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Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

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Oak Ridge, TN

Review Team
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Acronyms

ANC	Active Neutron (Coincidence or Totals) Counting
BJC	Bechtel Jacobs Company
BOP	Compressor Blow-Out Prevention Line (3/4-in-diam copper piping)
CL	Statistical Confidence Level (associated with specified uncertainty)
D&D	Decontamination and Decommissioning
DA	Destructive Analysis
DOE	U.S. Department of Energy
DOE/OR	U.S. Department of Energy, Oak Ridge Operations
DOT	U.S. Department of Transportation
DQO	Data Quality Objective
EM	DOE Office of Environmental Management
EM-21	DOE Office of Cleanup Technologies
EM-23	DOE Office of Core Technical Group
ETTP	East Tennessee Technology Park
γ	Gamma Ray
GDP	Gaseous Diffusion Plant
Ge	Intrinsic Germanium Detector
HQ	Headquarters (Washington DC) Offices of the DOE
LANL	Los Alamos National Laboratory
LEU	Low-enriched Uranium
MMES	Martin Marietta Energy Systems
N	Neutron
NaI	Sodium Iodide
NDA	Nondestructive Assay
NMC&A	Nuclear Material Control and Accountability
NTC	(Passive) Neutron Totals Counting
NCS	Nuclear Criticality Safety
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Reservation

PNNL	Pacific Northwest National Laboratory
QA	Quality Assurance
SVL	Compressor Seal Vent Line (3/4-in-diam Copper Piping)
USEC	United States Enrichment Corporation
WAC	Waste Acceptance Criteria

TABLES

FIGURES

APPENDIX

EXECUTIVE SUMMARY

The DOE with concurrence from the D&D contractor has chartered an assessment of the methods and procedures used to obtain the original NDA results of holdup deposits at the K-25 and K-27 uranium gaseous diffusion facilities in Oak Ridge. The assessment has been performed by an external review team with the participation of the D&D contractor, DOE, and DOE/OR. This document is the final report for the assessment.

The DOE provided the charter for this review. The review team spent a week in Oak Ridge attending meetings and participating in discussions with expert contractor staff. Substantial additional input for the review came from numerous written materials, unpublished and published. This final report of observations, findings, and recommendations in areas defined by the charter is based on information from the meetings, discussions, and documents.

The assessment of the Review Team is that the DOE/OR and BJC approach in using historical NDA data for the D&D of K-25 and K-27 is appropriate and generally acceptable. Resolving issues, addressing findings, and implementing the recommendations documented in this report will reconcile specific technical concerns.

The review team generally endorses the technologies and protocols for 1980-1990's portable holdup measurements. A combination of measurement control applied to the portable gamma and neutron NDA, an ongoing program of monthly confirmation measurements using the same generic NDA methodology in the 15-year period since the original measurements were performed, and documentation of the original measurements and methodology establishes both reliability and continuity – up to the present time – for the original measurements. Should analysis upgrades based on improved techniques or matured understanding of the deposits be necessary, such upgrades can be implemented without the need to repeat the original holdup measurements.

An important finding in the category of the validity of the NDA measurement results obtained using these technologies and protocols is the absence of defined confidence levels (CLs) for the declared NDA uncertainties. The corresponding recommendations include implementing empirical and numerical approaches to obtain realistic uncertainty terms at specified CLs, and define uncertainty at the given CL for the original NDA measurement result.

Gamma and sometimes neutron measurements are used for the same type of equipment. Some equipment was measured by both techniques. Unless realistic uncertainties are of a magnitude that explains observed discrepancies between gamma and neutron NDA results, using one or the other measurement approach may be unjustified.

The review found specific issues with aspects of the NDA of uranium deposits in process piping, one being that documentation for this methodology appears incomplete. The other issue concerns the manner in which algorithms for gamma self-attenuation are implemented for measurements of the process piping.

The nearly five-million linear feet of process piping is also the focus of concerns over possible gaps in the nondestructive survey measurements of these holdup deposits and corresponding risks of undiscovered large deposits that could threaten safety during the D&D. The review team recommends investigating some practical solutions to the potential survey gaps including implementing alternative approaches (other than more nondestructive survey measurements) to fill the gaps. Nonetheless, additional nondestructive measurements of holdup deposits in process piping are a likely need for addressing the gaps. Because most process piping has not been measured by quantitative NDA, efforts to justify the use of a lower survey threshold would be well spent.

Some alternative NDA measurement methods recommended in this report will fill some of the measurement gaps for process piping. Others will validate the existing holdup NDA measurements. All including the original holdup NDA results will support the D&D in economically fulfilling requirements for nuclear safeguards, nuclear safety, transport of waste, or disposal of the waste.

The review team encourages a continuing dialog between the contractor and outside experts on NDA measurements and technologies. These experts include the scientists and engineers who planned and implemented the original K-25/K-27 holdup measurements and others who designed and carried out the D&D at K-29/K-31/K-33.

1.0 INTRODUCTION

1.1 Purpose

The Department of Energy (DOE) Office of Environmental Management (EM) has chartered an independent review of the portable non-destructive assay (NDA) measurements of uranium performed in the K-25 and K-27 Buildings at the Oak Ridge Reservation (ORR) East Tennessee Technology Park (ETTP). The decontamination and decommissioning (D&D) of the two buildings must commence early in Fiscal Year 2005 in order to be complete by 2008. Many aspects of the D&D rely on information from the NDA measurements that includes the distribution of uranium, quantities of uranium and ^{235}U, and the uncertainties in the quantities. Bechtel Jacobs Company (BJC) is the contractor for the D&D.

The original NDA measurements performed 15-20 years ago are the basis for the recent safeguards declaration of special nuclear materials (SNM) inventory in K-25 and K-27. These NDA measurement results have also guided the Deposit Removal Project that identified process materials presenting higher risks to criticality safety and recently removed those of highest risk. The original NDA measurements will also be the basis for the safety protocols established for the D&D operations. Finally, the original NDA establishes the basis for compliance with regulations on the packaging, transport and storage of waste removed from K-25 and K-27.

A schedule for the D&D of K-25 is now in place. Because the NDA measurement results were not obtained recently, the DOE with concurrence from BJC is now seeking an assessment of the validity of methods and procedures used to obtain the original NDA results, the reliability of the NDA results, and the degree to which the results provide the information needed to fully execute the D&D of the facility. The Department of Energy convened an independent review team to assess the appropriateness and adequacy of the use of these NDA results by BJC. Recommendations for additional measurements and alternative approaches are among the information requested from this review of the previous NDA.

1.2 Scope

Underlying the protocols implemented for performing and interpreting the 1980’s-1990’s NDA measurements was a conservativism intended to ensure that sufficient controls would be in place for deposits that are potentially unsafe from the criticality standpoint. Because the scope of the review includes an assessment of this conservatism, it requires evaluating the reliability and validity of existing data at the specified confidence levels.

The K-25 and K-27 process buildings occupy a combined area that approaches a tenth of a square mile. Because the associated piping occupies a horizontal tier above that of the array of converters and compressors in the diffusion cascade, the area occupied by the equipment in which deposits are contained is effectively twice that of the building footprint. It is logical for the scope of this review to raise the question of whether portable measurements can even cover such equipment territory, determine what if any gaps exist in the measurement data, and recommend approaches to fill the gaps.

The NDA technology in use currently in K-25/K-27 is operated to acquire data that emulates the data obtained 15-20 years ago. This approach both affirms the reliability of older equipment from a standpoint of quality assurance (QA) and confirms that deposits remain unchanged since the time of the original measurements from a standpoint of nuclear materials control and accountability (NMC&A). However, because of the possibility that modern technology is capable of achieving a superior measurement result, the scope of the review includes recommending alternative technologies if needed to improve measurement results. A corollary to this aspect of the scope is recommending alternative analysis of the existing data to achieve a more accurate result and/or more realistic uncertainty

The existing NDA data must address needs of NMC&A as well as essential D&D activities that include nuclear criticality safety (NCS) evaluations and controls during the removal and handling of process equipment, Department of Transportation (DOT) requirements for transportation and disposal, and waste acceptance criteria (WAC) for disposal facilities. Though not exhaustive, this review includes an evaluation of the usefulness of the original NDA measurements in some of these areas of concern.

1.3 Background

The K-25 and K-27 Buildings at the ORR ETTP were constructed during the Manhattan Project and placed into service in 1945. The facilities were designed and built to house full-gradient cascades to produce uranium enriched in the ^{235}U isotope to the weapons grade level. The enrichment process consisted of diffusion of uranium hexafluoride (UF_6) gas through a massive mechanical cascade of repetitive process stages. Various portions of the two buildings operated through 1985, when all enrichment operations ceased at both buildings. There is no longer a mission for the facilities, which are slated for demolition by the end of Fiscal Year 2008.

Non-quantitative non-destructive measurements performed after 1985 surveyed all process equipment in K-25 and K-27. Quantitative nondestructive assay (NDA) measurements performed in the late 1980's on nearly 18,000 process equipment items in K-25 located and quantified the uranium in most equipment (all converters, compressors, copper piping, surge tanks, cold traps) in the enrichment cascade as well as selected process piping segments (those exceeding the sensitivity threshold of the survey measurements). Ongoing NDA measurements performed since the 1990's have supported the Verification/ Confirmation program – a statistically based NDA monthly measurement program that confirms whether there has been a diversion of Special Nuclear Materials from any process gas equipment or item.

The inventory of highly enriched uranium (HEU) in the K-25 Building not including NDA uncertainty is 1500 kg. The K-25 uranium mass is estimated assuming the entire 1500-kg mass of HEU at ETTP as of December 31, 1993, as announced by the Secretary of Energy, exists in the K-25 process gas equipment. The enrichment ranges from 20 to 93% ^{235}U.

The inventory of uranium mass in the process gas equipment in the K-27 Building not including NDA uncertainty is 1409 kg. The enrichment ranges from 0.7 to 20% ^{235}U.

The uranium is mostly present as a generally uniform and diffuse layer. The exceptions are locations at which moist air in-leakage occurred. Gaseous UF_6 reacted with water vapor at these locations to produce solid UO_2F_2, which accumulated continuously as air in-leakage in the presence of UF_6 persisted. Therefore, thicker deposits of uranium holdup are observed in equipment near sites of air in-leakage.

2.0 THE REVIEW PROCESS

The review process included several mechanisms for transferring relevant information to members of the review team. This began with telephone discussions/conferences and a charter provided to members of the review team in advance of the November 2004 visit to Oak Ridge. Also in advance of the visit, the members of the review team received mailed copies of unclassified documents relevant to the review topics. The visit to Oak Ridge commenced with a half day of presentations that provided the scope of the review topics to the members of the review team and introduced them to site personnel. The bulk of the week of the site visit consisted of meetings with site experts as well as reviews and analysis of classified information. The site-visit week ended with three presentations by members of the review team on the findings of the review.

2.1 Charter

The charter for the assessment process, as outlined in Appendices A and D, defined the following activities.

- Review the measurement protocols used for the NDA performed at K-25 in the 1980's – 1990's.
- (Determine the degree to which the measurement results are conservative. *Parentheses indicate that this activity is part of both the preceding and the following activities.*)
- Evaluate the reliability and validity of existing data at stated confidence levels.
- Determine if there are gaps in existing data (such as equipment not being measured) and indicate additional measurements/techniques if applicable.
- Evaluate the current NDA technology in use and recommend alternative technology if needed.
- Determine whether the existing NDA data are applicable for
    - NMC&A.
    - critical D&D activities such as
        - Nuclear Criticality Safety evaluations and controls during the removal and handling of process gas equipment.
        - Department of Transportation requirements for transportation and disposal.
        - Waste Acceptance Criteria (WAC) requirements for disposal facilities.
- Document the fulfillment of these chartered activities in a report.

The review team pursued the chartered activities during the assessment visit to Oak Ridge in the week of November 29, 2004 and in prior and subsequent reviews of documentation. Sections 2.2-2.5 below give an overview of the activities before and during the weeklong assessment. This report is the final item in the list above.

The review team members are A. P. Belian and P. A. Russo, LANL; and D. R. Weier, PNNL. Participants in the review process are R. W. Bartholomay, C. K. Brown, and K. D. Kimball, BJC; R. L. Mayer, USEC; P. G. Kirk, ORNL; W. A. Cain, DOE/OR; and T. C. Chee, DOE/EM-21. Appendix B provides contact information for review team members and participants.

2.2 Pre-review of Materials

Documents provided to the review team in advance of the assessment visit included relevant non-classified (but mostly OUO) reports: Bartholomay, Mayer91, Mayer91a, Mayer92, Herron, and Kucsmas. The review team used the comprehensive summary report by Bartholomay as a detailed roadmap of the scope of the previous measurements and the documents that describe these measurements. The Kucsmas report provides information on process equipment that was important, for example, in carrying out the Monte Carlo simulations described in Section 4 and Appendix F. The non-classified article by Herron and three by Mayer provided an advance description of the NDA measurement techniques as they were applied to low-enriched uranium (LEU) in K-27 and in K-29, -31 and -33 (respectively). Although details of the measurements for K-29, -31 and -33 necessarily differed, for reasons that originate in the lower ^{235}U enrichment, from those of K-25 and K-27, measurement equipment and many procedures were common to those used in K-25 and K-27.

2.3 Introductory Presentations

Appendix C, the agenda for the site visit, lists the presentations given at the entrance briefing on the first morning of the site visit. The following states the content of each presentation concisely, in the order presented.

