE SECRET

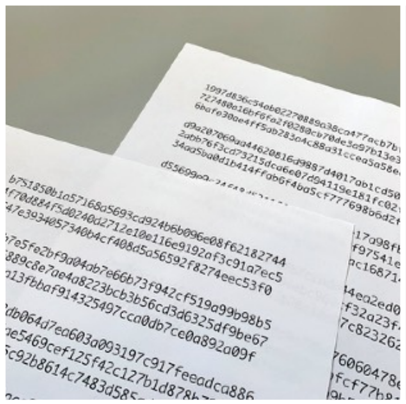
Requirement to protect sensitive information is typically the main reason for complexity of verification approaches; for example, mass of fissile material in a nuclear weapon

*Source: Author (top and bottom), U.S. DOE (middle)*

# CONFIRMING NUMERICAL LIMITS

## & WARHEAD MONITORING

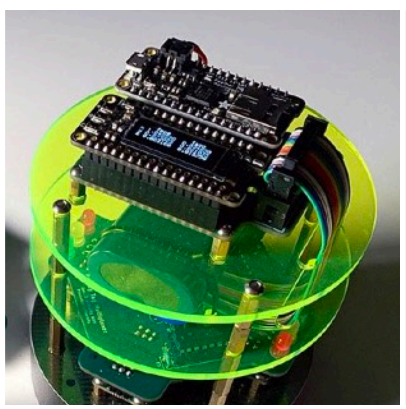
# WARHEAD MONITORING OPTIONS



## PRIVACY-PRESERVING (“HASHED”) DECLARATIONS

States provide declarations only in hashed form; entries can be revealed as needed to confirm correctness of such declarations during short-notice inspections

*For more, see: JASON, 1990; NAS, 2005; S. Philippe, A. Glaser, and E. Felten, Science & Global Security, 2019*



## BUDDY TAG

Instead of monitoring declared items directly, “buddy tags” are introduced as tokens to represent these items; initially, no access to any sensitive sites or items required

*For more, see: M. Kütt and A. Glaser, IEEE Sensors, June 2020*

## REMOTE MONITORING OF DECLARED ITEMS

Batches of warheads are containerized, sealed, and prepared for long-term storage
Storage location of containerized warheads can remain unknown/secret

*For more, see: A. Glaser and Z. Mian, Science, 361 (6406), September 7, 2018*

*Source: Sandia National Laboratories (top), author (middle and bottom)*

# Hashed Declarations

Verification Technology: Unclassified Version, JASON, 1990
Monitoring Nuclear Weapons and Nuclear-Explosive Materials, CISAC, National Academy of Sciences, 2005
S. Philippe, A. Glaser, and E. Felten, *Science & Global Security,* 27 (1), 2019

# “PRIVACY-PRESERVING DECLARATIONS”

```
ITEM 01: 67d97802b84a6db872aacc400a0f5eaeebcec52012503111891b0d1e89711605
ITEM 02: b3c22af3a5f9ecc51c5cf6b4604e2bef191e4ceb305c6ef4a9589206e0bd7e62
ITEM 03: 0b277554264c8d00e81fb4b0af3f39f753146c8881ce093d7d45e8212cce95ac
ITEM 04: 4161814ef03933b605958325ca0aa3a3d9d2106f8f79b2c28cec5e75ea70266b
ITEM 05: f5c53f5c375c22f6e20554d5d7488f1cc678caa4fdc50aca77057c4755d7b12b
ITEM 06: fb28390a1b3db5db0fb44534a8a8c8716dccf64aa41828658b5fcadaf82b37c8
ITEM 07: 368bfb3e543c11dec2511b38e59dd4dadf7eb0ed87d3128d8f3f13c0b37073c5
ITEM 08: a1e89078ac797a3cfc8423965ca966645b62e2e212597e81b9c2a2e041778fd4
ITEM 09: f7618c3fead199ec24dcdbf6854d993330a8870c9e6a313d15d8fd988877f813
ITEM 10: 2abd37560821d1e5007a26c3ec0e25a16c46dcea5258605e0a2ef207ecf98520
ITEM 11: 9280cac30c39ea62daf66f082f2a574ae865308be5bb49cce11dabebf26a6a8c
ITEM 12: f7467d431353ce15dfe0dc6395e9e6a8806afd3222467ffb5eb1105bfa90bb31
ITEM 13: 023cc75fce0d55eb9cce5aa4b9f79d20d3da555c98048abfcc147c797a8db642
ITEM 14: 4108821ea003aaceefdb8c2d86126c33a5315b62043b36d5e612bc831e446896
ITEM 15: 340bcbda4afb3409f2d750f0a3ac029270a27e727c83650d8b6417d8153765a2
ITEM 16: bca49804e0b0da52df8f533d91d680e26818752111538dea4401277bc6cfa2e3
```

Declaration in hashed form (with one entry per item)

