**DISCLAIMER**

SAND2025-13642R

# COnfirmation using Gamma-ray Non-Imaging Zero-knowledge ANti-mask Time-encoding (COGNIZANT) Final Summary Report

Peter Marleau

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# ACRONYMS AND DEFINITIONS

| Abbreviation | Definition |
|---|---|
| CENC | Creating the Environment for Nonproliferation Collaboration |
| COGNIZANT | COnfirmation using Gamma-ray Non-Imaging Zero-knowledge ANti-mask Time-encoding |
| CONFIDANTE | CONfirmation using a Fast-neutron Imaging Detector with Anti-image Null-positive Time Encoding |
| CONOPS | Concept of Operations |
| NELA | Nuclear Explosive-Like Assembly |
| NSSC | Nuclear Science and Security Consortium |
| ONV | Office of Nuclear Verification |
| TEI | Time-Encoded Imaging |
| VFUND | Department of State Verification Fund |
| ZKP | Zero-Knowledge Protocol |

# 1. INTRODUCTION

In potential future arms reduction treaties in which the numbers of nuclear warheads may approach small numbers, using delivery systems as a proxy for the warheads themselves may be insufficient. Therefore, a technical means of verifying the presence of a nuclear warhead may become necessary. Verifying that a declared item actually is a warhead is technically challenging within a verification regime: providing assurance to the monitoring party that a presented item is a warhead while protecting sensitive information about that warhead may be required. It is generally believed that strong assurance will require the confirmation of key attributes that may reveal closely-guarded critical design information. This provides high confidence to the monitoring party, but presents a risk of information loss to the host. A verification system must overcome this hurdle.

Over the last several decades, systems have been developed that balance host and monitoring partner needs by using sensitive information to confirm treaty accountable items (TAI) as warheads while sequestering that information behind an information barrier (1). These are designed to meet the needs of the host but places the onus on the monitor to authenticate the hardware, firmware, and software. Authentication requires that the monitor confirm that all components of the system have not been modified and work as intended.

In 2014, Glaser et al. proposed applying the concept of "zero knowledge protocols" (ZKP) from the field of cryptography to the problem of warhead verification (2). In mathematical cryptography, ZKP is accomplished by challenging one party to solve a problem that is only possible if that party possesses the information being authenticated. After repeated challenges, the party provides confidence that it possesses this information without revealing any details about the information itself. Systems have been in development based on this idea at both Princeton and MIT (2) (3) (4). The final measurement results produced by these systems can be viewed by both the host and the monitoring party without the worry of revealing sensitive information.

However, in both of these physical implementations, there remains an information barrier within the system. The need for a digital information barrier to protect a measurement result is eliminated, but it has been replaced with the need to sequester physical components of the system, potentially obfuscating the measurement process itself. Both implementations physically insert information into the system that requires protection to prevent undesired disclosure of sensitive information: in the Princeton method, one must physically load the complement of the expected image of a true warhead into the system, and in the MIT technique, one loads a collection of spectator foils whose thicknesses physically encrypt a measured spectrum. This complicates authentication of the hardware and measurement process. The CONFIDANTE/COGNIZANT concept developed in this project do not load sensitive information into the system at any time, and could therefore open the possibility of allowing the inspector to not only view the final data but also the measurement as it is being performed and all associated equipment.

## 1.1. CONFIDANTE

CONfirmation using a Fast-neutron Imaging Detector with Anti-image Null-positive Time Encoding (CONFIDANTE) is a time-encoded imager (TEI) (5) that confirms that the volumetric distribution of radiological material in two objects is identical without risking any image/design information.  TEIs consist of a single detector pixel surrounded by a rotating antisymmetric coded mask. The detection rate is unmodulated if and only if two objects placed on opposite sides of the system are identical in geometry and activity (see Figure 1). A positive confirmation is indicated by a constant count rate. Given this simple metric, the monitoring party may be allowed full access to the instrument before, during, and after confirmation without risking sensitive information.