Texas Chee of DOE EM HQ) mutually introduced representatives of DOE EM HQ, DOE/OR, D&D-contractor (BJC) management, D&D-contractor (BJC) technical staff, D&D-subcontractor (Canberra) technical staff, and the members of the review team.

Donna Perez of DOE/OR described the expectation of a complete and candid assessment of the NDA measurements performed at K-25 and K-27.

Wendy Cain of DOE/OR gave an overview of the physical plant emphasizing the expanse of K-25 and K-27, descriptions of equipment groups and sizes/layouts, and historical summary of measurements and deposit-removal activities. This presentation included a handout of information for reference.

Kevin Meyer of Canberra summarized gamma and neutron instrumentation and methodologies used for the K-25 NDA measurements, and gave a history on the sequence of these measurements carried out in K-25 in the late 1980s. This presentation also included a handout of information for reference.

Chad Brown BJC described the scope of the customer base for the NDA results and efforts to confirm ongoing relevance of the original measurements. He discussed NDA uncertainties for the holdup measurements and summarized the types of NDA measurements, the measurement parameters for different types of process equipment, and verification opportunities for each of the four major equipment groupings. This presentation also included a handout of information for reference.

Joe Alvarez, BJC, committed to providing the technical information and expertise required to support the needs of the review process.

Karen Shaffer, BJC, revealed that the declared inventory is fixed for purposes of NMC&A and described the NDA re-measurement/confirmation process that has been in effect for ~15 years since completion of the original NDA campaigns.

2.4 Classified Meetings, Discussions, Evaluations

Three full days of classified meetings and discussions were the primary activities for the weeklong site visit. The D&D contractor BJC made this possible by the continuous presence of several technical experts, who provided information directly; accessed requested data, documents, and reports (most classified); and scheduled/performed diagnostic measurements to confirm or eliminate specific theories regarding the NDA results. A principal scientist and NDA expert from the period of the original NDA measurements, now an employee of USEC, also participated in the discussions daily by telephone.

The classified reports included MMES1, MMES2, MMES3 and MMES4, which gave details of the measurement procedures and analysis algorithms for the header pipes, compressors, converters, and piping, respectively. Also very useful was Mayer89, which discusses the approaches and algorithms for performing the calibrations and measurements of holdup in converters using gamma and neutron detectors. Other useful documents are listed in Section 7.0 and are referenced throughout this report.

A complete review of the holdup measurements at K-25 and K-27 would examine (or generate) more information than is practical for the limited scope of the present review to achieve. The information of interest includes

- summary tables of measurement results organized by measurement type/equipment.
- summary tables of magnitudes of all corrections applied to measurements
- mapping of measurement locations onto plans of the equipment layouts.
- spatial mapping of nondestructive survey results in the plant
- spatial mapping of NDA results for deposit masses in the plant.
- control charts of the results of repeated measurements over time.
- the mechanical design of each type of process equipment.
- physical access opportunities and limitations.
- positions of detectors relative to deposits
- approaches/algorithms for equipment attenuation, background determination, and scattering.
- characteristics of detectors and associated shielding and collimation.
- characteristics of the measurement equipment.
- calibration methodologies and models.
- measurement methodologies.
- analysis algorithms.
- estimation of systematic error terms.

- propagation of error and determination of total measurement uncertainty.
- variations in deposit enrichment, composition and distribution.
- variations in measurement parameters at different locations on the same equipment.

The NDA data are not available currently in many of the presentation formats indicated in the list above, and even this long list only begins to cover the relevant details of NDA measurements of the number and variety performed in the GDP. It is not possible to explore all aspects of measurements performed at K-25 and K-27 in only several days of review meetings. However, developing an understanding of the soundness of some important aspects of the project – some generic and others specific but representative of a large fraction of the material and equipment – can encompass significant territory and aid in defining approaches that may be used to take in the remaining territory. The following paragraphs discuss important aspects of the project that were emphasized in three days of discussions.

The origin of the uncertainties assigned to the NDA measurement results was a topic that emerged many times in the course of the three days of discussion. The usefulness of the NDA data to certain customer interests (criticality safety for the D&D in particular; the packaging, transport, and storage of waste to some extent) relies on the assurance that the uncertainties are conservative. The best knowledge, rather than conservative estimates, of the actual measurement uncertainties is the requirement for NMC&A and is actually most beneficial for cost effectiveness of the D&D.

Converters are nearly 20% of the ~18,000 process equipment items. The four converter types in K-25 (K-27 uses only one of the four) represent the most complex measurement geometry of the GDP equipment. Half of the discussion time focused on converters. Gamma and neutron measurement data for converters (Bartholomay) show unusually high gamma results relative to those obtained with neutrons. Such gamma/neutron discrepancies exist for other equipment. The team requested additional data for other converters (and other equipment) measured by the two techniques to analyze statistical correlations between results of the two types of measurements and found no such correlation. The team also requested additional measurements on specific converters to help explain the high relative gamma results. Finally, the team requested information on the design of converters and the detector/measurement geometries in order to model the response to gammas and neutrons for a range of deposit distributions and explain the multiple discrepancies.

Gamma-ray attenuation is an important issue for 186-kev gamma rays used to measure HEU because attenuation effects can be very large at the relatively low gamma-ray energy. The attenuation effects associated with dense process equipment preclude the use of 186-keV gamma measurements of compressors in the K-25 facility, for example. The very large variation in equipment attenuation with changing distribution of deposits within complex equipment such as converters is a warning to the analyst to determine and incorporate the systematic effects of deposit distribution into the measurement uncertainty for the deposit quantity in each process equipment item. Finally, correctly incorporating the systematic effects of self-attenuation into the analysis of deposits in the process piping for which the correction for equipment attenuation is straightforward is an essential aspect of quantitative gamma-ray measurements that is most important for low gamma-ray energies and/or thick deposits.

Non-quantitative survey measurements of process piping covered the five million linear feet of this equipment. Quantitative measurements were made on only a small fraction – approximately one percent – of this piping. The adequacy of the survey measurements for all of the process piping and the quantitative threshold for these measurements are issues that the review team has considered.

2.5 Summary of Observations and Findings

Attendees at the exit briefing on the last afternoon of the site visit included the review team and the DOE. The review team provided preliminary observations and findings on the NDA measurements of holdup in K-25 and K-27 in three presentations (Appendices E, F, and G) at this briefing. The remaining paragraphs of Section 2 summarize the observations and findings of the review. These are grouped into the five charter categories (refer to Section 2.1). Sections 3 and 4 of this report contain detailed and sometimes technical discussions of the review topics (the information base for the review) and the findings, again organized into the five charter categories. Section 5 lists the recommendations from this review by charter category.

2.5.1 Protocols for NDA at K-25/K-27 in 1980's-1990's

Measurement hardware – detectors and electronics – and the data-reduction process used for the original measurements of holdup were sufficient to obtain appropriate data and acceptable quantitative results. Generically equivalent technology remains sufficient for current measurements. Measurement control implemented during the original measurements of holdup and currently assures the validity of the original measurement data. Legible, detailed, and intelligible hand-written records of the original NDA measurement results were archived and maintained and remain accessible. Equivalent ongoing NDA confirmation measurements provide safeguards assurances over time for large deposits of ^{235}U. The same ongoing NDA confirmation measurements provide continuity to the present for refinement or adjustment of original NDA results and re-evaluation of the uncertainties as needed based on new knowledge. The combined assurances of validity of the original data, accessibility of archived results, and empirical continuity of the NDA measurements to the present strongly reinforce a general endorsement of the use of the original NDA results. Supplementing this general endorsement are the remaining summaries of observations and findings, Sections 2.5.2 through 2.5.5.

2.5.2 Reliability/Validity of NDA within Stated Confidence Intervals

All NDA results for K-25 and K-27 are quoted with an intentionally conservative uncertainty of ±50% or ±100%, but the confidence level (CL) is unspecified because the uncertainties have not been derived for these NDA measurements of holdup. Furthermore, the quoted total NDA uncertainties of 50% or 100% may not always be conservative and may, in other cases, be overestimated. The gamma and neutron NDA results for converters are uncorrelated , which could indicate very large systematic effects in one or both measurements. The gamma results are also higher than the neutron results. Monte Carlo simulations of the gamma and neutron measurements of converters offer an explanation for the large discrepancies between the NDA results for the two measurement types. These simulations also support the choice of neutron over gamma NDA results for (high-mass) converters. The simulations indicate, in addition, that the neutron calibration for radial deposit distribution is reasonably conservative. Because the systematic effect of the radial deposit distribution is >100% for the Type-2 converter gamma NDA, it is likely that NDA results recorded for low-mass-converters (gamma in this case) are biased beyond the stated uncertainty. Additional simulations may prove that the neutron NDA results for large (Type 1 and 2) converters are relatively vulnerable to horizontal deposit distribution. The simulation results and the fact that equipment dimensions are massive are irrefutable indications that deposit distribution contributes substantially to systematic uncertainty in the NDA of holdup at K-25 and K-27. Nonetheless, the Monte Carlo simulations of gamma and neutron measurements for a given type of equipment are straightforward to implement given equipment and deposit parameters and can support determinations of measurement uncertainty and estimations of confidence levels. Regarding the NDA measurements of process piping, the documentation of the methodology for holdup measurements and analysis of steel piping (MMES4) appears to be incomplete. Furthermore, the algorithms for gamma self-attenuation as indicated in MMES4 appear to be implemented incorrectly.

2.5.3 Gaps in NDA Results and Additional Measurements/Methods

The campaign of non-quantitative nondestructive survey measurements that preceded the quantitative NDA measurements of deposits at K-25 and K-27 was a practical screening approach to identifying large deposits of high priority. Performing quantitative NDA on the higher mass deposits correctly prioritized these efforts. Most processing equipment (all converters, compressors, SVL and BOP piping, surge tanks, and cold traps, for example) were measured by quantitative NDA. However, most of the process piping, which is ~5 million feet in length, was not measured by quantitative NDA. Furthermore, potential gaps in nondestructive survey measurements – such as those caused by insensitivity to the actual deposits because of large measurement distances for inaccessible gallery piping – are a source of concern for safety in the D&D project. Information in the existing gamma NDA results for 5000 segments of process piping may fill some of the gaps. This information includes possible correlations in existing NDA measurement results for piping segments. It also includes an empirical determination of a lower limit in the distribution of ^{235}U linear density for the 5000 measured piping segments. Graphical maps of the quantitative NDA results superimposed on sketches of process equipment could give further understanding of deposits in gap regions. An additional campaign of "quantitative surveys" of process piping is a possibility that could identify new piping candidates for NDA or segmentation.

2.5.4 Alternative NDA Technologies and Applications

Portable NDA holdup measurement technology is a quantitative diagnostic that complements ongoing needs of the D&D. Conservative loading of crates and drums (based on a large margin of error to avoid exceeding limits) to meet DOT requirements and the WAC is costly. Nonetheless, loaded crates and drums that exceed DOT limits must be opened and reloaded, which is also very costly. The ability to perform NDA measurements on the individual packages or items as these are loaded into containers for transport can optimize the process and reduce costs by avoiding use of excess of transport/waste containers but minimizing those that need to be opened for reloading. Use of NDA optimized to measure the segments created by breaking up large process equipment modules can validate the holdup NDA results for the intact equipment modules in early phases of D&D. This validation can ease scrutiny during subsequent D&D operations imposed on un-validated holdup NDA results. The converters are of great interest because of the large discrepancies between gamma and neutron NDA and because of current assumptions – now supported by Monte Carlo simulations – that the (lower) neutron NDA results are valid. Other equipment types that show gamma/neutron discrepancies are also candidates for validation of the holdup NDA by performing NDA measurements on equipment segments. The use of NDA on packages and NDA designed specifically to measure fully loaded crates can also validate the holdup NDA, in addition to addressing compliance on transport and storage requirements. Validating holdup NDA requires tracking process equipment and the corresponding segments through packaging and loading. The use of automated portable NDA can contribute – with a lower risk and cost compared to the original surveys – to eliminating potential gaps in the original survey measurements of process piping.

2.5.5 Applying NDA data for NMC&A and D&D (NCS, DOT, WAC)

Most of the 5 million linear feet of process piping was surveyed with a survey threshold of 2 g ^{235}U per 1.5 linear feet, but not measured by quantitative NDA and not included in the (NMC&A) accountability declaration. The unknown quantity of ^{235}U in this unmeasured portion has a very large upper limit, as determined by the survey threshold. The absence of additional NDA for the unmeasured piping could be costly for the loading of crates if justification for a lower threshold is not found. The deposit removal project used NDA results to identify deposits of potential NCS risk for subsequent cleanout before the D&D. This has reduced the safety risk for the D&D activities. The scheduled vent, drain, and, purge procedures will further reduce NCS risk during the D&D activities. Validation of the holdup NDA using NDA on packages and loaded crates will determine the accuracy of the holdup NDA results and indicate whether holdup uncertainty is over- or under-stated. Such validation may permit increased reliance on holdup results for DOT and WAC. Tracking all NDA knowledge – starting with the holdup NDA through the NDA performed on loaded crates and drums – to disposal is the sole continuity with the D&D process that could be historically beneficial for the long-term disposal. Such tracking validates the accountability closeout and documents the waste for long-term defense of its status.

3.0 REVIEW TOPICS

The following detailed discussion of the review topics is organized by headings consistent with those stated in the charter for the review and assessment. The charter is outlined in Section 2.1. This detail obtained during the review process is the information basis for the analysis and findings described in Section 4.