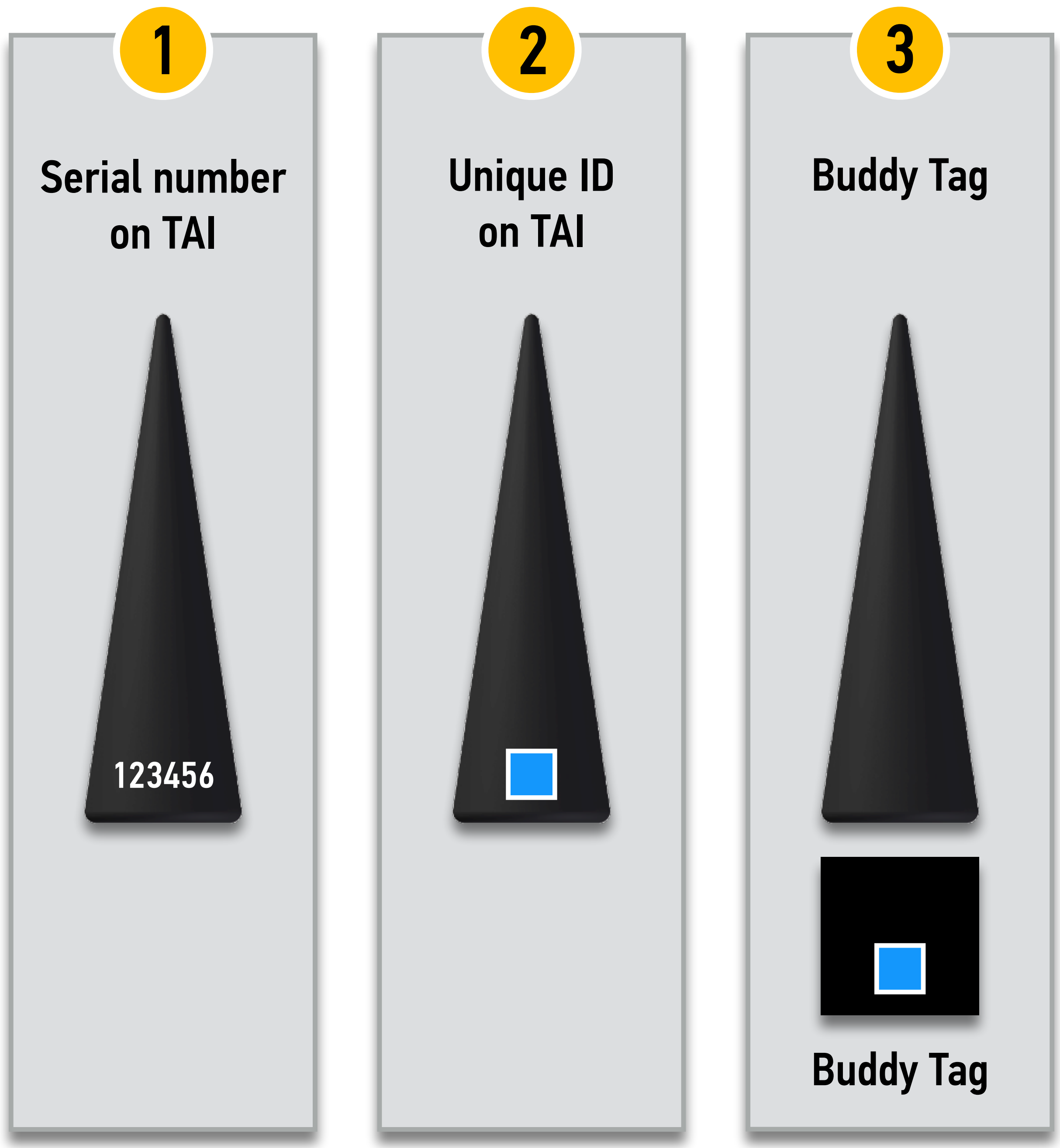
```
ITEM 01: 67d97802b84a6db872aacc400a0f5eaeebcec52012503111891b0d1e89711605
ITEM 02: b3c22af3a5f9ecc51c5cf6b4604e2bef191e4ceb305c6ef4a9589206e0bd7e62
ITEM 03: 8edd164eb3fd9116 SITE C :: W99 :: TIME 12345678 a562c8ffeefbc2fb
ITEM 04: 4161814ef03933b605958325ca0aa3a3d9d2106f8f79b2c28cec5e75ea70266b
ITEM 05: f5c53f5c375c22f6e20554d5d7488f1cc678caa4fdc50aca77057c4755d7b12b
ITEM 06: fb28390a1b3db5db0fb44534a8a8c8716dccf64aa41828658b5fcadaf82b37c8
ITEM 07: 368bfb3e543c11dec2511b38e59dd4dadf7eb0ed87d3128d8f3f13c0b37073c5
ITEM 08: 25b78703bcbdcfa7 SITE C :: W99 :: TIME 12345678 0e62292b6c2f98a3
ITEM 09: 184702dc19247c56 SITE C :: W99 :: TIME 12345678 6f2efeb7be00fc82
ITEM 10: 2abd37560821d1e5007a26c3ec0e25a16c46dcea5258605e0a2ef207ecf98520
ITEM 11: c02d3fee2ad8a77a SITE C :: W99 :: TIME 12345678 dfa54d7edc14494b
ITEM 12: f7467d431353ce15dfe0dc6395e9e6a8806afd3222467ffb5eb1105bfa90bb31
ITEM 13: 023cc75fce0d55eb9cce5aa4b9f79d20d3da555c98048abfcc147c797a8db642
ITEM 14: 4108821ea003aaceefdb8c2d86126c33a5315b62043b36d5e612bc831e446896
ITEM 15: 340bcbda4afb3409f2d750f0a3ac029270a27e727c83650d8b6417d8153765a2
ITEM 16: bca49804e0b0da52df8f533d91d680e26818752111538dea4401277bc6cfa2e3
```

Declaration with entries for Site C revealed

# Buddy Tag

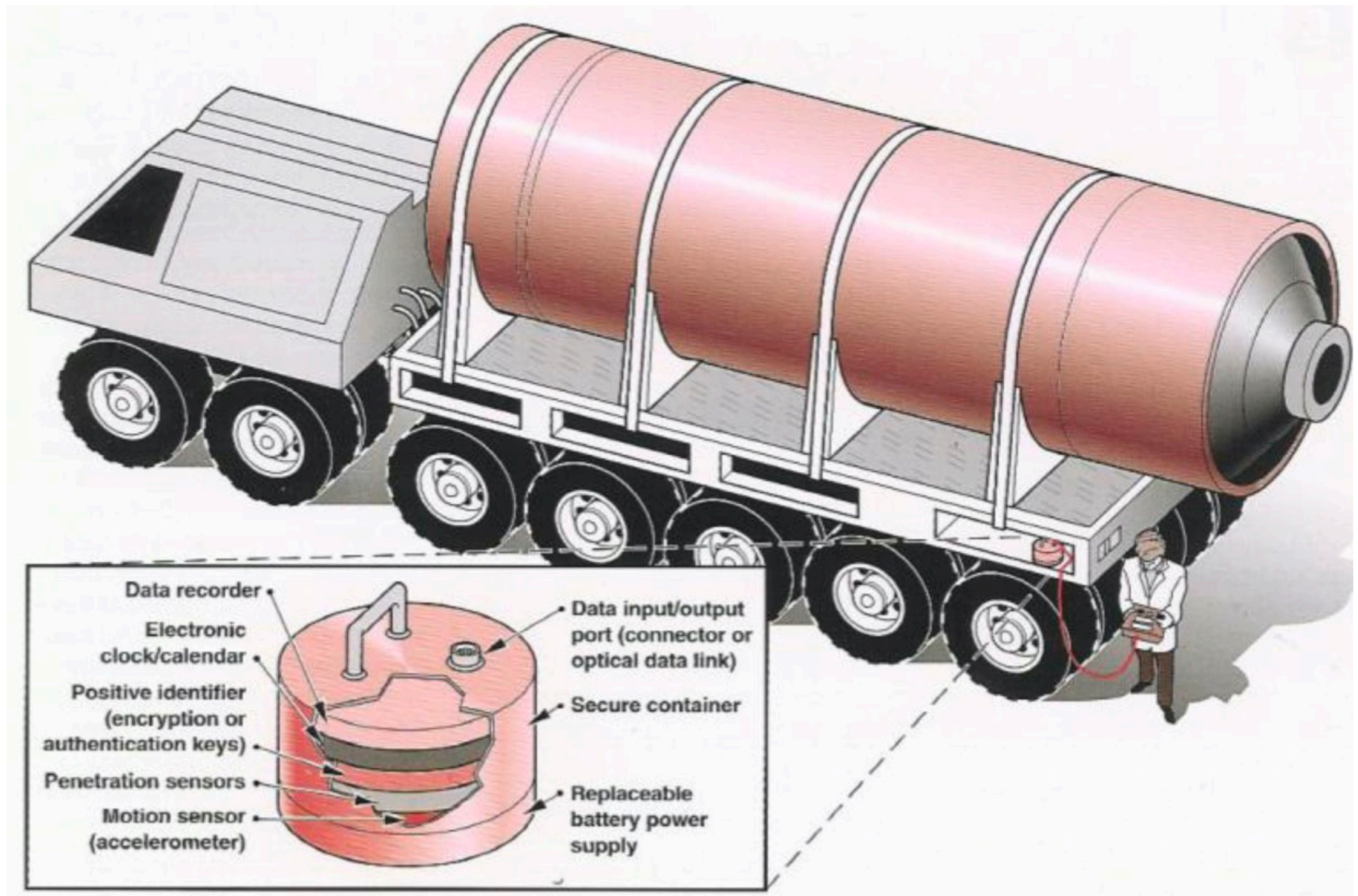
Verification Technology: Unclassified Version, JASON, 1990
Sandia National Laboratories, 1991
Princeton University and Sandia National Laboratories, 2015–2020