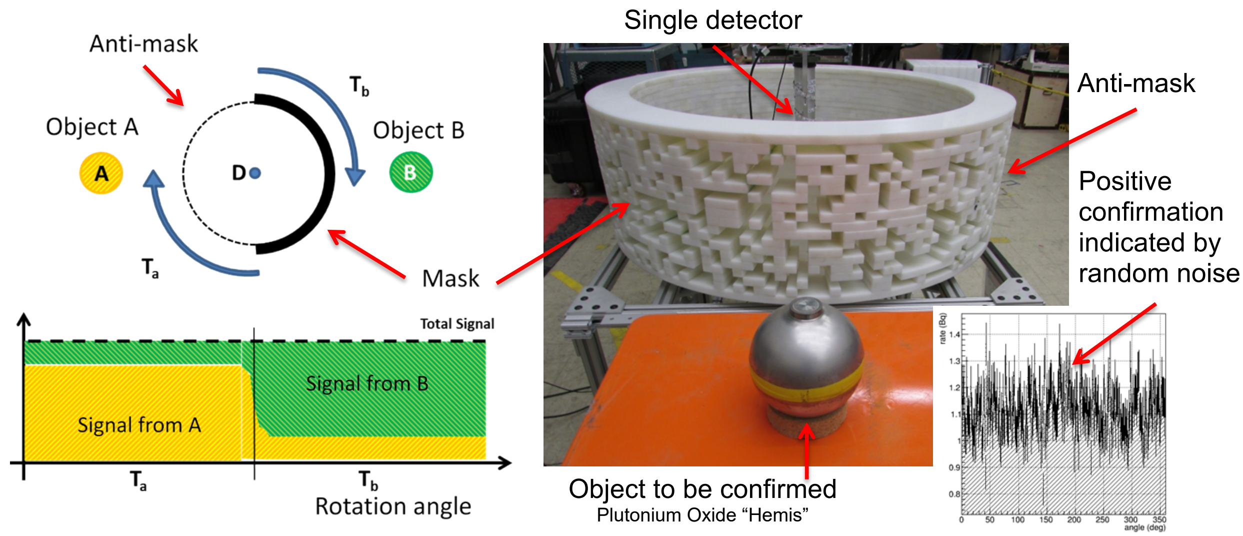


**Figure 1 - (Left, top) Top view of the simplest illustration of the CONFIDANTE concept. One half of the mask is the anti-mask of the other (left, bottom). If A and B are identical, then the sum of signals (y-axis) will be consistent with random noise as a function of rotation angle (x-axis) even though contributions from A and B vary. (Right) Photograph of the CONFIDANTE proof of feasibility demonstration confirming two objects are identical as indicated by a completely random signal (right inset)**

The prototype system seen in Figure 1 was designed, fabricated, and tested in a project funded by the Department of State Verification Fund (VFUND) in FY2016. Measurements, performance evaluation, and modeling studies have continued since this time through the PhD dissertation work of UC Berkeley graduate student Rebecca Krentz-Wee, funded by DNN R&D's Nuclear Science and Security Consortium (NSSC). Several proof-of-concept measurements of plutonium oxide hemispheres in both identical and different geometric configurations were made at Lawrence Livermore National Laboratory. Analysis of this data has established the proof-of-concept by demonstrating true positive and false positive rates indicating that the system can accurately confirm that two items that are declared to be identical in fact are, and that two items that aren't identical, are not. The results of these measurements have been presented in depth in reference (6).

The CONFIDANTE concept has been further developed under the Creating the Environment for Nonproliferation Collaboration project (CENC) by carefully optimizing the design of a new prototype. In this work, we have demonstrated that a spherical mask with a single central detector offers better performance both in terms of lack of imaging artifacts and a constant count rate as an indication of a true positive confirmation measurement. Design optimization studies have also determined that, because fast neutron count rates are expected to be relatively low (especially compared to gamma-ray count rates), it is preferable to use a larger central detector, even at the expense of imaging performance. When the number of counts per angular bin is too low, uncertainties from counting statistics dominate over any potential modulation in the distribution, thus making it difficult to identify the differences between two dissimilar objects.

CONFIDANTE was specifically adapted for warhead verification by designing the mask with anti-symmetry such that the pattern on one half of the cylindrical coded mask is the inverse of the other half. When two identical items are positioned on opposite sides of the system, the projection of radiation emitted by one item through the mask is the complement of the projection from a second item on the opposite side at all mask rotation angles; this is true if and only if the two items are identical in the distribution of their radiological and intervening materials along the line of site to the detector within the angular resolution of the system. Thus, the projections from the two items will sum to an unmodulated constant count rate as the mask is rotated *at all times*.

To illustrate this concept, the left-hand side of Figure 1 demonstrates the simplest possible anti-symmetric mask: a half-cylinder. Two items are placed at positions A and B while the mask rotates around detector D. A hypothetical radiation detection rate as a function of time is shown at the bottom. When the aperture is facing item A, the total count rate in the detector has a higher fraction of counts coming from item A than from item B. There may still be some fraction of signal from B because the mask is not perfectly opaque. When the mask rotates to occlude item A, the relative fractions of signal from A and B are reversed.

The line in the middle represents the point when an edge of the mask is aligned with the centerline of the two items. As the edge of the cylinder crosses the items, the signals are partially moderated, but still add to the same value. If items A and B are identical, the count rate in the detector as a function of the mask rotation angle will be consistent with a constant count rate (within Poisson counting statistics). If the items differ in shape or activity, then the count rate will exhibit larger variance around the mean value as the mask modulates their signals. Therefore, one way of measuring how alike two items are, is to measure how closely the distribution of count rates as a function of mask rotation angle follows that of a Poisson-distributed variable.

As is the case with template-based verification methods, at least one measurement must be made with a trusted treaty accountable item to impart confidence that the compared item is authentic. Once one item has been compared to the authenticated item, that confidence extends to all items that have been compared in a pairwise linked fashion. It is therefore possible to conduct such measurements with promise that this confidence will be imparted through comparison with an authenticated item in the future.

In this project we have investigate the trade-offs between design parameters such as the spatial resolution of the mask, size of the detector, detection efficiency, and measurement time through parametric modeling and use case studies. For example, when the detector is large relative to the projection of a mask element shadow onto the detector, partial attenuation effects during mask/aperture transitions will cause the detection rate to fluctuate.

Though this effect did not prevent us from demonstrating proof-of-concept in these measurements, it is possible that during longer or repeated measurements, these transition fluctuations could impart some sensitive design information. For relatively short measurement, the effect is small compared to overall modulation. However, if data were to be saved from many repeated measurements, those fluctuations could impart some sensitive design information.