3.1 Protocols for 1980-1990's Portable Holdup Measurements

The portable holdup measurements performed in K-25 and K-27 in the 1980's-1990's aimed to provide a conservatively high result for the mass of ^{235}U in each of ~18,000 process equipment items. The quoted uncertainties were also chosen to be conservatively large. The nondestructive survey measurements performed prior to the quantitative determinations of ^{235}U in process equipment scanned the full linear dimensions at a speed of 3 inches per second to cover all process equipment at K-25. The intention of this approach was to reduce the chance of overlooking any deposits that might pose risks during the long period of shutdown or in the course of the D&D. All converters, compressors, seal vent line (SVL) copper piping, blowout preventer (BOP) copper piping, surge tanks, and cold traps were subsequently measured by quantitative NDA. Only those steel process piping segments containing more than the minimum threshold mass of ^{235}U (2 g of ^{235}U per 18 in of pipe length) were re-measured as identified piping segments (10- to 20-ft lengths) by quantitative NDA.

Both portable gamma spectroscopy and neutron counting were performed with measurement control exercised using check sources of HEU metal. The procedures required that frequent measurements of the check source reproduce the reference result for the foil in order to continue measurements of holdup. The portable gamma measurements used NaI scintillator detectors, which are susceptible to gain drift with changing temperature. Some of these low-resolution scintillation detectors operated with active stabilization that maintains a constant gain. Rigorous use of HEU check sources with manual adjustment of the gain in the event of drift mitigates the effects of gain drift. Because no recycled material was processed at K-25 and K-27, discrete gamma-ray interferences – notably the 238-keV gamma ray near the bottom of the ^{232}U decay chain – were not present. Therefore, wide energy regions-of-interest on the 186-keV gamma ray were possible, reducing the sensitivity to gain drift. The portable neutron detectors were based on ^{3}He proportional counters. These are intrinsically stable as neutron detectors because of the very wide gap between amplitudes of pulses produced when neutrons are detected and the much smaller pulses caused by gamma interactions in the ^{3}He gas. This allows a relatively low discriminator setting for neutron detection, which results in constant detection efficiency.

The original hard copies of archived data from the portable measurements of holdup were both accessible and clearly written for unambiguous interpretation. Using analysis algorithms quoted in published procedures (such as MMES1, MMES2, MMES3 and MMES4) hand-calculated re-analysis of original raw holdup data obtained in measurements of specific but, for the most part, randomly selected process equipment were successful in verifying the documented holdup masses for this equipment in all but a small fraction of cases for each category of process equipment. (Bartholomay)

A consistent NDA approach to the re-measurement of ~500 selected items – those containing large deposits – has provided confirmation of deposit quantities in the selected process equipment items over time to satisfy requirements of NMC&A. Consistency is maintained in that the NDA emulates the original measurements despite changes in detectors (the same detector types are used) and electronics. Thus, calibration methods, collimation and shielding, detector positioning, energy regions, count time, background measurement procedures, and analysis methods are all the same over time. The ability to confirm the original quantitative measurement results establishes a continuity that may prove valuable as an empirical validation tool. Should any modification of the original NDA measurements or the uncertainties in these results become necessary or advisable, the confirmatory NDA will enable implementation as an adjustment (change in attenuation correction, validation of systematic effect of deposit distribution, *etc*.) rather than by re-measurement of the holdup deposits. This is because the adjustment can be verified empirically with the emulating technique, a result of the procedural continuity.

3.2 Validity of Existing NDA: Define Confidence Limits

Following the nondestructive survey of all equipment locations in the K-25 and K-27 facilities, quantitative gamma and neutron NDA measurements were performed on ~18,000 items of process equipment in K-25 and K-27. These measurements include the items indicated in Table 3.2.1, which represent >95% of the measured inventory of ^{235}U. Data for this table comes from information provided by Brown and Cain (Section 2.3). The techniques for NDA measurements of converters, compressors, steel piping and copper piping have been reported (MMES3, MMES2, MMES4 and MMES1, respectively).

Table 3.2.1. Equipment in K-25 and K-27 with Deposits Quantified by NDA

Equipment Category	**Number of Items in K-25 (K-25 & K-27)**	**Deposit/Item (kg ^{235}U)**	**NDA Method, Uncertainty**
Converters	~3000 (~3600)	≤ 2	γ & n, 50-100%
Compressors	~5500 (~6700)	≤ 0.7	n, 50%
Piping Segments (steel)	~5000 (~6000)	≤ 0.4	γ, 50%
Piping segments (Cu)	~11,000 (~13,400)	< 0.1	γ, 50%
Surge tanks	~20 (>20)	≤ 3	n, 50%
Cold traps	~10 (>10)	≤ 3	n, 50%

As communicated by Brown (Section 2.3) and reported by others (Bartholomay, Harris), very little verification of the quantitative NDA results has been carried out to date despite requests for such verifications. Destructive analysis (DA) of one compressor showed that the neutron NDA measurement result was high by 63% (~200 g ^{235}U), consistent with empirical evidence that deposits in the seal vent line (SVL; this piping is in close proximity to the neutron detector) give a positive bias to the compressor NDA result. Deposits in the piping of two SVLs measured destructively showed that the gamma NDA results for these deposits were biased high by 30% and 46% (6 and 12 g ^{235}U, respectively). Such positive bias is conservative. The magnitude is moderate to large.

No converter NDA measurements have been verified to date by DA, but measurements of many converters by both gamma and neutron methods provide some insight on the validity of these NDA measurements, as discussed in Sections 3.3 and 4.3. Neutron measurements were performed on converters with masses from gamma NDA exceeding 300 g ^{235}U. (Bartholomay) The neutron NDA result is used in the NMC&A database when both measurements exist. Both gamma and neutron measurement results are also available for other equipment (some surge tanks and cold traps) that use only the neutron NDA results in the NMC&A database. Planned validations based on analysis of "coupons" and equipment segments are discussed in Sections 3.3 and 3.4, respectively.

The uncertainties given in Table 3.2.1 for the NDA results were obtained from recommendations acquired by the field experience of others, and have been reported (Bartholomay, Harris) and communicated (by Brown and Cain, Section 2.3). These uncertainties are stated as ±50% for all equipment except the type 1 and 2 converters where the stated uncertainty is ±100%. The confidence level (CL) – 68%, 95%, or 99.7% – for the stated uncertainties is not given, however, because to date the uncertainties have not been developed from a statistical understanding of the systematic effects.

Stated uncertainties for the K-25 and K-27 NDA results were adopted under a belief that they are conservative despite absence of an understood confidence level. However, results of Monte Carlo modeling presented in Section 4.2 indicate that the uncertainties may actually be understated in some cases. The modeling examples also show how to determine those components of systematic uncertainty that are most difficult (costly, time consuming, demanding from standpoints of safety) to evaluate empirically. The multiple terms that contribute to the systematic uncertainty in portable NDA measurements for each equipment type should include calibration error, deposit distribution, detector positioning, ^{235}U enrichment (quoted by Harris and Bartholomay as 20%, but the confidence level is not stated), room background, equipment attenuation (primarily for gammas), self-attenuation (primarily for gammas), and scattering (primarily for neutrons).

3.3 Gaps in Existing Data, Possible Additional Measurement Needs

Several types of data related to the NDA measurement results include the NDA data itself, data from the nondestructive survey measurements, and data to validate the NDA measurement results. The high costs, health and safety risks to personnel, and an existing base of data that is already substantial all modulate apparent needs for additional data of these types, as discussed below. Making better use of the existing data by examining correlations, developing and validating models, and performing corrections based on known measurement parameters are all approaches that may reduce needs for additional measurements.

The design of non-quantitative nondestructive surveys of all equipment in K-25 and K-27 was a practical screening approach that allowed those responsible for measurements to focus the available resources for quantitative NDA on the highest-priority issues of criticality safety. While the equipment in certain equipment categories was all measured by quantitative NDA (converters, compressors, BOPs, SVLs, surge tanks, cold traps), a fixed screening threshold determined which steel piping would be measured by quantitative NDA.

Although the uniform (constant survey speed of 3 inches per second) non-quantitative nondestructive surveys claim a fixed sensitivity threshold (2 g ^{235}U per 18-inch pipe length), some of these measurements performed on relatively inaccessible equipment were necessarily made at very large distances: more than 10 ft compared to 2-3 ft. (Harris) The fraction of piping surveyed at the greater distances was not revealed, but the sensitivity threshold at such distances is more than one order of magnitude (up to possibly two) greater because of both solid-angle and room-background effects. Section 4.3 discusses measurement approaches to address potential gaps caused by deterioration of the sensitivity for surveys performed at greater distances.

Each individual survey result was used to screen against a fixed-threshold criterion. The cumulative results (locations of above-threshold deposits) were neither mapped spatially nor compared with quantitative NDA results at the corresponding locations. The possible additional information that such spatial correlations or comparisons would provide is discussed in Section 4.3.

Large measurement distances can also incur field-of view obstructions that bias NDA (particularly gamma) measurements low. Quantitative gamma NDA of certain inaccessible steel pipes may be subject to bias for this reason. (Harris) Section 4.3 discusses approaches to address potential negative bias in NDA results for such pipes.

Gamma NDA measurements were used exclusively for small-diameter copper piping (SVLs and BOPs). Gamma NDA measurements proved to be minimally effective for dense equipment such as compressors. Therefore, NDA measurements of compressors were performed exclusively using neutrons. Originally, gammas were used to measure all converters, surge tanks and cold traps. Concerns over self-attenuation caused a transition to neutrons for converters with more than 300 g of ^{235}U. Similar transitions occurred for surge tanks and cold traps, which – partly because of the much smaller numbers of these equipment items – have come to be measured by neutrons exclusively. Steel piping was originally measured using gammas exclusively, but some were also measured by neutrons. (Bartholomay) The data set containing both gamma and neutron NDA results for a large number of pieces of equipment of different types is of great potential value in validating models developed to provide estimates of systematic errors in NDA measurements of holdup. Such models can eliminate the need for costly validation based on DA.

Sampling of holdup deposits by removing small plate sections from equipment surfaces for destructive analysis of deposits is underway. Analysis of coupons is another approach to obtaining reference values for holdup deposit quantities. Such reference data can contribute to better understanding of the systematic uncertainty in the NDA measurements.

The near absence of validation data currently does not necessarily demand large investments in DA efforts, nor does it eliminate the possibility of evaluating systematic uncertainties and CLs for the K-25 and K-27 NDA measurements. The absence of validation data does force users and analysts to understand and evaluate systematic effects on the NDA results and determine their impacts with realistic models. Because the K-25 and K-27 NDA measurements involve only two portable measurement techniques and – despite very large numbers of process equipment items – only several types of equipment, a Monte Carlo modeling approach is reasonable and far more economical than obtaining validation results from DA.

Gamma and neutron NDA measurements of complex equipment such as converters and compressors used empirical calibrations that derive a specific response to uranium ^{235}U by measuring a known quantity (standard) that has been placed within the equipment. The drawbacks of this specific approach to calibration include the need to perform the calibration measurement for each new (deposit/equipment/detector) configuration and to include the departures from the calibration configuration (variations in equipment attenuation, self-attenuation, deposit distribution) into the estimates of systematic uncertainty for the measurement. More general approaches to calibration are possible for simple equipment such as pipes and tanks because simple models can accommodate changes in equipment, deposit distributions, and self-attenuation without incurring additional systematic uncertainty and without the need to recalibrate. However, it is important to use the models correctly.

The measurements of steel process piping (and potentially the measurements of the small-diameter copper SVL and BOP piping) used generalized models of line deposits to give a single calibration of the gamma measurement the flexibility of being implemented for different measurement distances. Although corrections for self attenuation of gamma rays were performed for the process piping segments (MMES4), these may have been implemented incorrectly such that the actual correction was underestimated and the NDA result for piping biased low from this additional effect. The properly implemented self-attenuation correction can be very large for 186-keV gammas. Because the correction algorithm is non-linear, the measurement uncertainty also propagates nonlinearly, and a large correction is typically accompanied by an inflation of the relative uncertainty. Because the large corrections are associated with large (thick) deposits that may involve safety concerns, it is important that the correction itself, or the uncertainty estimate at a minimum, be performed properly to clarify any potential impact on safety.

Section 4.3 references valid correction techniques for finite deposit widths and self attenuation and recommends approaches for implementing these. It also discusses implementing the nonlinear propagation of the systematic uncertainty caused by the correction for self-attenuation. Because of the non-linear correction, a numerical approach to implementing the multiple systematic as well as random contributions to the measurement uncertainty is recommended. Section 4.3 also describes and references the approach.

Section 4.3 discusses specific details as well as the impacts of the incomplete report on the NDA methodology for steel piping (MMES4) The actual methodology used to obtain the corresponding NDA results is uncertain from the standpoint of the review team.

3.4 Existing and Possible Alternative NDA

This Section invokes new NDA measurements, in addition to those already performed, that support meeting compliance requirements, validating or updating the results of NDA measurements already performed, and possibly supporting reduced costs of D&D. It also refers to procedural tactics that support optimized use of the new NDA methods.

The largest equipment items must be segmented in the course of the D&D in order to be compatible with the dimensions of transport containers. Implementing NDA near the segmentation site will offer benefits ranging from validation of the existing NDA to establishing compliance with DOT requirements and the WAC. The NDA measurements performed on the segments will also potentially increase the number of items that may be loaded for transport in that the only deposit mass available for any segment in advance of measuring the segments individually is that obtained for the intact equipment from the NDA of holdup.