# TAGGING OPTIONS



# THE ORIGINAL BUDDY TAG CONCEPT

## (FOR MOBILE MISSILES)




*Sabina E. Jordan, Buddy Tag's Motion Sensing and Analysis Subsystem, Sandia National Laboratory, Albuquerque, New Mexico, 1991*

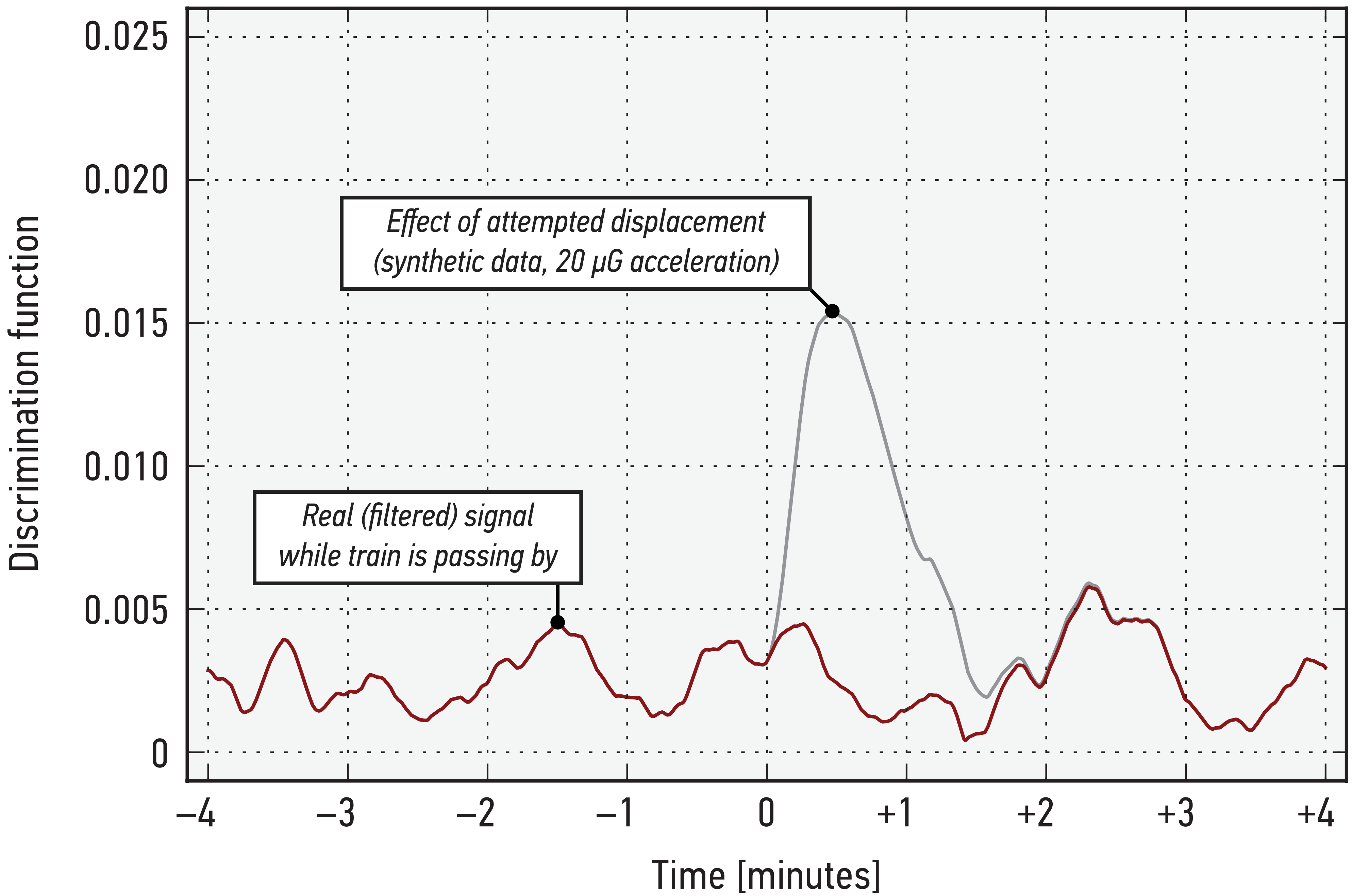
*Jim Fuller, "US START TID Development Program: The Quest for Extreme Security Unique Identifiers (1986–1992)," April 2006*

# 2020 BUDDY TAG PROTOTYPE


*A. Glaser and M. Kütt, "Verifying Deep Reductions in the Nuclear Arsenals: Development and Demonstration of a Motion-detection Subsystem for a 'Buddy Tag' Using Non-export Controlled Accelerometers," IEEE Sensors Journal, June 2020*

# ROBUSTNESS & SENSITIVITY

## OF THE 2020 BUDDY TAG PROTOTYPE




*A. Glaser and M. Kütt, IEEE Sensors Journal, June 2020*

# WARHEAD CONFIRMATION MEASUREMENTS

# Absence Measurements

# CONFIRMING NUMERICAL LIMITS

## MAY NOT NEED COMPLEX INSPECTION EQUIPMENT AND APPROACHES

*A nuclear weapon is any device that has been declared by the host party to be a nuclear weapon.*