## 2. COGNIZANT DESIGN

A prototype design for a gamma-ray version of the CONFIDANTE system, the COnfirmation using Gamma-ray Non-Imaging Zero-knowledge ANti-mask Time-encoding (COGNIZANT) system was optimized while incorporating solutions to many of the lessons learned from the CONFIDANTE proof-of-concept system. There were many components to the design that contribute to the performance of the system in different, sometimes opposing, ways under the constraints and requirements to be enforced.

For example, the system diameter was constrained to be 30-50 cm both to keep the overall weight down while using high density mask materials and for portability. With a smaller mask radius, the same mask aperture width leads to a larger angular resolution. If angular resolution is to be maintained, then both the apertures and central detector must also scale down in size. However, a smaller detector offers reduced absolute efficiency which increases the measurement time.

The time required to achieve a relevant discrimination task was also constrained to an hour or less. This requirement drives the central detector to larger volumes. However, to accommodate a larger detector, the mask apertures also need to be made larger. Without increasing the mask radius, this causes the angular resolution to increase.

A relevant discrimination task (e.g. discriminate between two objects whose images differ in a relevant way) and performance metrics were defined for this optimization task. Mask/detector geometries were then modelled, and performance estimated against the defined metrics to drive toward an optimum design. Design considerations included:

- Modulating Mask
    - Mass less than 50 kg – This will drive the mask to smaller diameters, thicknesses, and/or densities at the loss of attenuation/modulation.
    - Diameter less than 30-50cm – This constraint tends to drive up the angular resolution.
    - Spherical – This constrains the number of central detectors to one at the center of the sphere rather than several that are possible along the axis in a cylindrical geometry.
    - Aperture size – This is largely constrained by choice of detector size and mask diameter. An aperture too small for the size of detector causes unwanted fluctuations in the detection rate during confirmation measurements.
    - Mask material – We investigated various material types for their ability to modulate gamma-rays. We also considered other materials that better modulate thermal neutrons for the possibility of incorporating a thermal neutron imaging system if using an inorganic scintillator with thermal neutron capture capabilities.
    - Detector collimation – One of the mitigating factors that was identified in SAND Report 2018-7811, was to limit the field of view of the central detector to only the relevant direction. This was accomplished by collimation. We designed a collimating sleeve to limit the field of view in both directions (180 degrees apart) without introducing confounding artifacts from increased scattering within the system.
- Central Detector
    - Size – In general, it is desired to have a central detector that is as large as possible to achieve the statistics required to perform the discrimination task under time

constraints. However, the detector size is coupled to the angular resolution of the system; larger angular resolutions tends to degrade discrimination performance.

All of these factors were studied through a combination of modeling and targeted laboratory measurements. A design was presented to a design review panel, and comments and suggestions were incorporated where possible and documented in a Design Review Report[1] deliverable. For reference, also see the CONFIDANTE Demonstration Prototype Report (7).

The final design assembly drawings can be found in Appendix A for reference.

[1] COnfirmation using Gamma-ray Non-Imaging Zero-knowledge ANti-mask Time-encoding (COGNIZANT) - Design Review Report

# 3. CONOPS AND LABORATORY DEMONSTRATIONS

In conjunction with a follow-on effort funded by NA-243 ONV, a potential concept of operations (CONOPS) for the use of CONFIDANTE and COGNIZANT as a verification measurement in a hypothetical future arms control treaty was developed and demonstrated. The demonstration served as the COGNIZANT prototype's laboratory test and characterization.

The following CONOPS differs from previous laboratory operations in that complicated hardware like digital waveform samplers, digital computers, and data analysis were eliminated. Rather, data acquisition system was a single simple scalar counter, and the determination of whether two objects are positively confirmed to be identical was accomplished by comparing a count value to a set of thresholds. These were major steps taken toward simplifying the systems and facilitating authentication and certification.

The CONOPS is as follows:

- Inspection: the system can be opened and the Inspectors are allowed to jointly inspect the detector, connectors, electronics, motor and motor control, and mask under Host supervision.
- Functionality checks: a calibrated and trusted neutron check source is removed from joint custody for functionality measurements.
    - The Inspectors select a source distance and mask orientation for a functionality measurement.
    - The Hosts position the check source at the chosen distance, and align the mask to the requested orientation. Note that the Host is motivated to ensure that this functionality test passes.
    - The counter is set to zero, and a measurement of a predetermined length is conducted. The value from the counter is shown to the Inspectors.
    - The Inspector can confirm that this value is within statistical uncertainty of the expected count value given the measurement time and source distance selected.
- Preparations:
    - The Hosts position the mask to an orientation of their choosing.
    - The Hosts align two items that are declared to be treaty accountable on either side of the CONFIDANTE system.
    - The Inspectors set the counter alarms to the agreed upon minimum and maximum thresholds.
- Confirmation Measurements: the following sequence is repeated for an agreed upon number of mask orientations.
    - The Hosts position the mask to an orientation of their choosing. The Inspectors may visually verify the orientation to ensure that it has changed.
    - The Inspectors initiate a neutron counter measurement for the agreed duration. Note that the count values are not displayed to the Inspectors.