The possible scheduling of campaigns of additional gamma NDA measurements of process piping for lack of sufficient knowledge of the corresponding deposits should minimize cost and measurement time but maximize reliability and productivity. The use of automated acquisition of such data will support these goals

Section 4.4 discusses the recommended NDA and its benefits, logistics of the segmentation sequence, the useful comparisons of NDA results for segments, and the logical requirements for DOT and WAC declarations in the absence of NDA performed on the segments. It includes discussions of the capabilities and benefits of automated portable gamma NDA.

3.5 Usefulness of Existing NDA for NMC&A, D&D

The deposit removal project is an approach that relies on the NDA results to address NCS concerns in D&D operations. This project, described in an introductory presentation (Cain, Section 2.3), used results of the original NDA measurements to identify the deposits that pose high safety risks. The highest-risk deposits were removed in advance of the D&D with suitable precautionary controls implemented. Others will be addressed during the D&D, appropriately controlled for their risk statuses. The vent, drain, and purge procedure planned as a first step in the disassembly of process equipment will also reduce NCS risks during disassembly by removal of volatile, liquid, or loose materials.

The total inventory declaration, currently stated as an absolute quantity, should include both the quantity of SNM and a statement of the uncertainty with CL indicated. This establishes the boundaries for accountability and waste disposal for long-term defense of the waste status. Long-term defense of the waste status also argues for tracking the individual item masses (NDA results), uncertainties, and CLs from the D&D through transport to disposal. Section 4.5 discusses implications of incorporating a defendable uncertainty and the CL on NCS, NMC&A, DOT requirements and the WAC.

The current inventory declarations for K-25 and K-27 (approximately 1500 kg of uranium at each facility) consist of the sum holdup quantities measured by NDA. They exclude holdup that resides in approximately 4.2 million linear ft of process piping, most of which was not measured quantitatively because signals did not exceed the survey threshold of 2 g ^{235}U per 1.5 linear feet. Section 4.5 addresses possible approaches to realistic estimates of the potential contribution from the unmeasured portion and the implications of accepting this threshold for deposits in the unmeasured process piping.

4.0 REVIEW FINDINGS

Section 4 is a detailed description of findings. The findings of the review team are derived from information provided in reports, presentations and discussions of the NDA measurements performed at K-25 and K-27. Section 3 reviews this information. The findings are also based on analysis, presented in Section 4.2 in particular, of some of this information. The findings are organized by headings consistent with those stated in the charter (Section 2.1) for the review and assessment. Note that Sections 2.5.1-2.5.5 each constitute a summary of the detailed findings given in Sections 4.1-4.5, respectively. Finally, Sections 5.1-5.5 list the recommendations derived from the findings in Sections 4.1-4.5, respectively.

Section 4.2 addresses the validity of the existing NDA results for holdup. The findings vary for different categories of process equipment. Therefore, Section 4.2 has been subdivided into subsections for converters, compressors, piping segments, surge tanks and cold traps (4.2.1-4.2.5, respectively). Subsection 4.2.6, a summary of 4.2.1-4.2.5, is provided because of the scope of Section 4.2.

4.1 Protocols for 1980-1990's Portable Holdup Measurements

Protocols and priorities for the portable NDA measurements of holdup were established to be intentionally conservative in order to minimize the chance that unsafe deposit quantities would go undetected by the NDA measurements. Therefore, and unlike procedures that were followed in the D&D of K-29, K-31 and K-33, nondestructive survey measurements were performed on all process equipment at the K-25 and K-27 facilities. The analysis of measurement data to obtain ^{235}U mass used the credible deposit models that tend to maximize the measured quantity. (The example of converters is discussed below.) Finally, the assigned measurement uncertainty came from applications of a single model to measurements of a diverse collection of HEU reference materials (rods, plates, powder, foils, filter media…) to define a conservative measurement uncertainty of ± 50%, or ± 100% for some equipment.

Protocols and priorities for the portable NDA measurements of holdup established reliability through measurement control that demanded periodic reproducibility in the measurement of a check source of HEU metal to guarantee proper performance of equipment. Furthermore, use of stabilized gamma spectroscopy electronics for many of the quantitative gamma-ray NDA measurements provided automatic compensation for temperature-dependent gain drift experienced by the NaI scintillator systems. The helium-3 detectors used for the neutron measurements are intrinsically stable against this type of drift.

An accessible, intelligible, and seemingly complete archive of measurement/measurement-control data and parameters has helped to maintain the longevity of NDA measurements in the15-to-20 years between the period when these NDA measurements were performed and time of completion of the D&D. A robust assurance of this longevity has been the monthly re-measurement of selected items/deposits at K-25 using original NDA methodology. This practice preserves options for any analytical upgrades that may be necessary to improve results in order to a meet a higher standard at a later time without the need to repeat the original measurements. The recommendations below for a correct implementation of the gamma-ray self-attenuation correction for deposits in certain piping segments can be implemented analytically, without the need for additional measurements, because of the continuity maintained by the ongoing measurement process.

4.2 Validity of Existing NDA: Define Confidence Limits

Focus on the charter request to determine validity of the existing NDA data within the specified confidence limits revealed that the CLs themselves are not defined for the stated uncertainties in the original NDA results. Although each measurement, in the interest of conservatism, is assigned an uncertainty (±50% for most equipment) derived from experience with measurements of diverse deposits using a single calibration, the design of equipment specific to the gaseous diffusion process is complex beyond the diversity of the materials used to obtain this uncertainty. Therefore, it is appropriate to question whether the stated/chosen uncertainty is indeed conservative, even for an assumed 68% (or 1σ) CL. The low gamma-ray energy used for NDA of ^{235}U increases the complexity for converters measured by gamma techniques, but the complex design of the converters also influences the uncertainty in the neutron measurements as well. The additional issue with the assigned uncertainty of ±50% (±100% for Type 1 and Type 2 converters) is that the CL for this uncertainty is not defined.

Self-attenuation corrections were used in the gamma-ray measurements of holdup in the process piping. These corrections were not implemented properly, but any of several alternative approaches can remedy this. As a result of continuity established by ongoing confirmation measurements that implement the original methodology and emulate the original technology, no re-measurements of the process piping (aside from scheduled confirmation measurements) are necessary in these cases.

The overview of validity of the existing holdup data covers five categories of equipment in the K-25/K-27 facilities: converters, compressors, piping segments (steel is emphasized below but the discussion is also relevant to copper piping), surge tanks, and cold traps. The greatest emphasis has been on the converters and piping in that the approach to measuring holdup in these two types of equipment are quite different. Benefits of the Monte Carlo analysis applied to converters and discussed below are also discussed for compressors, surge tanks and cold traps.

The discussions below apply generally to both K-25 and K-27. If the NDA measurements in K-27 used the 1001-keV gamma-ray from the ^{238}U decay daughter instead of the 186-keV gamma-ray of ^{235}U, a separate Monte Carlo analysis will be necessary to determine measurement uncertainties for identical equipment in these two facilities. This straightforward adaptation of the Monte Carlo calculations is illustrated below.

The discussions below assume that it is reasonable to accept the original NDA results if they appear conservative (the model tends to give a high result in the realistic range of possible results) but that a valid uncertainty must accompany such results. The discussions below also assume that if the original NDA results tend to be low, as would be the case if the gamma self-attenuation correction is underestimated, such a bias should be eliminated.

Finally, the discussions below assume that it is necessary to specify the CL for every specified uncertainty. Therefore, these discussions as well as the findings and observations assume that it is necessary to derive the measurement uncertainty from the relevant parameters (listed above at the end of Section 3.2) of each measurement rather than rely on recommendations from other experience that excludes the technologies of gaseous diffusion. Deriving these uncertainties is relatively straightforward for measurements that have already been completed because measurement geometries are not evolving, and much is known from both surveys and the quantitative measurement results about the range of deposit distributions.

4.2.1 Validity of existing holdup data for converters

The review of measurement procedures, analysis techniques, and results of the quantitative NDA during the week-long site visit began with and focused primarily on deposits in converters. Converters hold a major portion of the total declared inventory of ^{235}U in K-25 and K-27, as indicated in Table 3.2.1. Their complex design and extended dimensions add significant uncertainty to portable NDA measurements including those that use neutrons but especially those based on gammas. The focus below is on Type 1 and 2 converters for which both neutron and gamma NDA results exist. This equipment is unique from the NDA standpoint in that the assigned uncertainty for the NDA results is ±100% (CL is not specified). The K-27 facility uses Type-2 converters exclusively.

Gammas are measured at four positions for Type-1 and -2 converters. Neutrons (used only when the gamma NDA result exceeds 300 g ^{235}U) are measured at two positions, as shown in Figure 4.2.1.1, taken from Appendix F. Bartholomay compiled results for neutron and gamma NDA measurements of high-mass converters. These show much higher mass results for gamma than neutron measurements. Figure 4.2.1.2 is a plot, taken from Appendix G, of the neutron *vs*. gamma NDA results for ^{235}U mass for high-mass converters. (Those with a gamma mass of 150 g ^{235}U are considered high-mass by addition of the 100% uncertainty.) Varying magnitudes of the gamma-neutron discrepancies are surprising and often disturbingly large.

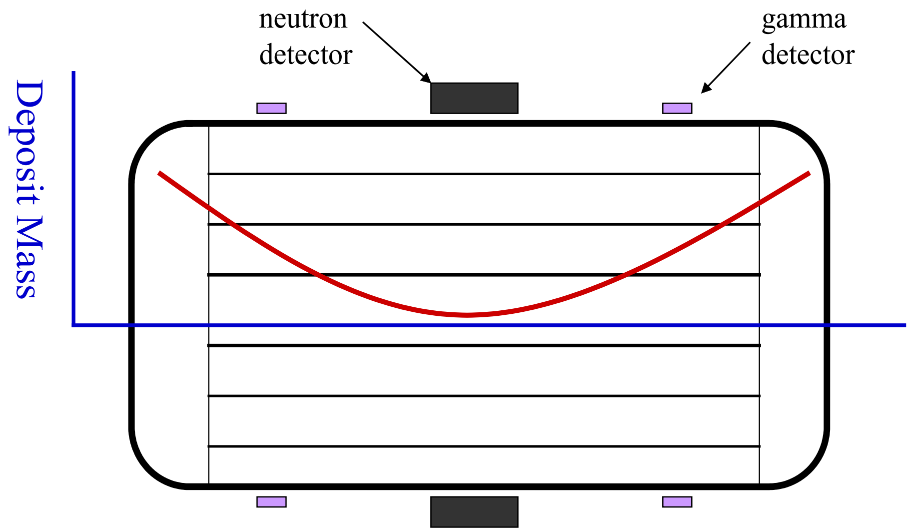

Figure 4.2.1.1. Sketch of Type-2 converter indicates positions of gamma and neutron detectors for NDA measurements of holdup deposits. The red curve indicates a hypothetical example of a uranium deposit distribution that is non-uniform in the horizontal dimension with larger deposits at both ends.

The tendency for deposit models and assumptions to underestimate gamma attenuation combined with numerous effects (including moderation, scattering, and alternative chemical forms) that tend to enhance neutron signals relative to the calibrated response would tend to shift the balance to high neutron results relative to gamma. Thus, the existence of a very large systematic effect other than these typical examples is indicated. The absence of any visible or analytically detectable correlation between neutron and gamma results, as presented in Appendix G, suggests that the effect is large, and possibly complex (influenced by more than one independent parameter) in that the expected correlation between the two measurements is washed out. A variable effect (sometimes shifting gamma results low relative to neutron) can also explain the occasional high neutron result. Deposit distribution effects can be large, complex and variable.

A distribution of uranium in the converter that differs from the calibration assumption is a plausible systematic effect that could lead to large gamma-neutron discrepancy. This seems particularly apparent for the larger Type 1 and 2 converters because the gamma and neutron detectors are positioned differently in the horizontal dimension as illustrated in Figure 4.2.1.1. The calibration was developed for horizontally uniform deposits. If deposits concentrate toward the horizontal center of the converter, neutron results for the same deposit will be higher than gamma results. If deposits concentrate toward either or both horizontal ends of the converter, as illustrated by the red curve in Figure 4.2.1.1, gamma results for the same deposit will be higher than neutron results.