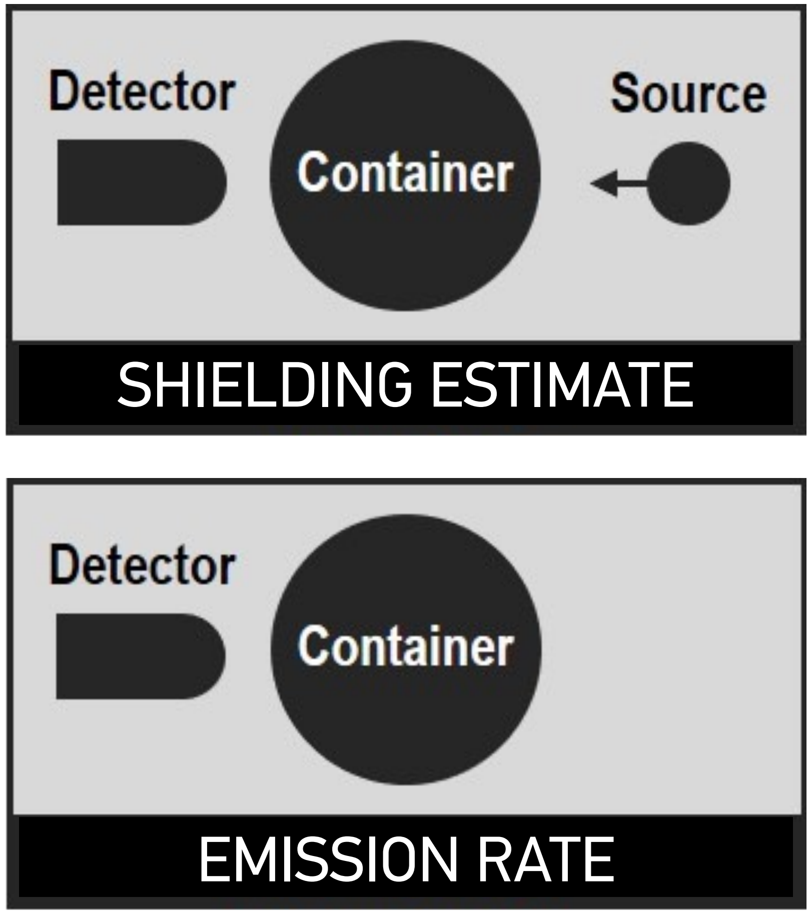
*An object is accepted as a non-treaty-accountable item if (a) it does not exceed an agreed radiation level (neutron/gamma or combined) or if (b) the inspector can confirm its nature as a non-treaty-accountable item, for example, through direct visual access.*

*A. Glaser, "Ceci N'est Pas Une Bombe: Toward a Verifiable Definition of a Nuclear Weapon," 58th Annual INMM Meeting, Indian Wells, CA, July 2017*

*See also: Verification of Nuclear Weapons Declarations, Report by Working Group 4*
*International Partnership for Nuclear Disarmament Verification (IPNDV), 2020, www.ipndv.org/reports-analysis*

# ABSENCE MEASUREMENTS

## USING LOW-RESOLUTION GAMMA SPECTROMETRY





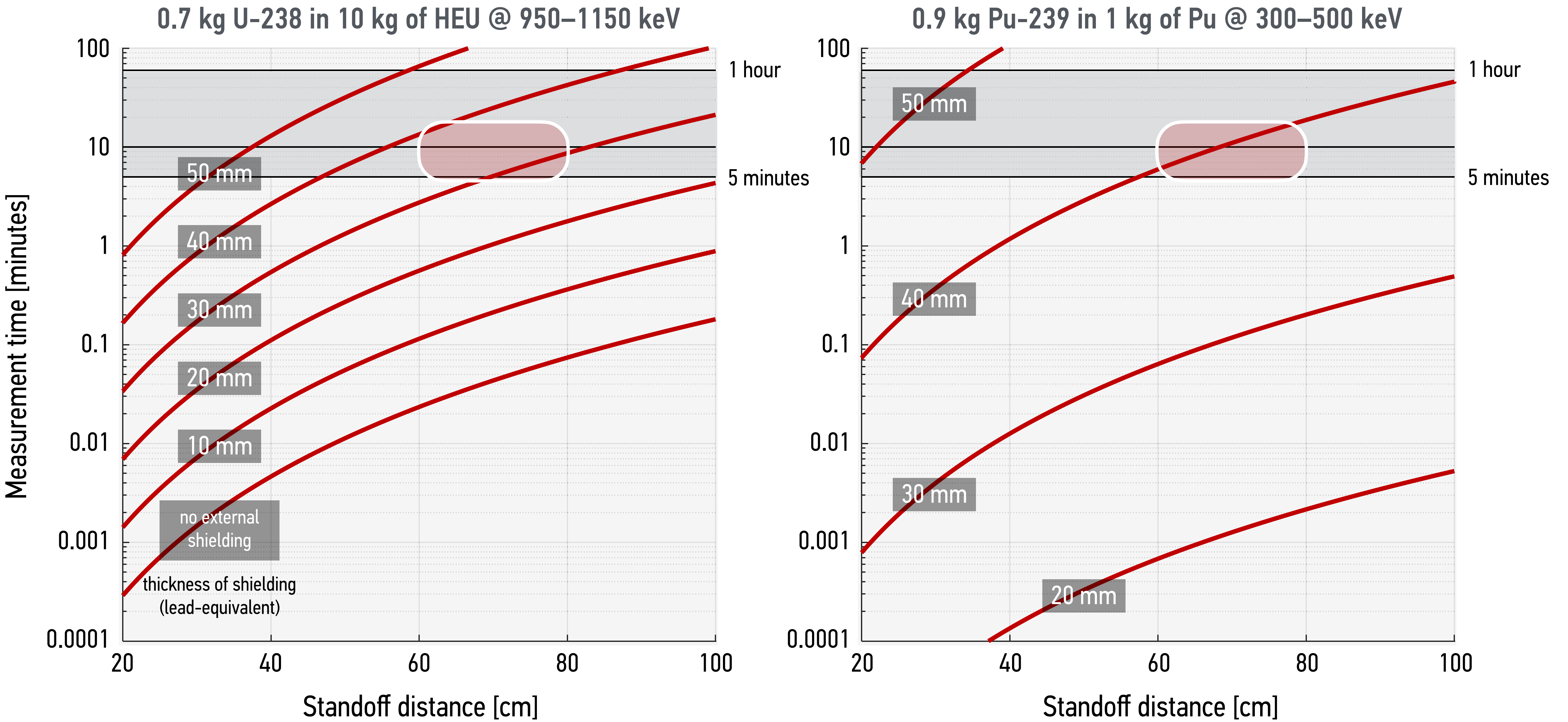
Measurements could be very straightforward, perhaps, only based on gamma measurements
Inspection could include two separate steps to determine (1) amount of shielding in container and (2) emissions from container/item

U-235 is difficult to detect, focus on U-238 (1.001 MeV) instead; plutonium has most prominent emissions in 300–500 keV region

If host is honest, no sensitive information at risk
Certain sensitive objects (e.g. “trainers” with depleted uranium) may have to be declared as treaty accountable