- When the measurement is complete, the Inspectors confirm that neither threshold alarm has been activated (i.e. the final count value is not below the minimum nor above the maximum).
- Inspectors reset the neutron counter and notify the Hosts that the next mask orientation measurement is ready to commence.

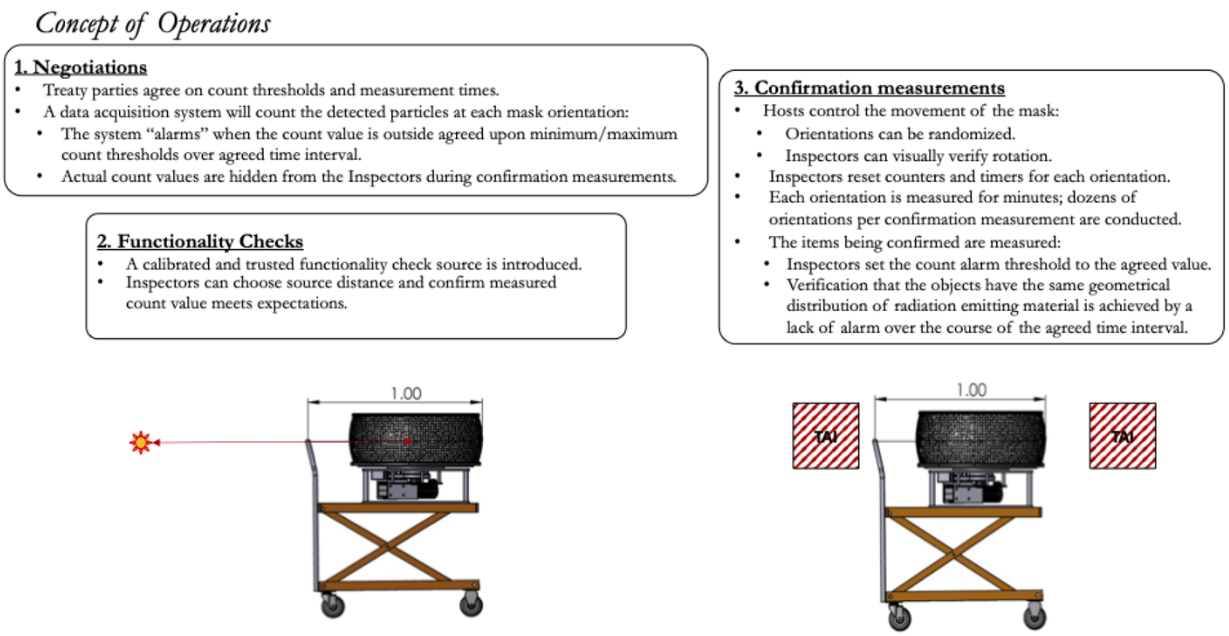


**Figure 2 - An overview of a potential CONOPS for COGNIZANT and CONFIDANTE confirmation measurements.**

These CONOPS were demonstrated using a pair of radiation sources with matched activities on either side of each system. They were spun by a movement stage to form "ring" sources on average. Positive confirmation configurations (true positives) were arranged with both sources moved through identical 5cm, 10cm, and 15cm radius rings, while negative confirmation configurations (true negatives) were arranged by one source at 5cm, 10cm, and 15 cm radius rings, while the other was 7cm, 12cm, and 17cm radius rings respectively.

The rate of true negatives vs. true positive rate was predicted through modeling and then demonstrated in a series of measurements. The two systems can be seen making these measurements in the laboratory in Figure 3. The demonstration validated our modeling predictions. The details of the demonstration and results of the measurements are reported in a journal article submitted to the Journal of Science and Global Security (8).

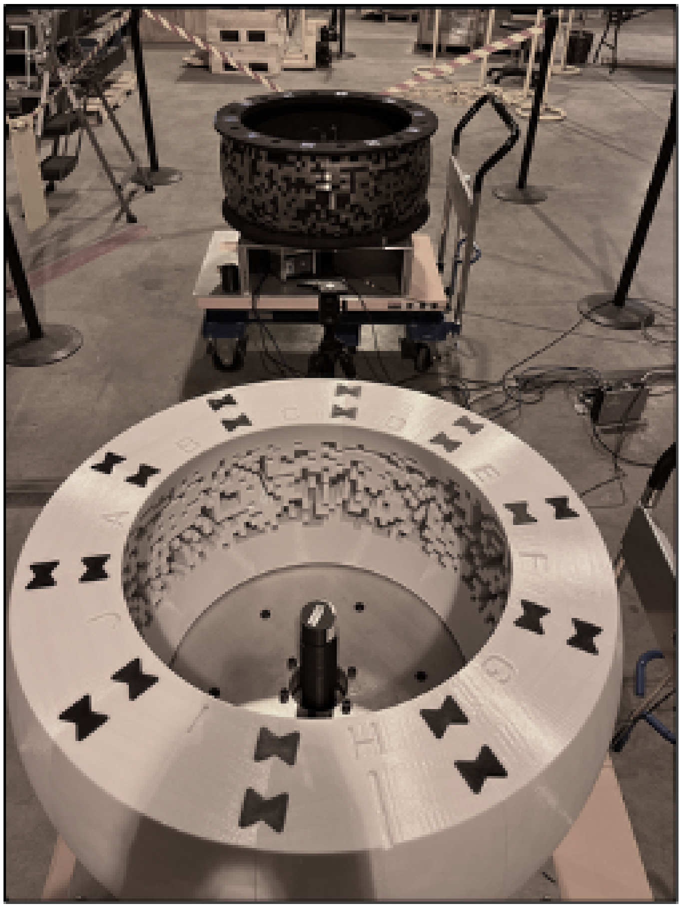

**Figure 3 – The CONFIDANTE (front) and COGNIZANT (back) systems in a series of characterization measurements in the laboratory.**

# 4. USE CASE STUDIES

The purpose of the Use Case Studies task was to develop a platform for high fidelity simulations that can be used for predictive modeling of complex item geometries, and to evaluate the impact of nuisance parameters such as environmental backgrounds and scattering and potential variation within items being measured.