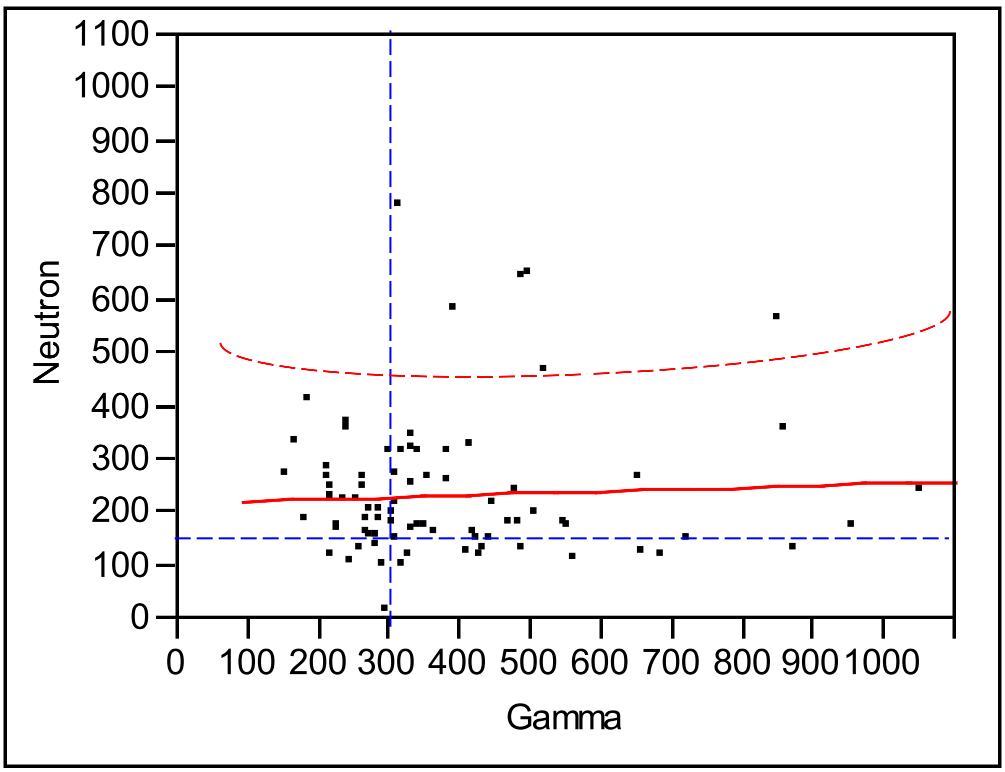

Figure 4.2.1.2. The mass of ^{235}U (g) determined by neutron NDA is plotted vs. the mass of ^{235}U (g) determined by gamma NDA. The vertical dashed line indicates the gamma NDA result (300 g ^{235}U) above which neutron NDA is performed. The horizontal dashed line indicates the neutron NDA result (150 g ^{235}U) above which equipment will be segmented during D&D.

A simple set of measurements was carried out in the morning of day three of the four-day site visit to test this possibility empirically. The count rate for the 186-keV gamma ray was measured at three positions across the top of three Type-2 converters, each with a large gamma-neutron discrepancy (the ^{235}U mass for the gamma NDA exceeded that for the neutron NDA by factors of

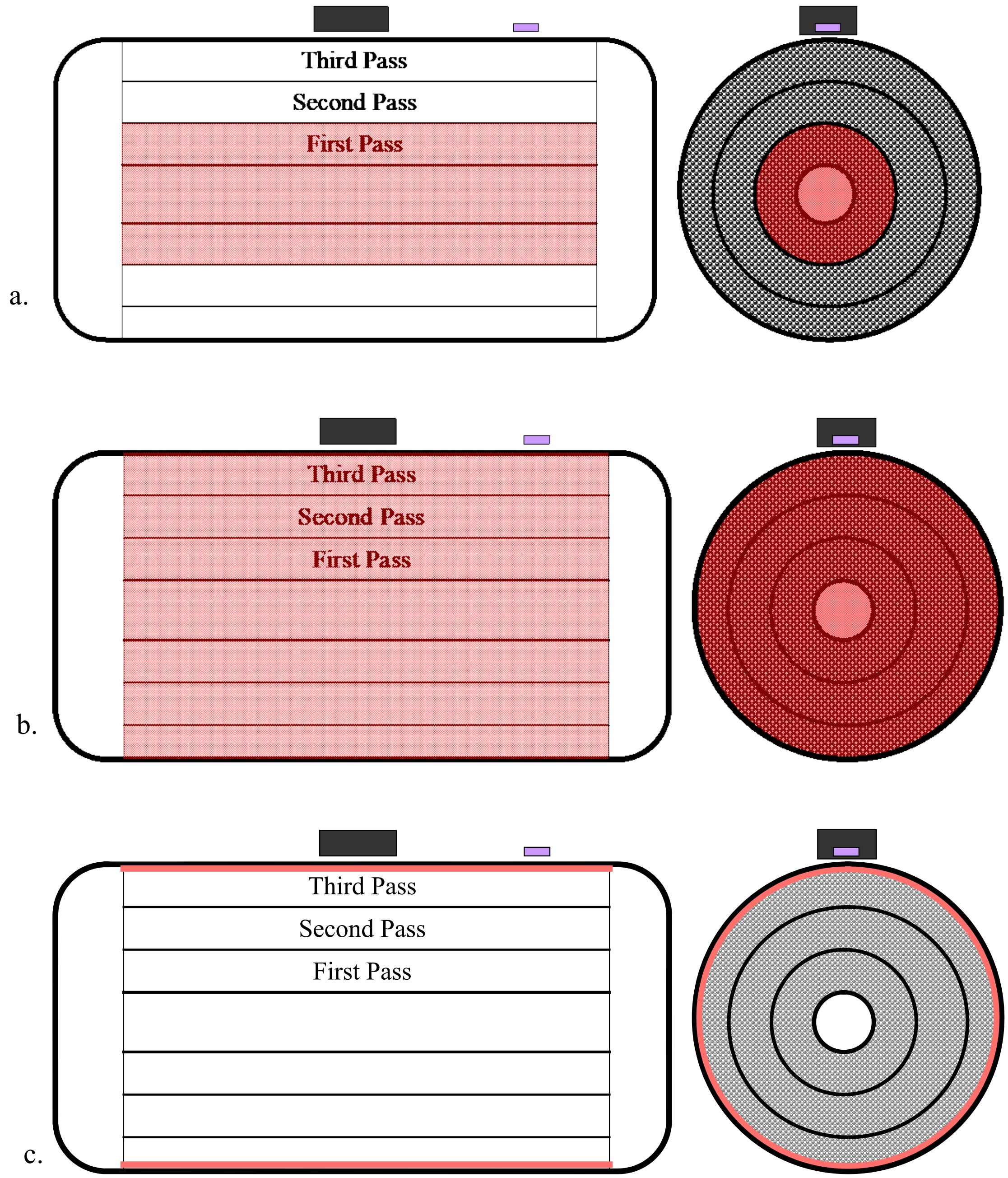

Figure 4.2.1.3. Three sketches of the longitudinal (left) and transverse (right) cross sections of the Type-2 converter show the a) first pass, b) uniform, and c) shell models for radial distribution of uranium within the converter. Red shading indicates the uranium deposit. Refer to Figure 4.2.1.1 for information and a key on the gamma and neutron detectors and their positions.

3, 4 and 7). Two were the normal positions for gamma measurements and the third was vertically equivalent to the first two positions but at the horizontal position for a normal neutron measurement. The results indicated no statistical difference in the gamma-ray rates among the three measurements made on each converter, empirically negating the hypothesis of non-uniformly large concentrations of deposit toward the horizontal ends of the converter. The possibility of a non-uniform deposit in the radial dimension was considered next. The calibration was actually developed for a radially non-uniform deposit residing in the first-pass region of the converter only (Figure 4.2.1.3a). This deposit model was selected because the corresponding calibration is conservative, giving a higher mass result than the true mass if a measured deposit tends to be uniformly distributed throughout the (first-, second- and third-pass) volumes of the converter, for example. Figure 4.3.1.3b illustrates the uniform-deposit model. In the absence of attenuation, the effect on gamma and neutron measurements of rearranging a constant mass of ^{235}U between these two (first-pass and uniform) deposit distributions might be very similar for the two types of measurements. However, internal converter hardware attenuates the 186-keV gamma rays significantly so that redistributing deposits from first-pass to uniform enhances the gamma result more than the neutron because of reduced gamma attenuation.

It is very difficult to test the radial deposit distribution hypothesis empirically. Therefore, three distributions of the same ^{235}U deposit mass were modeled along with the gamma and neutron detectors and the Type-2 converter. Monte Carlo techniques were used to determine the gamma and neutron responses to each deposit distribution. Two of the three distributions were the first-pass and uniform distributions, and the third was the shell distribution shown in Figure 4.3.1.3c. The results of the Monte Carlo simulations for the gamma and neutron responses are given in Table 4.2.1.1 as ratios to the first-pass response because it represents the calibration model for these detectors. The models and Monte Carlo simulations were developed and run on day three of the four-day site visit after the empirical gamma data were obtained and reviewed.

The results in Table 4.2.1.1 reveal that the gamma results are enormously enhanced as the deposit distribution shifts toward uniform from the first-pass calibration model while the corresponding enhancement in the neutron result is small. If a uniform deposit in the Type-2 converter is measured, the gamma result would be biased by +163% while the neutron bias would be only +16% for the uniform deposit distribution. Should the deposit distribution shift from uniform toward the containment shell of the converter, the bias for the neutron result remains less than +37% while the gamma bias approaches +500%. Consult Appendix D for additional details on the Monte Carlo results.

Table 4.2.1.1. Monte Carlo Simulated Gamma and Neutron Response for Type-2 Converter: Three Deposit Distribution Models

Response Ratio (to First-pass Response)	Neutron	% NDA Bias	Gamma	% NDA Bias
Uniform/First Pass	1.16	16%	2.63	163%
Shell/First Pass	1.37	37%	5.87	487%

This Monte Carlo result reinforces the likelihood that the uniform model for deposit distribution is better suited to actual deposits than the first-pass model because the model illustrates that deposits of ^{235}U more-or-less uniformly distributed throughout the volume of the Type-2 converter can account for the observed gamma-neutron discrepancies where the gamma result exceeds that for neutrons. A “tighter axial” distribution than that shown in 4.2.1.3a could explain the occasional result in which neutron exceeds gamma. Although mechanisms have been proposed for deposits that tend toward a “shell” distribution, additional empirical information reinforces the concept of volume-uniformity of converter deposits. Table 4.2.1.2 lists the internal surface area of each of the four converter sizes in the K-25 plant. This very large variation in gas-contact surface area is actually tracked by the average holdup of total uranium in each converter type such that the ratio of uranium holdup to total surface area is relatively constant for the four converter types, supporting a uniform model of deposit distribution.

Table 4.2.1.2. Internal Surface Area of Converters

Converter Type	Facility	Internal Surface Area Ratio (Normalized to Area of Converter Type 4
1	K-25	20.3
2	K-25, K-27	12.3
3	K-25	3.5
4	K-25	1

The Monte Carlo result also powerfully reinforces the following findings and recommendations for NDA measurements of converters at K-25 and K-27.

- The choice of neutron over gamma NDA results for (high-mass) converters is justified.
- The neutron calibration model for radial deposit distribution is reasonably but not extremely conservative, giving NDA masses that are somewhat high relative to the true masses of ^{235}U for uniformly distributed deposits.
- The contribution of radial deposit distribution effects alone to the systematic uncertainty in the gamma NDA results for Type-2 converters is larger than the stated 100% total uncertainty for the NDA measurements of Type-2 converters. This observation impacts a substantial fraction of the stated inventory in that most converters are not high-mass converters and, therefore, have only gamma NDA measurements. It is also possible that the recorded ^{235}U masses for low-mass converters (measured by gamma) are biased high, beyond the limits of the stated (100%) uncertainty in the NDA mass.
- Comparable Monte Carlo simulations should be performed to determine the additional contribution of horizontal deposit distribution effects to the systematic uncertainty in both gamma and neutron NDA results for Type-2 converters. Note the relative vulnerability of the neutron measurements in this case because of the single horizontal detector position.
- Monte Carlo simulations of the contributions of radial and horizontal deposit distribution effects to the systematic uncertainty in the gamma and neutron NDA results for Type-1, Type-3 and Type-4 K-25 converters should be performed.

- If gamma NDA measurements performed on the K-27 Type-2 converters use 1001- (rather than 186-) keV gamma rays, then Monte Carlo simulations of the contributions of radial and horizontal deposit distribution effects to systematic uncertainty in the gamma NDA results for Type-2 converters should be repeated for the higher gamma energy.

The following additional generic recommendations (applicable to NDA measurements of holdup in general) follow from the Monte Carlo result.

- The realistic contribution of each term that adds *significantly* to systematic uncertainty in portable NDA measurements for each equipment type should be determined at the 68% (1σ) CL (or 3σ, or…) and correctly combined to give a total systematic uncertainty for each type of measurement. Relevant effects include calibration uncertainty, deposit distribution, detector positioning, ^{235}U enrichment, room background, equipment attenuation (usually for gammas), self-attenuation (usually for gammas), and scattering (usually for neutrons). Such determinations should be made for each type of equipment for gamma and neutron measurements individually. Some effects will be *insignificant*.
- The 1σ (or 3σ, or…) systematic and random uncertainties should be combined to give the total uncertainty for each measurement. When systematic error dominates, which is likely for gamma measurements of converters, random error may be ignored to simplify the required effort. Note that random (counting statistics) error can be large in short counts.
- All stated uncertainties should also specify the CL.
- Pursue all opportunities to compare existing gamma and neutron NDA results, such as those for surge tanks or cold traps. Evaluate systematics that may produce discrepancies observed (as Bartholomay has noted) between the two NDA measurement types. Use the comparisons to reinforce results of Monte Carlo simulations that may be used to estimate systematic uncertainties such as those that arise from variable deposit distributions.