# ABSENCE MEASUREMENTS

## USING LOW-RESOLUTION GAMMA SPECTROMETRY



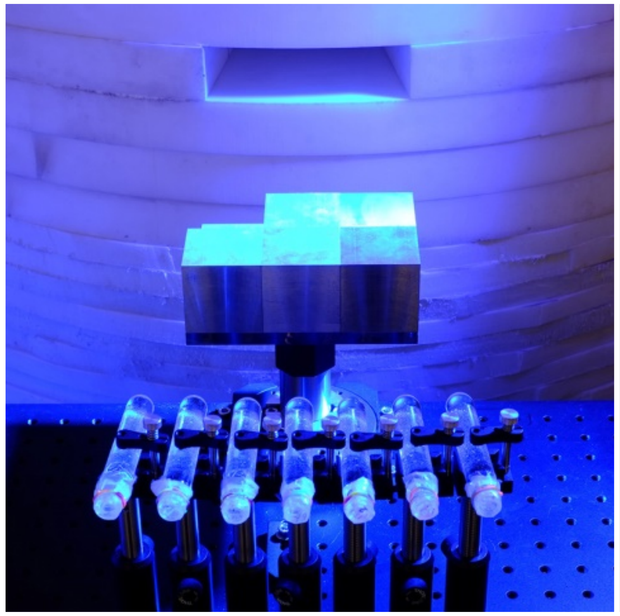

Values are for a 2" x 2" sodium-iodide detector and a solid ball of fissile material (maximum self-shielding)

*Estimates by Eric Lepowsky and Jihye Jeon; see also Steve Fetter et al., "Detecting Nuclear Warheads," Science & Global Security, 1 (3–4), 1990*

# Zero-knowledge Verification

# ZERO-KNOWLEDGE VERIFICATION

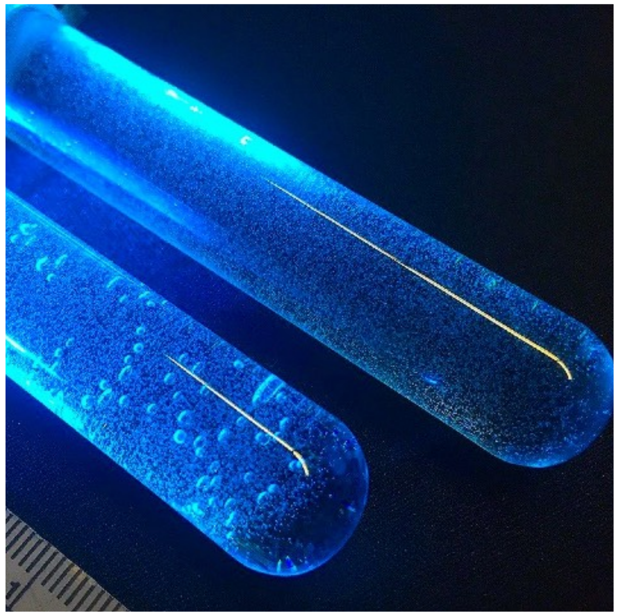
## WITH NON-ELECTRONIC, PRE-LOADABLE DETECTORS



### 14-MEV NEUTRON RADIOGRAPHY FOR OBJECT COMPARISON

Neutron transmission radiography using high-energy (14 MeV) neutrons is effective in detecting geometric and elemental differences

In 2016, demonstration of a physical zero-knowledge proof for different configurations of two-inch metal cubes



### PRE-LOADABLE NON-ELECTRONIC DETECTORS (YALE)

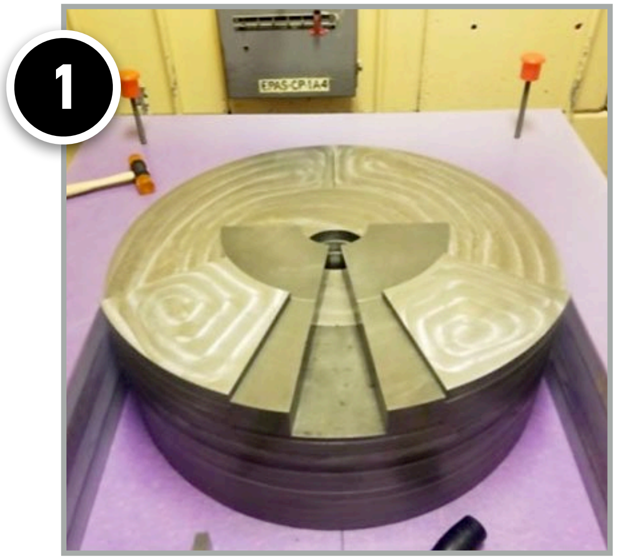
Superheated droplet detectors (developed by Yale) allow preloading and offer a way to implement proposed zero-knowledge protocol

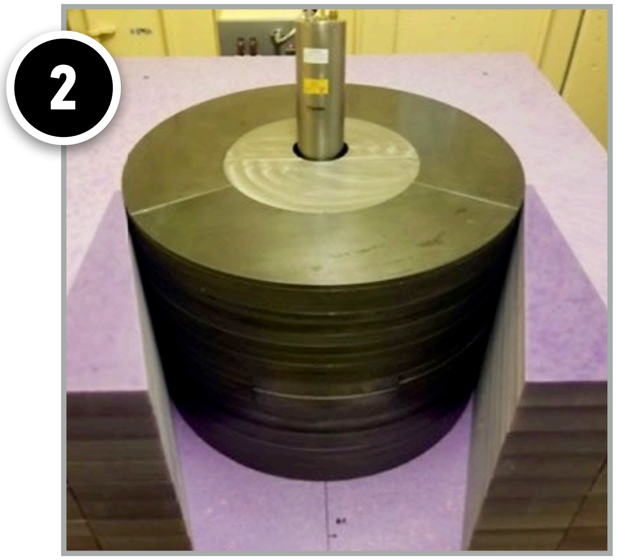
Detectors are insensitive to gammas and avoid detector-side electronics (and their functionality can be confirmed by inspectors post measurement)