For the design and optimization of the geometries and patterns of the time encoded imaging system of COGNIZANT (Confirmation using a Gamma-ray Non-Imaging Zero-knowledge Antisymmetric Time-encoding), a ray tracing modeling framework was developed. This has been sufficient for that purpose and has provided reasonable predictions for bare sources without any intervening attenuating materials, but the sources of interest in these studies are complicated assemblies that include emission, transmission, and scattering, rendering these tools less effective.

Furthermore, in prior studies with the CONFIDANTE system, the importance of environmental factors such as scattering from the floor and in the mask of the system itself was demonstrated. To mitigate some of these factors, we have developed a collimator in which the detector fits. Studying the improvement in system performance and optimizing the collimator design can only be done with modeling that includes these effects.

Toward this end, we have developed an MCNP modeling framework to incorporate full radiation transport physics into our predictive modeling. Because the COGNIZANT system is dynamic (i.e., it rotates over the course of the measurement), this was not a straightforward endeavor. A single complete measurement requires 300 separate data acquisitions, each with a 1.2-degree mask rotation between them. Therefore, the modeling framework must automatically create 300 different MCNP input cards, run the radiation transport, and then implement a detector response function, just to simulate a single item.

This framework was completed and compared to laboratory measurements of simple sources to validate the process. Predictive modeling was conducted to inform potential measurements of items at Pantex.

Further, several possible sources of variability between items were identified as worthy of further study in a previous effort funded by NA-243 Office of Nuclear Verification (ONV). This variability was introduced in the modeling effort to gain an understanding of how they may impact a CONFIDANTE/COGNIZANT measurement's true positive rate as well as what sensitive design information might be put at risk if the variability cannot be controlled.

The results of these studies were reported in the deliverable, "CONFIDANTE and COGNIZANT Use Case Studies[2]".

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[2] SAND2023-14305

# 5. PANTEX MEASUREMENT CAMPAIGN

Through a series of measurements we sought to collect the data necessary to evaluate the performance of both the COGNIZANT and CONFIDANTE prototype systems. The central objectives for planning of the measurement campaign were:

- Objects should offer realistic signatures relevant to potential future nuclear arms control treaty verification that may include warhead confirmation.
- Objects should include both neutron and gamma-ray signatures to test the performance of both detection systems
- Ideally, there will be two or more of the same object to present positive confirmation test cases. If this is not possible, then positive confirmation data sets will be synthesized from two statistically independent measurements of the same singular object with a 180-degree rotation phase offset.
- There should be pairs of objects with geometric differences that probe the angular sensitivity of both detection systems.

The Pantex Plant was able to offer five Nuclear Explosive Like Assemblies (NELAs) to serve as potential performance evaluation objects and were subsequently included in this project. All of the NELA options comprise only the physics package; their high explosives (HE) and electrical components have been removed. These items are stored in magazines in Zone 4 where the measurement also took place.

Two of the NELAs were selected and the measurement campaign commenced the week of August 25$^{th}$, 2025. There were several obstacles to be overcome, but in the end the project team successfully collected data from both NELAs with both the CONFIDANTE and COGNIZANT systems. This enabled us to demonstrate both a positive confirmation (i.e., two items are identical) and negative confirmation (i.e., two items are different) using (1) fast neutron imaging, (2) gamma-ray imaging in the 300 keV – 475 keV range relevant to plutonium emissions, and (3) gamma-ray imaging in the 700 keV – 3000 keV range relevant to U-238 and U232 (and U-235 by proxy).

Predictive modeling for the measurements were reported in the deliverable "CONFIDANTE and COGNIZANT Use Case Studies[3]". The details of the campaign, results of the data analysis and performance evaluation, and enumeration of lessons learned were reported in the deliverable, "CONFIDANT/COGNIZANT Measurement Campaign"[4].