The detailed recommendation for converters is to use the neutron NDA results when available, use Monte Carlo to evaluate systematic effects of deposit distribution for all converter types, and evaluate and report uncertainties (and specify the CLs) in the neutron NDA results determined as described above. The uncertainties in the gamma measurements (of low-mass converters) should also be evaluated (including Monte Carlo determinations of the distribution effects) as described above and adjusted to reflect large systematic effects such as those of deposit distribution. Consideration should be given to the fact that because of the conservative choice of the (first-pass) calibration model, these large effects are not symmetric. They contribute greatly to positive but hardly at all to negative bias in the gamma NDA, and should probably be reported as such. A final note is that additional issues arise if the realistic uncertainties determined by Monte Carlo simulations of the systematic effects of deposit distribution cause the total uncertainty in measurement results to exceed limits specified by data quality objectives (DQOs).

4.2.2 Validity of existing holdup data for compressors

Compressors also hold a major portion of the total declared inventory of ^{235}U in K-25 and K-27, as indicated in Table 3.2.1. Neutron measurements are performed on all compressors because equipment is too dense and thick for gamma. These measurements are performed with the detector located at one position at the surface of the compressor. Similar to converters, the calibration of the quantitative neutron NDA measurement of compressor deposits fixes the model for deposit distribution. Vulnerability to the systematic effects of variable deposit distribution is enhanced when measurements involve just one detector position

The stated uncertainty in the neutron NDA result for compressors is ±50%. This may be conservative at the 1σ level (68% CL) but perhaps not at 2σ or 3σ (95% and 99.7% CLs, respectively). The systematic effect of deposit distribution as a substantial contributor to uncertainty in NDA of holdup is one of several error terms that should be determined for measurements of compressors in order to estimate total systematic NDA uncertainty and CL.

The use of Monte Carlo modeling is recommended to evaluate systematic effects of changing deposit distributions on NDA results for compressors calibrated for a fixed deposit distribution. The effectiveness of the Monte Carlo simulation result requires knowledge of a realistic range of deposit distributions in compressors and knowledge of process equipment materials, dimensions, *etc*. so that simulations can determine the systematic contribution in a specified CL of variable deposit distribution to NDA measurement uncertainty. Aside from needing specific information on equipment and deposits, Monte Carlo simulations are straightforward to implement.

4.2.3 Validity of existing holdup data for piping segments

The linear extent of steel process piping is 4.2 million feet. The nondestructive gamma survey measurements performed prior to performing quantitative NDA measurements of steel piping scanned this piping at a rate of 3 inches per second (for a total scanning time of 5000 hours) with a declared sensitivity of 2 g ^{235}U per 1.5 linear feet. Subsequent NDA measurements were performed on all piping segments with deposits exceeding the ^{235}U sensitivity threshold. The linear extent of these above-threshold segments amount to approximately 1-2% of the total length of steel piping. Therefore, deposits in the steel piping that are unmeasured by quantitative NDA (~4 million linear feet) could contain up to 2 g ^{235}U per 1.5 linear feet of piping. Although this represents a credibly thin surface deposit for most pipe diameters, the corresponding upper limit in ^{235}U inventory in the unmeasured portions of the steel piping is substantial (~5000 kg) from this simple viewpoint. The inventory in the unmeasured portions is not included in the total inventory declaration. Refer to Section 4.3 for discussions of potential undeclared inventory and gaps in the NDA measurements.

Quantitative gamma NDA was performed on the above-threshold segments of process piping almost exclusively. Table 3.2.1 indicates that these contribute significantly to the declared inventory of ^{235}U. Segment lengths in this case might be 10-20 ft. The gamma NDA measurements of line deposits were calibrated with HEU standards. (MMES4) Corrections for gamma self-attenuation were applied to the measured results (MMES4) for steel pipes, but finite widths of the line deposits were not accounted for (Harris). Implementation of corrections for self attenuation and impacts of ignoring corrections for finite deposit widths are discussed below.

Unlike steel process piping, of which only a small fraction (~1-2%) of the total linear dimensions was measured by quantitative (gamma) NDA, all small-diameter copper piping (SVL and BOP) segments were measured by quantitative gamma NDA. The discussions below apply as well to gamma NDA of the copper piping. Although the discussions below focus on measurements using the 186-keV gamma ray from ^{235}U decay, they also apply – with the analysis parameters appropriately adjusted – to measurements of the 1001-keV (^{238}U-daughter) gamma ray that may have been used for gamma NDA of piping in certain locations in the K-27 facility.

The stated uncertainty in the gamma NDA result for piping segments is ±50%. This may be conservative at the 1σ level (68% CL) and perhaps even at 2σ or 3σ (95% and 99.7%cls, respectively) if deposits are thin. However, the non-linear correction algorithm for gamma self-attenuation causes the relative measurement uncertainty to inflate when deposits are thick, as discussed below. Therefore, it is important for thick deposits in particular to determine and propagate known-CL systematic error terms for piping segments into total systematic uncertainty.

Three possible issues have been identified in the analysis methodology used to obtain holdup mass from gamma measurements of deposits in piping segments at K-25 and K-27. All potentially cause the NDA measurement result to be biased low. 1) The correction algorithm for self-attenuation of gamma rays as described in the documentation of methodology for measurements of steel piping (MMES4) is applied incorrectly, causing a negative bias in measured results. 2) Ignoring the finite widths of the line deposits also incurs negative bias, although it is not clear whether deposit width is actually accounted for in the calibration. 3) The calculation of measured areal density (the deposit parameter that is corrected for self attenuation) underestimates this parameter causing additional negative bias.

Measurements of HEU holdup in pipes as line deposits produce the mass per unit length of piping (or linear density) of ^{235}U directly from the measurement. The product of linear density and length of the pipe segment is the mass of ^{235}U. The analyst first corrects the measurement for continuum counts under the gamma ray peak, room background, gamma attenuation by the equipment (the pipe wall in this case). It then remains to correct the linear density for the finite width of the line deposit (the calibration for the measurement of the line deposit assumes that the line has no width) and then correct this result for self-attenuation. Because the correction for self-attenuation is non-linear in that the relative correction is a function of the measured linear density, it must be applied after all other corrections are made. Therefore issue 1) above is treated last in the remaining discussion.

Addressing Issue 2), the pipe diameters in K-25 and K-27 are variable, up to 16 inches. (Bartholomay) The measurement distance for pipes is 24 inches for diameters up to 4.5 inches and 40 inches for larger diameters up to 16 inches. A substantial portion of the piping has the large diameter. (Harris) The gamma detectors are collimated to one inch (diameter and depth). Ignoring the finite source correction for a 16-inch-wide deposit measured at the 40-inch distance with such a detector incurs a negative bias between 10% and 15% (Russo00 and Russo04, Equations 18-22). Propagation of this bias through the self-attenuation algorithm will inflate it to a larger percentage when deposits are thick. The documentation does not clarify whether the finite deposit width is included in the calibration for line deposits of each fixed diameter measured at a specified distance. Expert review and validation of the calibration methodology is recommended to assure that the effect of the finite deposit width is included. Corrections can be implemented for any given measurement distance and pipe diameter without the need for re-measurement of pipe segments in the event that this effect is not included.

Addressing Issue 3), the documented analysis methodology for piping segments (MMES4, or Bartholomay Equation 11) includes determining the measured ("estimated") uranium areal density t in g U/cm^2 by dividing the uncorrected ^{235}U mass by the product of pipe segment diameter (inches), pipe segment length (inches), ^{235}U enrichment and a constant (60.8). The constant appears to be about an order of magnitude too large – causing an underestimate of areal density and of the correction factor for self-attenuation – if mass is expressed in grams and enrichment as a decimal. Expert review and validation of this expression is also recommended.

Issue 1) is the documented correction algorithm for gamma-ray self-attenuation (MMES4, or Bartholomay Equation 10). This expression shows the correction factor CF_{SA} as an exponential function of measured mass – that is, measured thickness $t(M)_{est}$ – when the derived expression is actually an exponential function of true mass t(M). One approach to correcting for self-attenuation is to solve the expression for CF_{SA} iteratively. That is, apply the expression as documented (MMES4, or Bartholomay Equation 10) to the measured mass to get an initial value for CF_{SA}, correct the measured mass and recalculate CF_{SA} using the corrected mass, *etc*., until CF_{SA} converges. Iteration complicates the evaluation of random and systematic error. Another approach that avoids iteration – simplifying both the correction procedure and error propagation – is to define CF_{SA} as the ratio of true to measured mass and invert the equation to obtain true mass as a function of measured mass in a simple analytical (logarithmic) expression published elsewhere. (Russo04 Equation 25a) Rewriting this equation using Bartholomay's notation gives

$$t(M) = -(\ln[1 - \mu \cdot t(M)_{est}])/\mu$$

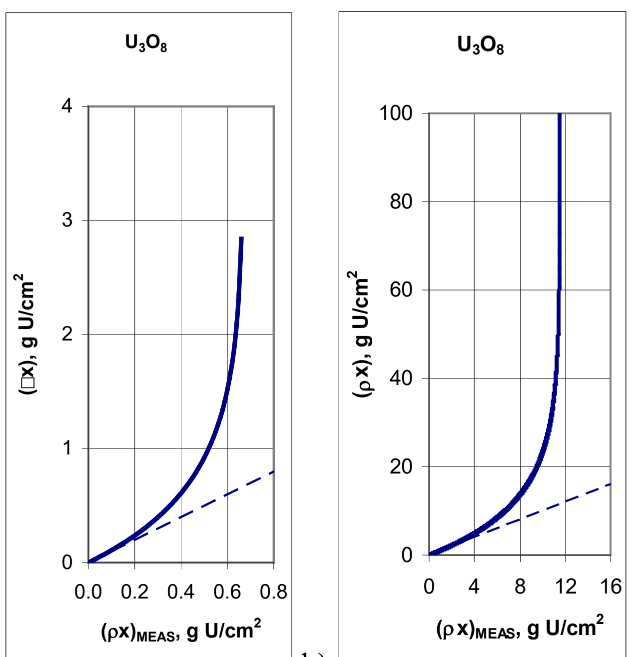

Figure 4.2.3.1. True vs. measured thickness (areal density of uranium, g/cm^2) is plotted for a)186-keV and b) 1001 keV gamma rays from U_3O_8 as determined by Equation 25a (Russo04). Measured thickness is that determined experimentally from the specific holdup mass corrected for the effects of room background, equipment attenuation, and the finite source dimension. The straight line has a slope of 1, so the correction factor for self-attenuation is the ratio of the curved to the straight line.

where t(M) and $t(M)_{est}$ are Bartholomay's notation for true and measured "thickness" (uranium areal density in g U/cm^2, equivalent to ρx and ρx_{MEAS} in Russo04), and μ is the normalization mass attenuation coefficient (Russo04 Table VIII.1) for UO_2F_2. Expert review of the use of CF_{SA} in the context of this discussion is recommended. An additional observation for consideration by experts is related to the constant 2.740 in the equation that defines CF_{SA}. This constant should correspond to the normalizing mass attenuation coefficient (Russo04, Table VIII.1) for UO_2F_2, with an expected value of ~1.5 cm^2/g or possibly less. (Russo04, Equation 67)

The effects of gamma-ray self-attenuation can be large at 186 keV but also at 1001 keV. Figure 4.2.3.1 is a graph of true vs. measured areal density of U_3O_8, whose attenuation characteristics are indistinguishable from those of UO_2F_2 at 186 keV and nearly indistinguishable at 1001 keV. The vertical portion of these curves indicates the measured result for deposits of infinite thickness for each gamma-ray energy. If areal density (thickness) of uranium measured at 186 keV is 0.2 g/cm^2, Figure 4.3.2.1a illustrates that the deposit is nearly infinite in thickness at the 3σ level if 1σ for the measured thickness is 50%. The graph also illustrates that relative uncertainty in the true result is inflated compared to the relative uncertainty in the measured result when the measured result falls on the curved portion of the graph (above 0.2 g U/cm^2 at 186 keV). The algorithm for propagating uncertainty through this curved region is published (Russo00, and Russo04 Equation 26). Although Figure 4.3.2.1b shows that curvature at 1001 keV begins at a twenty-times-greater thickness, LEU may have one-to-two orders of magnitude less ^{235}U for the same uranium thickness. Self attenuation corrections are not possible for infinitely thick deposits. Following the expert review of CFSA recommended above, use of this published algorithm is strongly recommended to determine the inflated random and systematic error terms for relatively thick deposits that are corrected for gamma self-attenuation. This approach will establish the CL and identify the possible inflated errors that could exceed the current stated uncertainty of ±50% for piping segments.

Evaluating realistic systematic errors for the thinnest pipe deposits may not be justified, but the total error (random plus systematic with CL specified) for deposits in pipe segments measured at 186 keV whose measured thickness equals or exceeds 0.1 g U/cm^2 should be determined, based on the information in the previous paragraph. It is likely, although actual data were not available to confirm the expectation, that this screening limit will eliminate most of the 5000 piping segments that have been measured by quantitative gamma NDA. The corresponding limit at 1001 keV is 2 g U/cm^2. Identify the deposits in piping segments whose measured thicknesses equal or exceed these limits. Establish proper procedures for use of the self-attenuation correction algorithm, and implement these procedures for all deposits that exceed the stated thickness limits using the algorithm and corresponding uncertainty correctly for these cases.

Regarding small-diameter (3/4-inch) copper piping (SVL or BOP) segments, a larger fraction of these may exceed the specified thickness limits because the chance of plugged lines is greater for small diameters. Corrections for gamma self-attenuation were not performed for this equipment, whose ^{235}U quantities are likely underestimated as a result. The priority for implementing proper self-attenuation corrections and/or evaluating the realistic error terms for a specified CL may be lower in this case if the geometry precludes any safety risks. A recommendation is to review this situation to confirm the safety status, evaluate any other drivers, and – if appropriate –

implement self attenuation corrections for the small-diameter copper piping. Implementation is straightforward for the constant, known diameter and known length of piping.