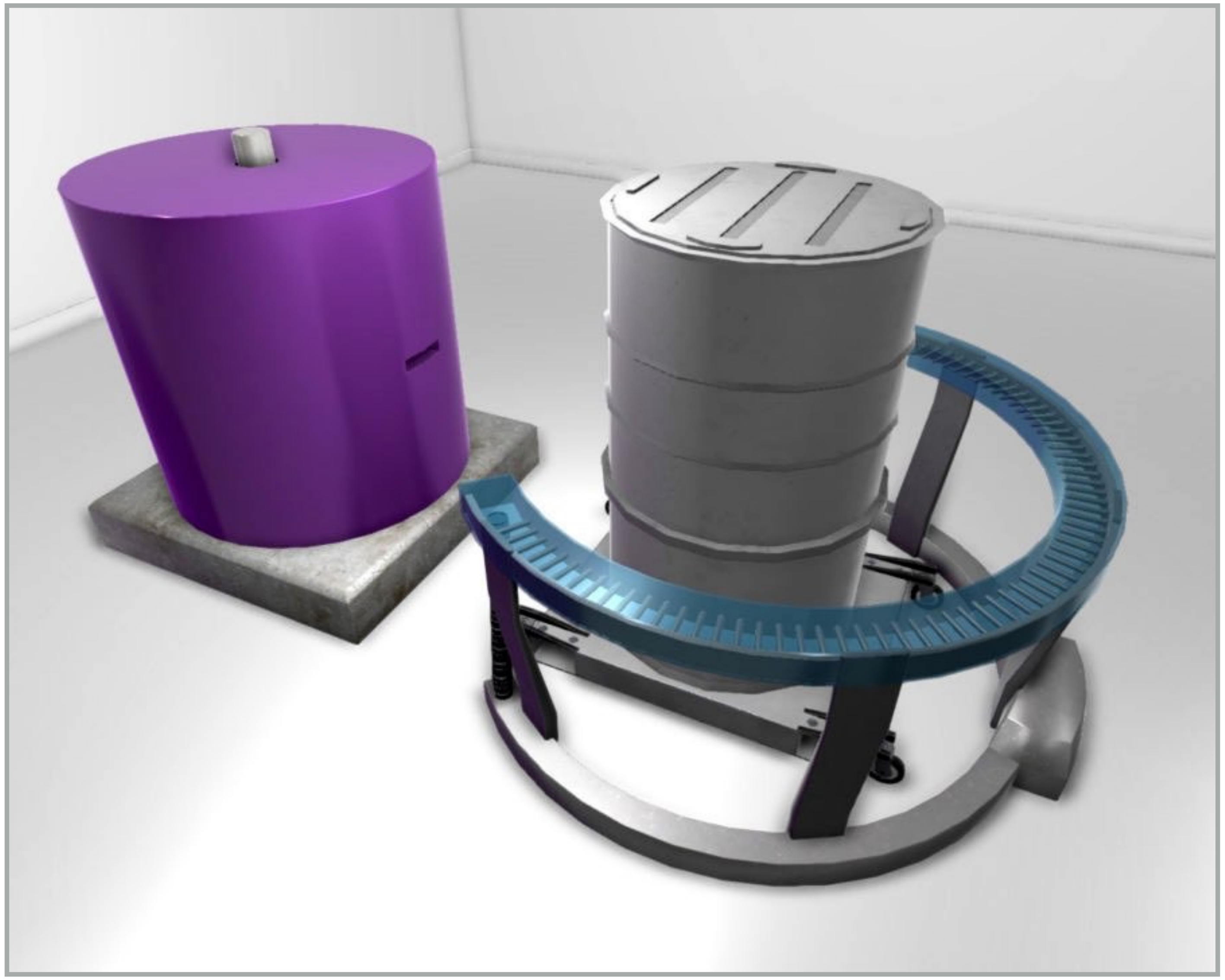
*A. Glaser, B. Barak, and R. Goldston, Nature, June 2014; S. Philippe et al., Nature Communications, September 2016*

# EXCALIBUR @ PPPL

## (EXPERIMENT FOR CALIBRATION WITH URANIUM)



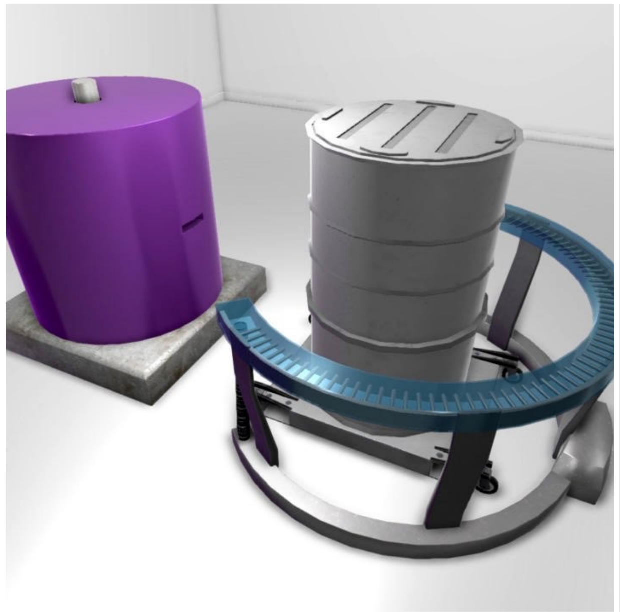



*Michael Hepler, Zero-knowledge Isotopic Discrimination for Nuclear Warhead Verification, PhD Thesis, Princeton University, May 2020*

# ZERO-KNOWLEDGE VERIFICATION

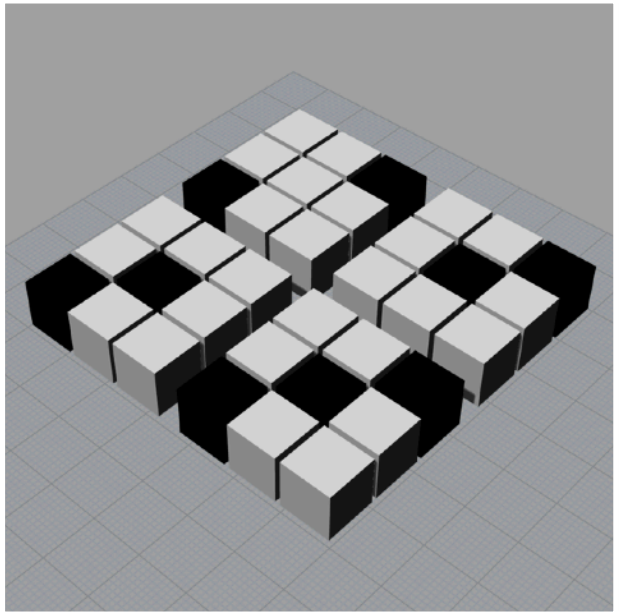
## STATUS AND NEXT STEPS



### SETUP FOR TRANSMISSION MODE & MODERATED MODE

The revised configuration maximizes fraction of neutrons with energies below 1 MeV to selectively drive fission events (e.g. in U-235 vs U-238) and detect these with side detectors to provide improved isotopic sensitivity

*Note: Side detectors need additional shielding to reduce background (not shown in rendering)*



### RESULTS (MONTE CARLO SIMULATIONS)

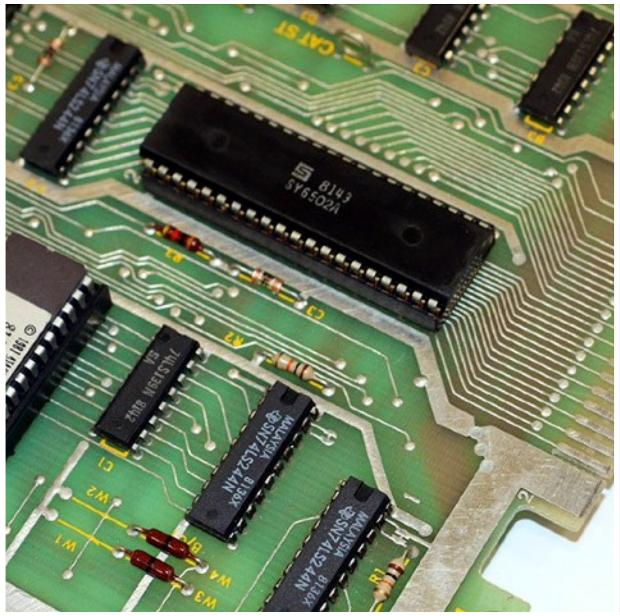
The system can detect substitution of 500 g of uranium-235 limited by counting statistics in bubble detectors (here: 48 detectors, ~350 bubbles per detector)