[3] SAND2023-14305
[4] SAND2025-12638

# 6. REFERENCES

1. *Nuclear warhead verification: a review of attribute and template systems.* **Yan, J., Glaser, A.** 2015, Science & Gloval Security, pp. 157-170.
2. *A zero-knowledge protocol for nuclear warhead verification.* **Glaser, A., Barak, B., Goldston, R.J.** 2014, Nature, Vol. 510, pp. 497-501.
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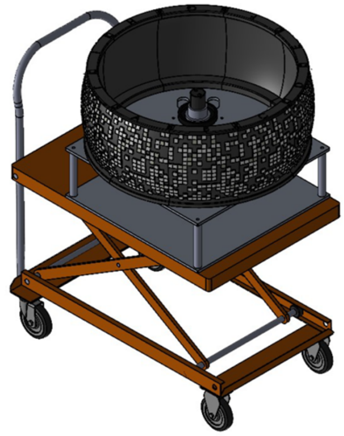
4. *Nuclear disarmament verification via resonant phenomena.* **Hecla, J.J., Danagoulian, A.** s.l. : Nature Communications.
5. *Demonstration of two-dimensional time-encoeded imaging of fast neutrons.* **Brennan, J., et. al.** s.l. : Nuclear Instruments and Methods in Physics Research A, 2015, Vol. 802.
6. *Proof of concept demonstration of CONFIDANTE (CONfirmation using a Fast-neutron Imaging Detector with Anti-image Null-positive Time Encoding.* **Marleau, P., Krentz-Wee, R., Schuster, P.** Baltimore : s.n., 2018. Proceedings of the INMM Annual Meeting.
7. *CONFIDANTE Demonstration Prototype Report.* **Marleau, P., Krentz-Wee, R.** 2021. SAND2021-0190R.
8. *Demonstration and Concept of Operations for a Zero-Knowledge Protocol Passive Imaging Measurement for Arms Control.* **Sweany, M., Marleau, P., Tiano, E.** 2025, Vol. (submitted).

# APPENDIX A. COGNIZANT ASSEMBLY DESIGN DRAWINGS

| Revision | Date | Name |
|---|---|---|
| A | 1/25/22 | KCS |

COGNIZANT System Specifications
1. Weight without cart: 113 Kg
2. Weight with cart: 218 Kg
3. Height Range Actual: 0.945 m-1.965 m
4. Height Range Planned: 0.945 m-1.4m
5. Footprint: 1.0 m X 0.78 m
6. Mask Material:
   Tungsten inserts
   Nylon 12 frame
7. Rotational speeds typ: 0.5 RPM
8. Rotational mass: 75 Kg
9. Center of mass without cart:
   X =-8 mm
   Y = 12 mm
   Z = 285 mm



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| | CHECKED | | | |
| | ENG APPR. | | | |
| | MFG APPR. | | | |
| INTERPRET GEOMETRIC TOLERANCING PER: | Q.A. | | | |
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**PROPRIETARY AND CONFIDENTIAL**
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| Revision | Date | Name |
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| A | 1/25/22 | KCS |

CONFIDANTE System Specifications
1. Weight without cart: 67 Kg
2. Weight with cart: 172 Kg
3. Height Range Actual: 0.945 m-2.05 m
4. Height Range Planned: 0.945 m-1.45m
5. Footprint: 1.0 m X 0.78 m
6. Mask Material:
   3D Printed PC
7. Rotational speeds typ: 0.5 RPM
8. Rotational mass: 25 Kg
9. Center of mass without cart:
   X =-17.84 mm
   Y = 22,96 mm
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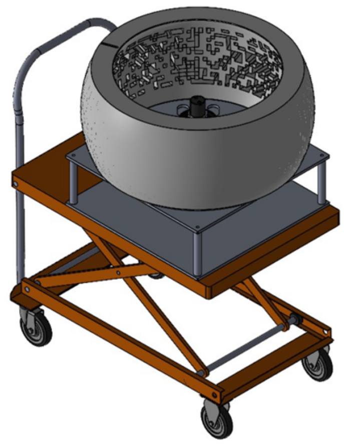

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COMMENTS:

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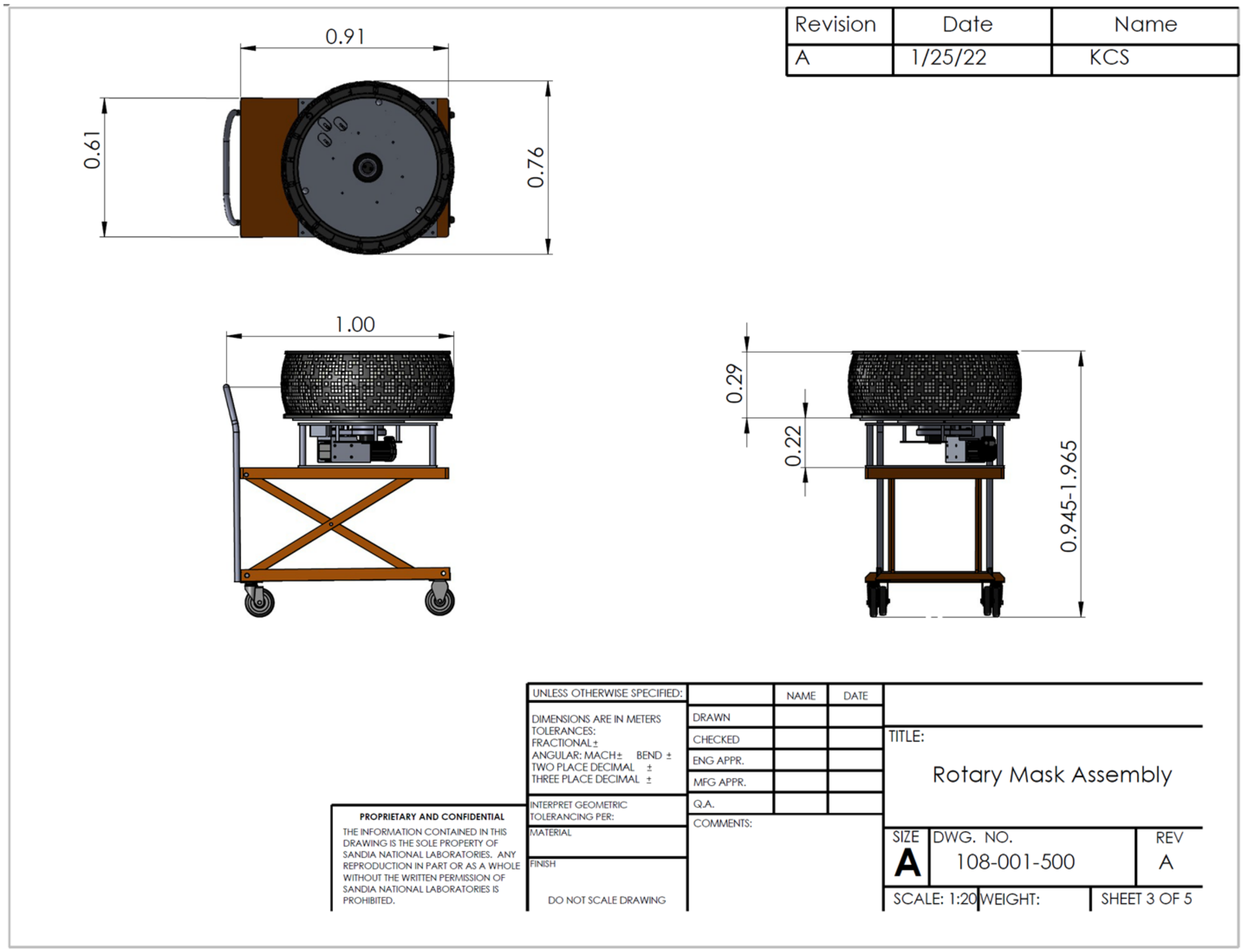
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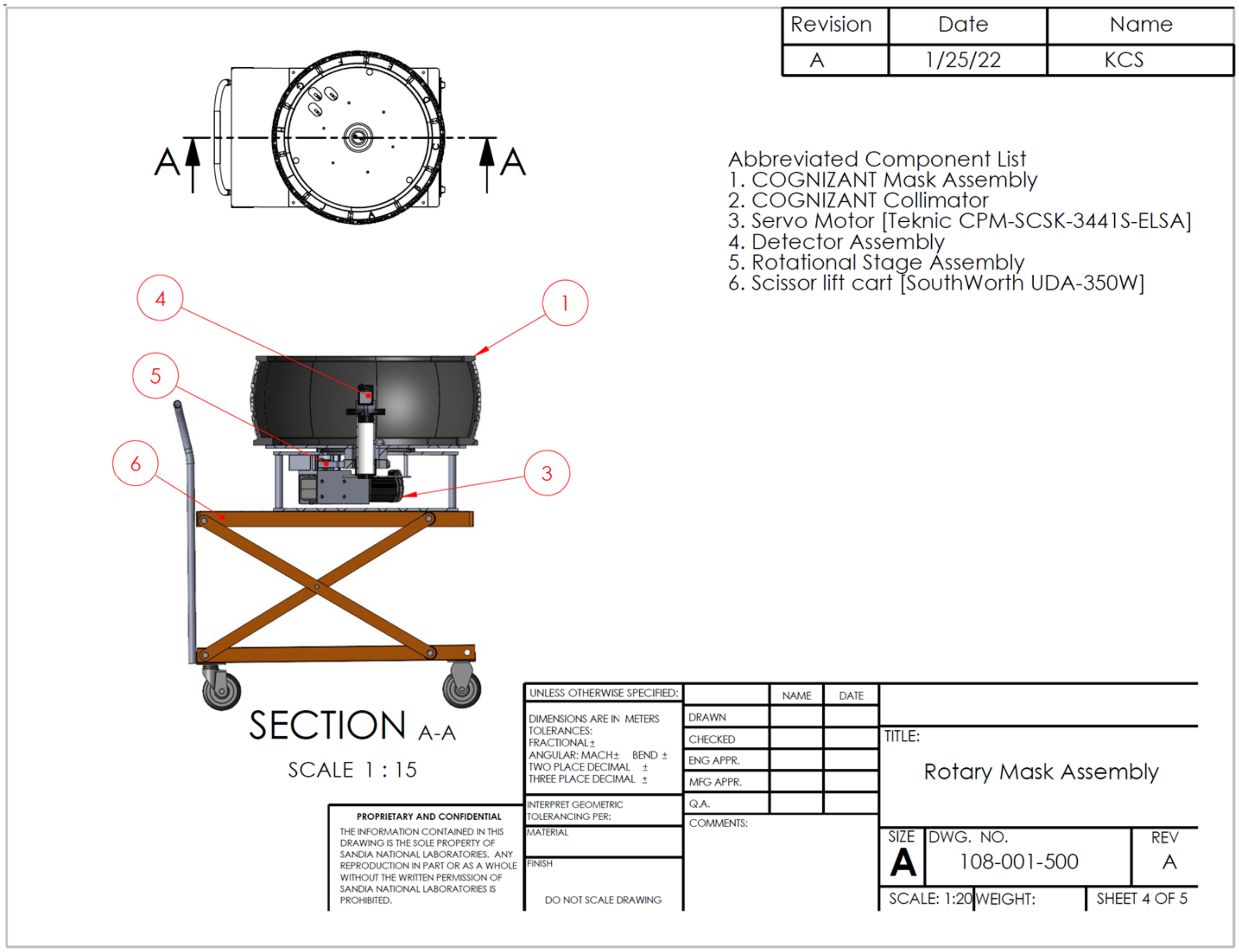