Consider as an additional recommendation the numerical approach to evaluating the total uncertainty in holdup measurements for piping segments and other equipment. (Russo04 Section IX.8) This approach is easy to implement. It indicates the dominant sources of uncertainty, can be readily upgraded with additional systematic error terms, and provides the option to determine the uncertainty required for any (perhaps the most variable) parameter in order to achieve a particular total NDA measurement uncertainty. The latter benefit may offer an approach to screening deposits in piping segments that is simpler than that achieved by setting the conservative limit of ≥0.1 g U/cm^2 for $t(M)_{est}$ of deposits whose total error should be determined.

A final note on the methodology for holdup measurements and analysis of steel piping is that the methodology documentation (MMES4) is incomplete. This is also noted elsewhere (Bartholomay, Harris), and Bartholomay has observed that the actual analysis parameters for piping differ from those stated in MMES4. It is difficult for further reviews of these techniques, including those proposed above, to proceed without documentation of the actual methodology that was implemented. A recommendation is to update and complete the documentation of the methodology for gamma NDA of the piping segments. Extend updates to the methodology for SVL and BOP copper piping segments (MMES1) if CF_{SA} is implemented for this equipment.

4.2.4 Validity of existing holdup data for surge tanks

While surge tanks are relatively few in number in K-25 and K-27, as indicated in Table 3.2.1, each holds a substantial quantity of ^{235}U. Although gamma measurements were used originally, neutron measurements are performed on all surge tanks with the detector located at two positions near the tank. Similar to converters, the calibration of the quantitative neutron and gamma NDA measurement of deposits in surge tanks fixes the model for deposit distribution.

The stated uncertainty in the neutron NDA result for surge tanks is ±50%. This may be conservative at the 1σ level (68% CL) but perhaps not at 2σ or 3σ (95% and 99.7% CLs, respectively). The systematic effect of deposit distribution as a substantial contributor to uncertainty in NDA of holdup is one of several error terms that should be determined for the surge tanks in order to apply it to estimates of the total systematic uncertainty and CL.

Monte Carlo modeling of gamma and neutron responses is recommended to evaluate systematic effects of changing deposit distributions on NDA results for surge tanks calibrated for a fixed deposit distribution. An effective Monte Carlo simulation requires knowledge of a realistic range of deposit distributions in surge tanks of process-equipment materials and dimensions so that the simulation can determine for a specified CL the systematic contribution of variable deposit distribution to NDA measurement uncertainty. Aside from the need for specialized information on deposits and equipment, the Monte Carlo simulations are straightforward to implement.

The original gamma-ray measurements of surge tanks were performed with the detector located at 20 positions near the surge tank. Nonetheless, agreement between gamma and neutron is reasonable for several cases that were examined. (Bartholomay) A comparison of the complete set of gamma and neutron NDA results for the surge tanks is recommended. The empirical results compared to those obtained from the simulations can provide a useful validation of the systematic effects of changing deposit distributions determined by Monte Carlo simulations.

4.2.5. Validity of existing holdup data for cold traps

Cold traps, like surge tanks, are also relatively few in number in K-25 and K-27, as indicated in Table 3.2.1, but each holds a substantial quantity of ^{235}U. Neutron measurements are performed on all cold traps. These measurements are performed with the detector located at ten positions at the surface of the cold trap. Similar to converters, the calibration of the quantitative neutron and measurement of deposits in cold traps fixes the model for deposit distribution.

The stated uncertainty in the neutron NDA result for cold traps is ±50%. This may be conservative at the 1σ level (68% CL) and perhaps even at 2σ or 3σ (95% and 99.7% CLs, respectively) because measurements are made at 10 locations on the cold traps. The systematic effect of deposit distribution as a substantial contributor to uncertainty in NDA of holdup is one of several error terms that should be determined for the cold traps in order to apply it to estimates of the total systematic uncertainty and CL.

The use of Monte Carlo modeling of the neutron response is recommended to evaluate systematic effects of changing deposit distributions on NDA results for cold traps calibrated for a fixed deposit distribution. The effectiveness of the Monte Carlo simulation result requires knowledge of a realistic range of deposit distributions in the cold traps as well as knowledge of the equipment materials and dimensions so that the simulation can determine in a specified CL the systematic contribution of variable distribution to the NDA measurement uncertainty. Aside from the need for specialized information on deposits and equipment, the Monte Carlo simulations are straightforward to implement for cold traps.

4.2.6 Summary for Section 4.2

The following is a detailed summary of the observations, findings, and recommendations for Section 4.2. Refer to 2.5.2 for a condensed summary of these observations and findings. The recommendations are listed in 5.2.

The confidence levels (CLs) – 68%, 95%, and 99.7%, corresponding to 1σ, 2σ, and 3σ limits – for stated uncertainties in NDA of K-25 and K-27 holdup deposits are not specified because the current stated uncertainties are not derived for the parameters relevant to the K-25/K-27 holdup measurements. The stated total uncertainties of 50% or 100% may not be conservative in some cases and may be grossly overestimated in others.

Monte Carlo simulations determined the systematic effects of radial variations in the deposit distribution on gamma and neutron NDA for Type-2 converters. Performing Monte Carlo simulations of the effects of radial deposit distribution for Type-1, -3 and -4 converters is recommended. The relatively low sensitivity of the neutron NDA to variations in the radial deposit distribution justifies the choice of neutron over gamma NDA results for (high-mass) converters. The Monte Carlo results also indicate that the neutron calibration for radial deposit distribution is reasonably conservative in that the results for the likely deposit distribution may be 10-15% high from the distribution effect.

Gamma measurements determine the NDA results for low-mass converters. The Monte Carlo simulations show a very large impact of variations in radial deposit distribution alone on converter quantities determined from 186-keV gamma measurements. This may justify a near-term adjustment of uncertainties on the gamma NDA values for the low-mass converters. Radial deposit distribution contributes >100% to Type-2 low-mass converter uncertainty. Furthermore, the recorded low-mass-converter (gamma) NDA results may be biased high beyond stated uncertainty.

The use of Monte Carlo to determine the contribution of horizontal distribution of deposits to uncertainty in gamma and neutron NDA results for Type-2 converters is recommended. Compared to gamma NDA, large-converter (Type-1 and -2) neutron NDA may be relatively vulnerable to horizontal deposit distribution because neutrons are measured at only one horizontal measurement position compared to two for gammas. The use of Monte Carlo to determine the contribution of horizontal distribution of deposits to uncertainty in gamma and neutron NDA for Type-1, -3 and -4 converters is also recommended. Repeat Monte Carlo simulations of the contributions of deposit distribution to gamma NDA uncertainty for 1001-keV measurements of (K-27) Type-2 converters if the higher-energy gammas were used.

Deposit distribution contributes substantially to systematic uncertainty in holdup NDA. Use Monte Carlo simulations for contributions of deposit distributions to uncertainty in NDA for cold traps, compressors (neutron), surge tanks (gamma and neutron), and piping (gamma).

Monte Carlo simulations for gamma and neutron NDA measurements are straightforward given equipment/deposit parameters. The use of realistic variations in these parameters will determine realistic contributions of systematic error terms at 68% (1σ) CL (or 3σ, *etc*.).

The estimates of systematic uncertainty for each equipment type should include the following: calibration error, deposit composition, deposit distribution, detector positioning, ^{235}U enrichment (its uncertainty is quoted as 20%, but the CL is not stated), room background, equipment attenuation (primarily for gammas), self-attenuation (primarily for gammas), and scattering (primarily for neutrons). Determine both random (when significant) and systematic effects in uncertainty for a given CL for each measurement/equipment type. Combine the error terms to get total systematic uncertainty for each measurement/equipment, and then combine systematic and random uncertainties to give the total measurement uncertainty. The inclusion of the specific random uncertainty (from counting statistics, which vary from one measurement to the next for the same measurement/equipment) may not be necessary for each measurement when the systematic error dominates. State the CL for all stated uncertainties.

Consider a numerical approach to evaluating the total NDA uncertainty. Also consider including an asymmetric uncertainty when appropriate for certain terms such as converter radial deposit distribution effects, which appear to impact bias. Pursue all opportunities to compare neutron and gamma NDA results for converters and surge tanks in order to validate the Monte Carlo results (and the error terms that these results provide) for such equipment.

Ignoring the finite width of line deposits incurs negative bias from a geometric standpoint which is subsequently compounded in a self-attenuation correction that underestimates the effect because of nonlinearity. (Furthermore, the current use of the self-attenuation algorithm as described in MMES4 may underestimate the effect, further compounding the negative bias in gamma NDA of process piping.) Determine by expert review if deposit width is included in analysis of piping segments measured at 186 keV, and implement the finite-width correction for thick deposits ($t(M)_{est} \geq 0.1$ g U/cm^2) if it is not included If piping segments were measured at 1001 keV, implement these changes for $t(M)_{est} \geq 1$ g U/cm^2.

The documented equations for self attenuation of deposits in pipes include constants that may not be valid and therefore may bias the measurement results. Submit the constant 60.8 (MMES4, Bartholomay Equation 11) to expert review for validation in the context of the discussion in Section 4.2.3. Submit constant 2.740 (MMES4, Bartholomay Equation 10) to expert review for validation in the context of the discussion in Section 4.2.3. The algorithm for self-attenuation appears to be implemented improperly, underestimating the results for deposits in process piping. Submit use of self-attenuation correction of steel piping segments CF_{SA} to expert review in the context of the discussion in Section 4.2.3. Re-evaluate self-attenuation corrections for process piping segments with thick deposits $t(M)_{est} \geq 0.1$ g U/cm^2 for 186 keV and $t(M)_{est} \geq 1$ g U/cm^2 for 1001 keV.

Consider numerical approaches to evaluating uncertainty components and the total uncertainty in holdup measurements of piping. Such approaches allow inclusion of the influence of the nonlinear algorithm for self attenuation on each individual error term.

Corrections for gamma self-attenuation by deposits in small-diameter copper piping were not implemented despite the possibility that these effects are large for measurements at 186 keV. Confirm safety status of these deposits and evaluate any other drivers for self attenuation corrections for deposits in copper piping. If appropriate, implement self attenuation corrections as described for the steel process piping to analysis of holdup deposits in copper piping segments. Alternatively, estimate these effects and verify that the stated uncertainties are inclusive.

The documentation for the NDA methodology for process piping (MMES4) is not up to date and is incomplete. Update and complete the documentation of methodology for gamma NDA of piping segments.

4.3 Gaps in Existing Data, Possible Additional Measurement Needs

All process equipment in K-25 and K-27 were measured initially by non-quantitative gamma surveys. The nondestructive gamma survey measurements performed prior to performing quantitative NDA measurements of steel piping scanned this piping with a declared sensitivity of 2 g ^{235}U per 1.5 linear feet. Non-quantitative nondestructive surveys was a practical screening approach. Quantitative NDA for higher mass deposits correctly prioritized efforts required for NDA.

All equipment in most of the process equipment groups in K-25 and K-27 (including converters, compressors, small-diameter copper piping segments, surge tanks, cold traps) were measured subsequently by quantitative NDA.

Subsequent to the nondestructive survey measurements, quantitative NDA measurements were performed on those piping segments with deposits exceeding the ^{235}U sensitivity threshold. Only 1-2% of the total length of steel piping has been measured quantitatively. Therefore, deposits in approximately 4 million linear feet of steel piping that are unmeasured by quantitative NDA could contain up to 2 g ^{235}U per 1.5 linear feet of piping, corresponding to an upper limit in ^{235}U inventory in the unmeasured portions of the steel piping of approximately 5000 kg. The inventory in the unmeasured portions is not included in the total inventory declaration.

The additional possibility exists that the nondestructive gamma scanning has missed large deposits of potential safety concern and even potential accountability interest. A separate report (Harris) describes specific access issues that forced measurement distances of 10 feet or more for some piping. Large deposits could go undetected because of a lack of sensitivity and effects of obstructions and interferences at such large distances.

A further concern related to gaps in the measurements of process piping is average spacing between measured segments. A total of 5,000 relatively short piping segments were measured by quantitative NDA in approximately 5 million linear feet of process piping. The average (unmeasured) distance between measured segments, ~1000 feet, is large. Bartholomay discusses concerns raised in other reports (Canberra) that the specific locations of piping segments measured by quantitative NDA are neither marked nor mapped in some cases because of security reasons, among other issues.

Additional information on the deposits in process piping is needed. Existing data might be used initially. The measurement-to-measurement repeatability in the monthly confirmation measurements for each deposit location measured more than once should be provided for each equipment/measurement type. These data should be plotted in the form of control charts (normalized result vs. time) to identify any possible long-term systematic effects. Use the repeatability information – for piping segments in particular – as a baseline for interpretations of the data as described below.

An analysis of the measured results for piping segments is called for. Correlations between ^{235}U linear density and pipe diameter could provide useful systematics or raise important warning signals. Such correlations with process location could also be useful in this way. The empirical lower limit in the distribution of ^{235}U linear density in the 5000 measured piping segments could establish (or destroy) confidence in the expectation for the survey threshold of 2 g ^{235}U per 18 inches. Evidence for a lower actual threshold could impact the D&D process positively. Evidence for a higher threshold might influence the design of a program of additional measurements of the process piping.