Experimental campaign at PPPL currently planned for different configurations of (enriched and depleted) uranium cubes to confirm isotopic sensitivity

# Vintage Verification

# VINTAGE VERIFICATION

## "TRUST THROUGH SIMPLICITY AND OBSOLESCENCE?"



### IDEA

Use simple, quasi open-source hardware from 1970s; backdoors and hidden switches unlikely in hardware designed in the distant past, at a time, when use for sensitive measurements was never envisioned

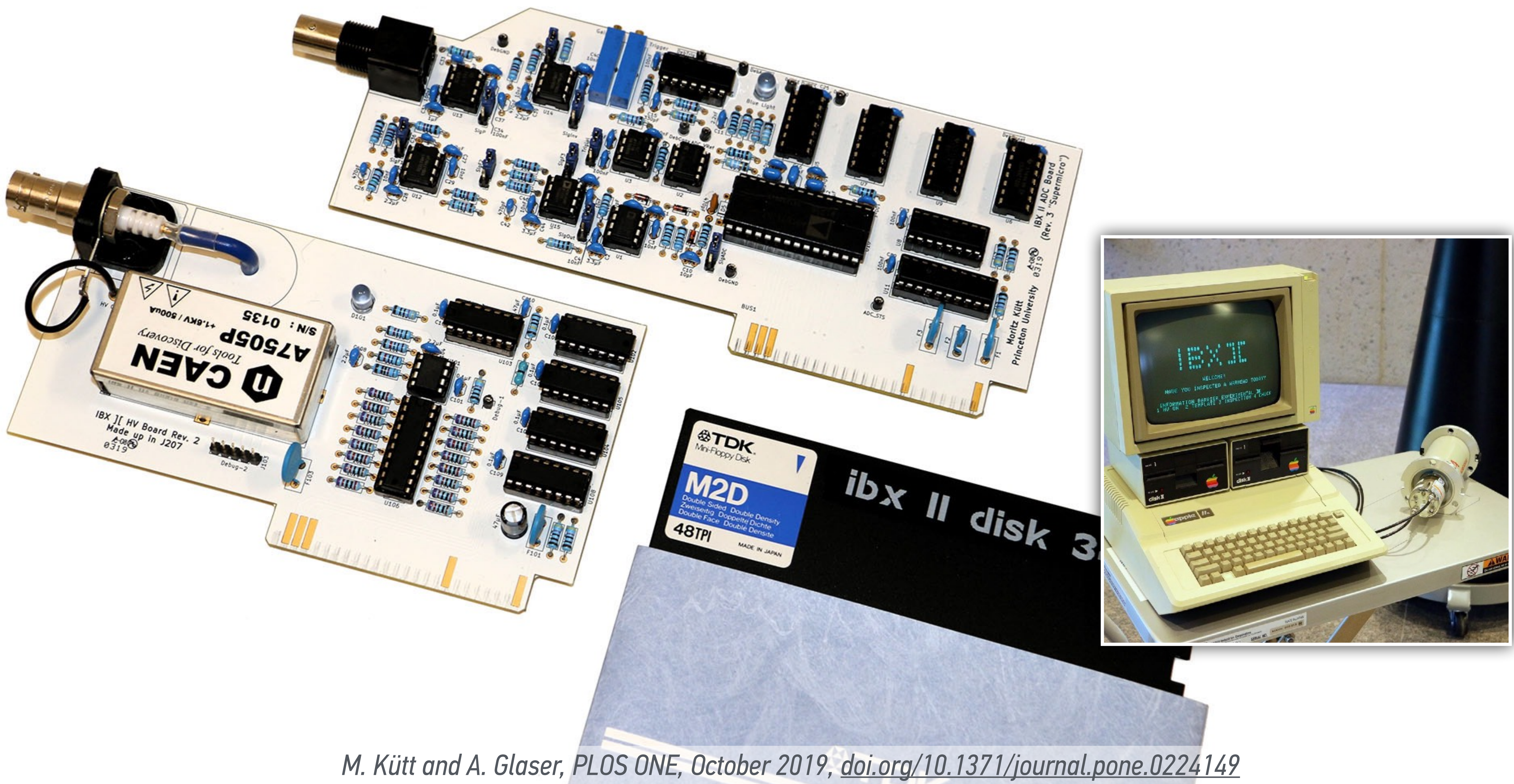
### IMPLEMENTATION / PROTOTYPE

MOS 6502 (3,500 transistors, 1 MHz) and an Apple IIe, combined with a standard sodium-iodide detector and using a template-matching approach; achieves ~ 2000 cps and acquires statistically robust data in 1–2 minutes; ability to detect small differences in signatures