Revision
Date
Name
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KCS
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A
Abbreviated Component List
1. COGNIZANT Mask Assembly
2. COGNIZANT Collimator
3. Servo Motor [Teknic CPM-SCSK-3441S-ELSA]
4. Detector Assembly
5. Rotational Stage Assembly
6. Scissor lift cart [SouthWorth UDA-350W]
4
1
5
3
6
SECTION A-A
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UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN METERS
TOLERANCES:
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TWO PLACE DECIMAL ±
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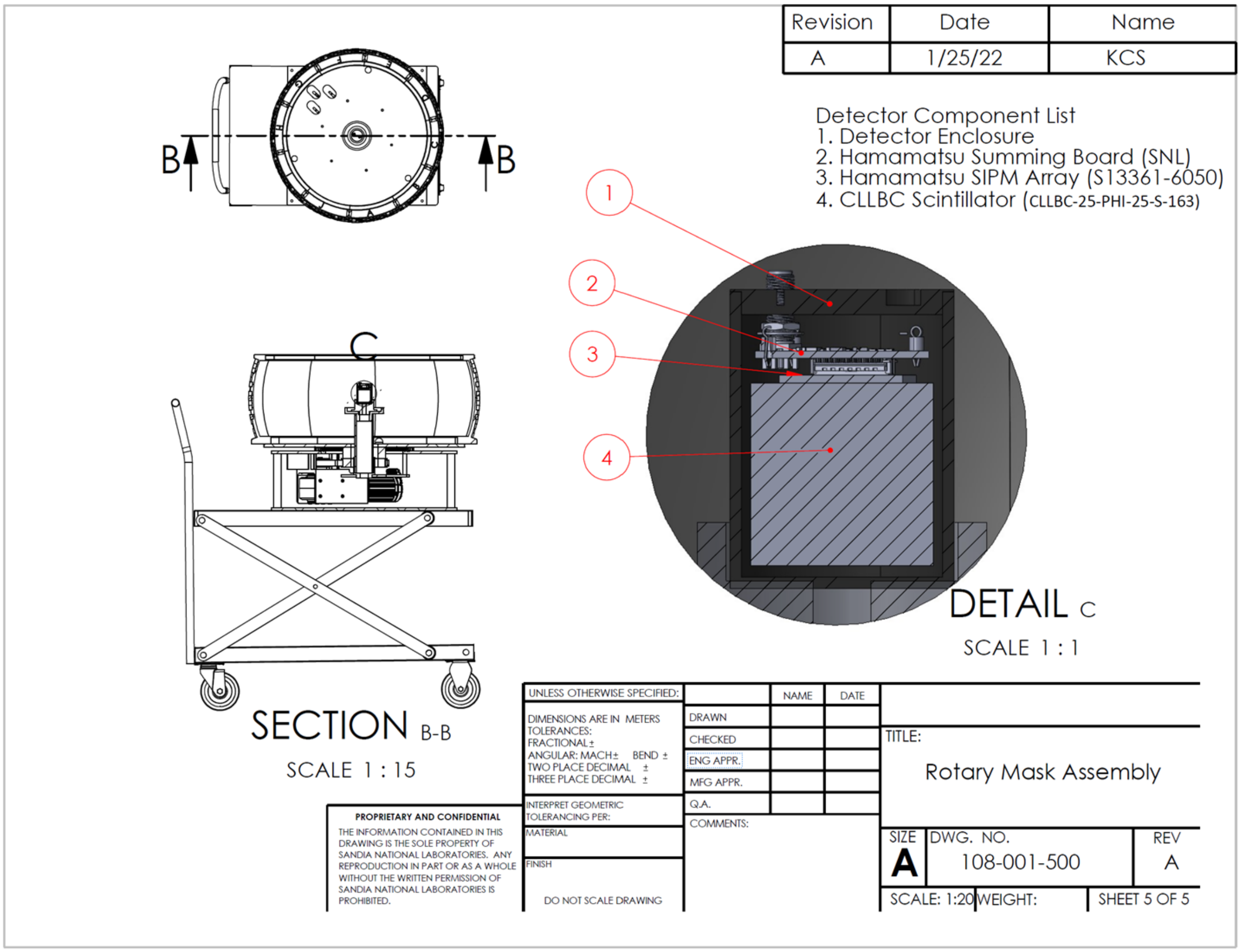

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KCS
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3. Hamamatsu SIPM Array (S13361-6050)
4. CLLBC Scintillator (CLLBC-25-PHI-25-S-163)
B
B
C
1
2
3
4
DETAIL C
SCALE 1 : 1
SECTION B-B
SCALE 1 : 15
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN METERS
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
TITLE:
Rotary Mask Assembly
SIZE
A
DWG. NO.
108-001-500
REV
A
SCALE: 1:20
WEIGHT:
SHEET 5 OF 5
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