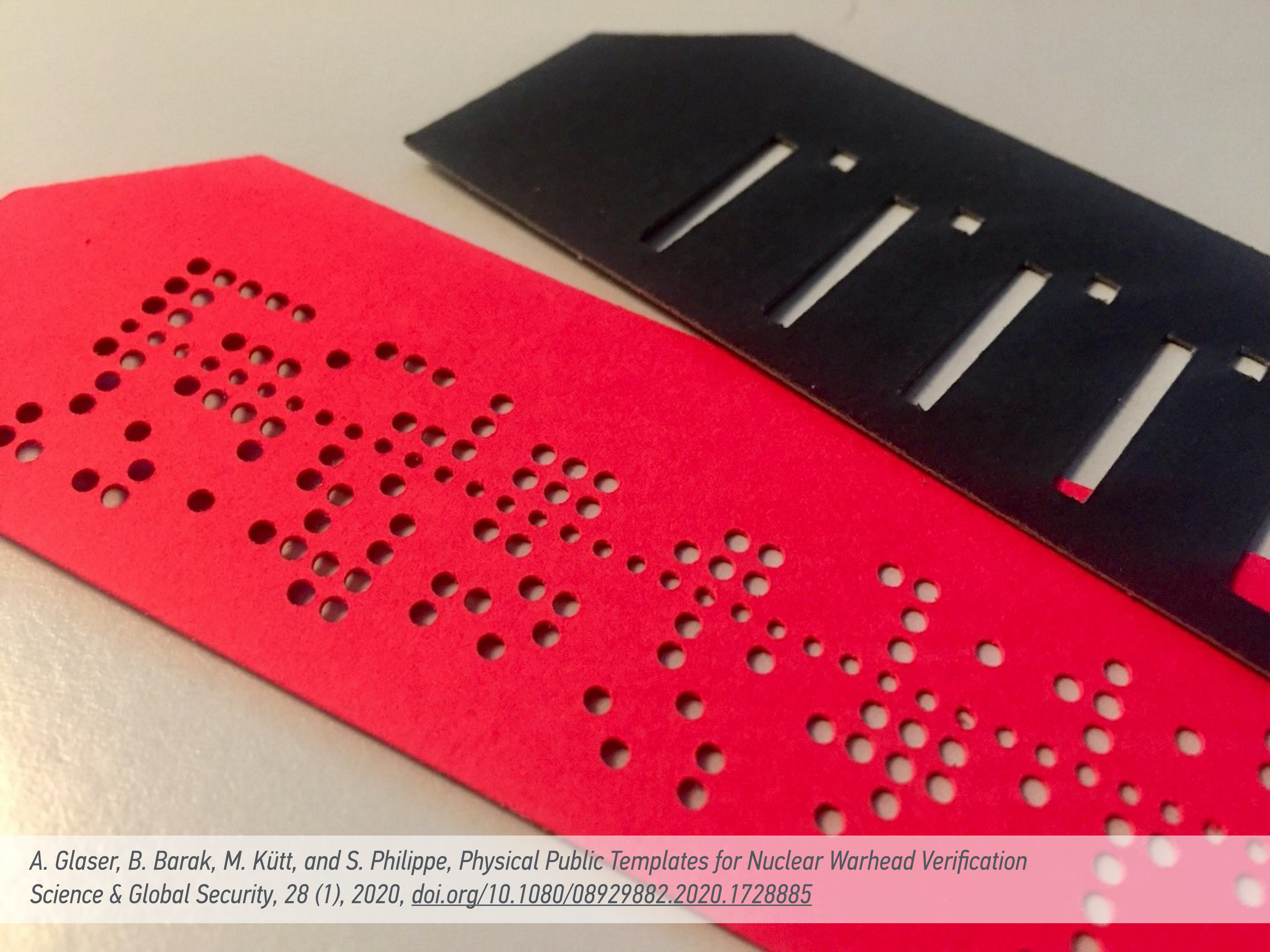
*M. Kütt and A. Glaser, PLOS ONE, October 2019, doi.org/10.1371/journal.pone.0224149*

# INFORMATION BARRIER EXPERIMENTAL II

## (STANDARD SODIUM-IODIDE DETECTOR & 12-BIN TEMPLATE)




M. Kütt and A. Glaser, PLOS ONE, October 2019, doi.org/10.1371/journal.pone.0224149



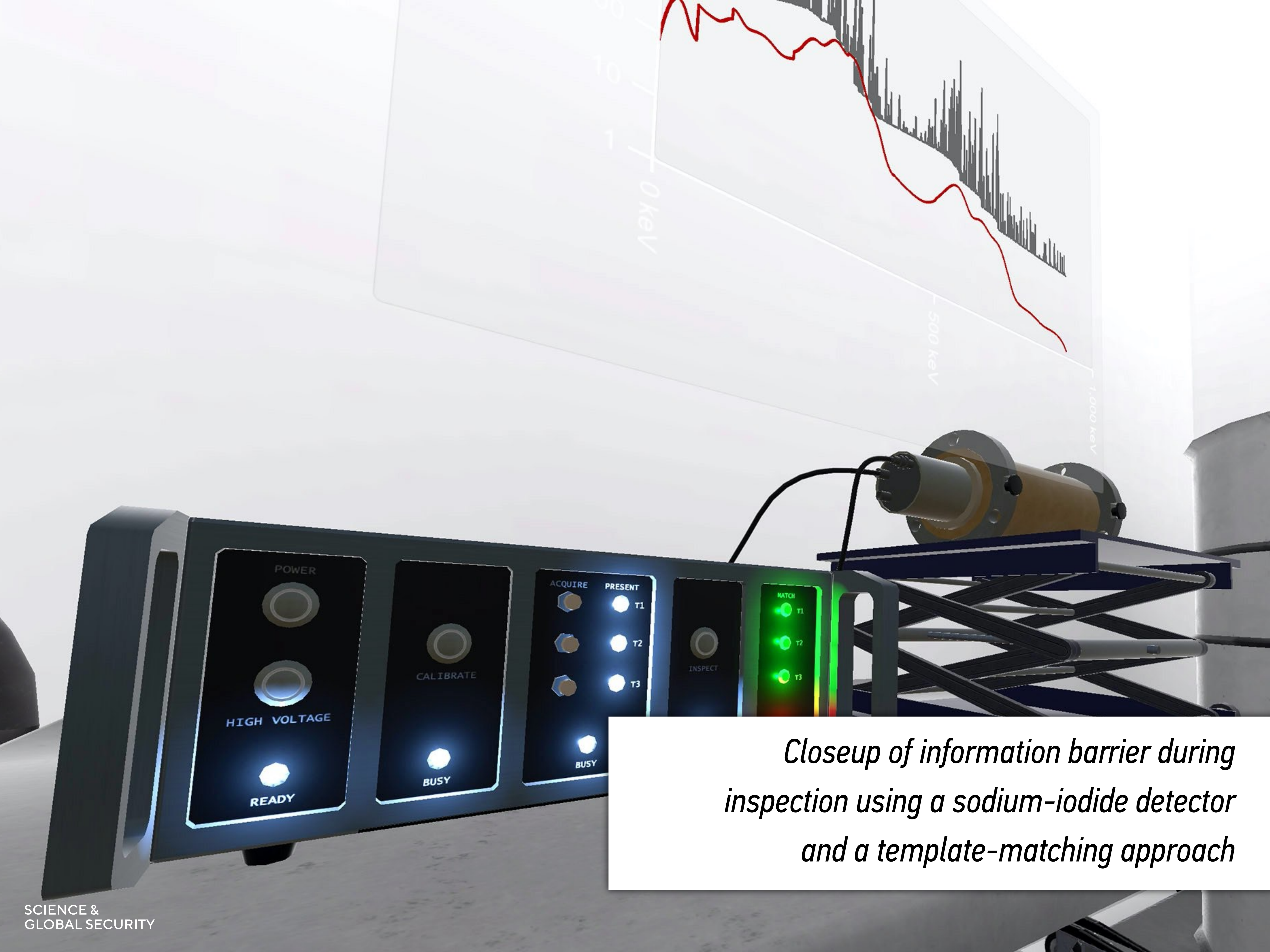
A. Glaser, B. Barak, M. Kütt, and S. Philippe, Physical Public Templates for Nuclear Warhead Verification
Science & Global Security, 28 (1), 2020, doi.org/10.1080/08929882.2020.1728885

# Virtual reality

AS A TOOL FOR THE JOINT DEVELOPMENT OF NEW VERIFICATION APPROACHES


DEMO REEL
UNMAKING THE BOMB VR
PRINCETON UNIVERSITY | GAMES FOR CHANGE | PHL-COLLECTIVE

*Storage bunker with warhead storage containers; Inspectors can select one or more containers for inspection with information barrier*




*Closeup of information barrier during inspection using a sodium-iodide detector and a template-matching approach*

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