Graphic maps of measured deposits in piping could be useful in several ways. The systematics of the linear distribution of measured deposits could support conservative estimates of deposits in locations lacking quantitative measurements. Such maps could also assist in the cleanout process. Superimposing maps of above-threshold survey regions or measured deposit masses with process equipment features such as seals, bends, tees, flanges, *etc*. could lead to other types of conservative estimates concerning deposits in areas where measurements do not exist. Marking the linear regions of limited access where survey measurements were likely ineffective would be an important addition to these maps. Finally, the maps would be an essential resource for a program in which additional measurements might be performed to validate the existing NDA results for mass and support the expectations for sub-threshold quantities of ^{235}U (< 2 g per 18 inches) in unmeasured areas.

It is likely that much of the discussion in the next paragraph is naively stated because the review team is not familiar with the engineering aspects of the D&D process. The ideas themselves might be recast into a more practical sequence/plan than that indicated in order to achieve the same result. However, the final recommendation for automation should be considered seriously for any additional measurement campaigns planned for process piping.

An additional program of measurements of process piping may be called for ultimately. Initial measurements could support the plans for decoupling extended piping lengths from the process. Quantitative gamma measurements might verify the linear deposit density at specific locations on the piping marked for invasive mechanical decoupling. A maximum linear density could be prescribed for these locations to avoid cutting into substantial deposits. Once extended lengths of piping are detached from the process for a defined process area, a well-controlled (to the extent possible given PPE requirements) series of gamma measurements might be carried out on the segments, well marked for identification and beginning/end distinction, to support the disassembly of the extended piping. Automated acquisition/storage of data from such measurements, which might be performed in a “quantitative survey” mode should be implemented to make the most of measurement time. (Refer to Section 4.4 for further details.) Use the automated measurements to indicate possible safety concerns and identify possible additional candidates for D&D segmentation.

4.4 Existing and Possible Alternative NDA

The need for portable NDA measurement capability persists throughout the D&D process. Retain, maintain, and support the current portable NDA measurement capability including appropriately trained and experienced personnel, throughout D&D.

The loading of crates or drums for transport and storage can incur extra expense for the D&D project if the loading is excessively conservative – requiring additional crates, crate measurements, transport, and storage space – to avoid exceeding DOT limits or meeting the WAC. However, non-conservative loading can incur the significant costs of opening and removing packages from loaded but overpacked crates or drums. The capability to measure packages at the site of loading the crate or drum will benefit the economy of the D&D and provide a direct measurement result for each item in the transport/storage container in case of need to locate a particular item for removal. Relatively movable NDA measurement technology such as gamma-isotopics and neutron measurements with slab detectors, will support measurements of packages of different dimensions and allow the mobility necessary to function at the crating site where numerous items enter and leave by various transport means. Coarse sorting for inclusion of like items for a single crate or drum based on gamma isotopics will simplify the interpretation of measurements performed on the packed crate/drum. Passive neutron measurements using slab detectors can be applied to the measurements of process equipment segments alongside the segmentation site.

The NDA measurement technique for the loaded crates or drums should be penetrating of multiple layers of dense process equipment. An option is active neutron assay of packed crates and drums with gamma isotopics for interpretation of the measurement results. The active neutron method can also serve as a referee technique on any questionable NDA result. The active neutron technique can be applied to the measurements of process equipment segments near but not likely alongside the segmentation site.

Portable gamma NDA may be used to perform additional measurements on process piping not previously measured by quantitative NDA. Automating the acquisition of this NDA data will maximize the duty factor for measurements, nearly eliminating the time between measurements required to record data manually and eliminating the unreliability of manual recording. The automation will also allow implementation of quantitative surveys, such that the survey technique of scanning the process piping acquires data that can be interpreted quantitatively. Applying this approach to extended process piping segments decoupled from the process so that access issues are reduced or eliminated will simplify the scanning and allow controlled positioning. Automation already developed for counts of finite time performed in rapid succession is in use at facilities in Oak Ridge and immediately available. (Smith) Some modifications to the automation of data acquisition would be required to accommodate automated acquisition of data in the scanning mode for quantitative surveys.

The NDA of process equipment segments should be executed to optimize the use of the measurement results to benefit subsequent measurements. The sum of NDA results for equipment segments should validate the portable NDA for the intact equipment. This validation allows the segmentation to proceed according to a plan that utilizes the NDA results for holdup deposits. Therefore, segment sequentially, performing NDA on the segments for comparison with the holdup NDA before proceeding on further segmentation. Always perform segment NDA on an individual segment. Always complete a timely comparison of the original holdup NDA result for the intact equipment with that obtained from the sum of segments. Re-evaluate holdup deposit quantities and uncertainties for the intact equipment as indicated by analysis results of segments. Until NDA is performed on an individual segment, it retains the total quantity and uncertainty determined from holdup measurements of the original item.

4.5 Usefulness of Existing NDA for NMC&A, D&D

Quantitative portable NDA of deposits in most K-25/K-27 equipment satisfies requirements for NMC&A currently. The D&D contractor should consider any possible additional NMC&A or security requirements and, if applicable, adjust present D&D plans accordingly. One possible issue applies to the process equipment that was surveyed nondestructively but not measured by quantitative NDA. Applying the upper limit for the survey measurements of 2 g ^{235}U per 1.5 linear feet to ~ 4 million feet of process piping gives an upper limit of 5000 kg of ^{235}U for un-quantified deposits in this process equipment. Although 2 g ^{235}U per 1.5 linear feet is a credible thin-layer deposit for process equipment, 5000 kg of ^{235}U for un-quantified deposits is not an acceptable result for NMC&A.

If it is not possible to empirically infer (by analysis of the 5000 NDA measurements of piping segments as discussed in Section 4.3) an upper limit in the linear density of ^{235}U that is smaller than the survey threshold 2 g ^{235}U per 18 inches, consider measurement approaches. Sampling the unmeasured piping with quantitative gamma NDA before the D&D of this equipment commences should be considered to determine a more realistic limit for the un-quantified deposits in the process piping. Implementing automated portable gamma NDA described in the previous section for extended segments of decoupled process piping is another option. If alternatives are not developed to obtain a better estimate of deposit quantities in the unmeasured process piping, the upper limit for the survey measurements must be also be considered for this equipment for purposes of loading containers to meet requirements for transport and disposal (DOT and WAC). This may be unacceptable from the standpoint of cost.

The deposit-removal project addressed deposits of greatest safety concern. The plans to vent, drain, and purge equipment prior to mechanical decoupling mitigates many possible safety issues with deposits.

Conservative uncertainties applied to NDA of deposits reduces concerns about unsafe deposits. Although many uncertainties are likely overstated, some uncertainties may as yet be underestimated. The example is gamma NDA of low-mass converters, although the low mass of the deposits in these converters does alleviate this particular concern somewhat. Defining CLs for uncertainties derived specifically for each type of measured equipment is in the best interests of NCS, particularly if the possibility of understated uncertainty exists.

Segmentation and subsequent NDA of the segments for high-mass items reduces quantities in individual packages and decreases the NDA uncertainty. Both reduce the NCS risk.

Realistic determinations of systematic uncertainty in the NDA measurements is most important for criticality safety. The example of the converters illustrates this point. The use of Monte Carlo modeling of the NDA measurement to determine large error terms for variable deposit distribution is recommended.

Implementing NDA for packages at the crate loading site supports meeting crate loading limits for DOT and satisfying the WAC. Maintain NDA information on individual items and, in addition, sum deposit quantities/uncertainties of crated items for transport and burial or storage at waste disposal sites. Implementing NDA for packed crates provides the required measurements for DOT and the WAC. Propagate the uncertainties in the NDA results for packages, some of which may be holdup NDA results, to obtain the total uncertainty for loaded transport containers.

5.0 RECOMMENDATIONS

Section 5 lists the recommendations, stated or implicit, that follow from the analysis, observations and findings of Section 4. The recommendations are grouped under headings consistent with the charter statements (Section 2.1), as for Section 4. Refer to the corresponding headings in Section 4 for details associated with each recommendation.

The Review Team indicates some recommendations as discretionary (D) on the part of the contractor in that benefits weighed against the costs may be deemed small and relatively unjustified. All recommendations beginning with "Consider…" are implicitly discretionary. Furthermore, the results of the "expert reviews" recommended in some cases below may invalidate other related recommendations.

The basis for these recommendations is good practice in performing analytical measurements and using the results of such measurements, consistent with a realistic approach to the activities of the D&D. Develop alternatives to specific valid recommendations that achieve equivalent results if a recommendation imposes unrealistic consequences for the D&D.

5.1 Protocols for NDA Measurements at K-25/K-27 in 1980's-1990's

There are no recommendations regarding the protocols for NDA measurements at K-25 and K-27 in 1980's-1990's. The review gives these measurement protocols a general endorsement. The recommendations below qualify this endorsement.

5.2 Reliability/Validity of NDA within Stated Confidence Intervals

- Determine/simulate effects of radial deposit distribution for each converter type.
- Adjust uncertainty on converter quantities determined from 186-keV gamma measurements.
- Use Monte Carlo for contribution of horizontal distribution to uncertainty in gamma and neutron NDA for Type-2 converters.
- Use Monte Carlo for contributions of radial and horizontal distributions to uncertainty in gamma/neutron NDA for Type-1, -3 and -4 converters.
- Repeat Monte Carlo simulations of deposit distribution contributions to gamma NDA uncertainty for 1001-keV measurements of (K-27) Type-2 converters.
- Use Monte Carlo for contributions of deposit distributions to uncertainty in NDA for cold traps, compressors (neutron), surge tanks (gamma and neutron), and piping (gamma).
- Include the following error terms – retaining the dominant term(s) – in estimating realistic systematic uncertainty for each equipment/NDA-measurement combination:
  - calibration error.
  - deposit composition.
  - deposit distribution.
  - detector positioning.
  - ^{235}U enrichment. (Its uncertainty is quoted as 20%, but the CL is not stated.)
  - room background.
  - equipment attenuation (primarily for gammas).
  - self-attenuation (primarily for gammas).

- scattering (primarily for neutrons).

- Include both random (when significant) and systematic effects in uncertainty, and CL.
- Determine realistic contributions of systematic error terms at 68% (1σ) CL (or 3σ, *etc*.).
- Combine error terms to get total systematic uncertainty for each measurement/equipment.
- Combine systematic and random uncertainties to give the total measurement uncertainty.
- State CL for all stated uncertainties.
- Consider numerical approach to evaluation of total uncertainty.
- Propagate asymmetric uncertainty for converter deposit distribution effects. (D)
- Pursue all opportunities to compare neutron and gamma NDA results for converters, surge tanks.
- Determine by expert review if deposit width is included in analysis of piping segments.
- Implement (for $t_{est} \geq 0.1$ g U/cm^2) correction for finite deposit width if it is not included.
- Submit the constant 60.8 (Bartholomay Equation 11) to expert review for validation .
- Submit constant 2.740 (Bartholomay Equation 10) to expert review for validation.
- Submit use of self-attenuation correction of steel piping segments CF_{SA} to expert review.
- Consider numerical approach to evaluating the total uncertainty in piping holdup.
- Confirm safety status and other drivers for self attenuation corrections for copper piping.
- If appropriate, implement self-attenuation corrections for copper piping segments.
- Update/complete documentation of methodology for gamma NDA of piping segments.

5.3 Gaps in NDA Results and Additional Measurements/Methods

- Evaluate repeatability in monthly confirmation NDA of piping measured more than once.
- Look for correlations in existing measurement results for piping segments to obtain useful systematics or important warning signals of potential use to the D&D project. (D)
- Look for correlations between ^{235}U linear density and pipe diameter. (D)
- Look for correlations between ^{235}U linear density and process location. (D)
- Get lower limit in ^{235}U linear density distribution in 5000 measured piping segments.
- Graphically map the linear distribution of measured deposits. (D)
- Map above-threshold survey regions vs. linear position. (D)
- Map measured deposit mass and linear deposit density vs. linear position. (D)
- Map deposit linear density as indicated by analysis results of “coupons”, if applicable. (D)
- Superimpose locations of seals, bends, tees, flanges, etc. on the maps. (D)

- Mark linear regions of limited access on these maps. (D)
- Consider additional gamma NDA to validate existing NDA results for mass.
- Consider additional gamma NDA to verify expectations for < 2 g ^{235}U per 18 inches at unmeasured locations.
- Consider well-controlled gamma NDA on labeled decoupled piping segments.
- Consider portable automated technology for any new NDA campaigns on process piping.
- Consider "quantitative surveys" for any new NDA campaigns on process piping.
- Identify possible new candidates for D&D segmentation if additional NDA measurements are performed.

5.4 Alternative NDA Technologies and Applications.

- Retain/support portable measurement capability including trained teams through D&D.
- Consider slab-detector neutron measurements for package NDA at crate loading site.
- Consider Ge for gamma spectroscopy/isotopics and package sorting at crate loading site.
- Consider active neutron measurements for NDA of loaded crates.
- Consider Ge for gamma spectroscopy/isotopics of loaded crates.
- Consider slab-detector or active neutron NDA measurements for equipment segments.
- Consider Ge for gamma spectroscopy/isotopics at segmentation site.
- Consider automated gamma NDA of process piping for D&D phase.
- Consider automated gamma "quantitative survey" of process piping for D&D phase.
- Segment sequentially: analyze segment deposits before proceeding on further segmentation.
- Always re-measure deposit quantities for individual segments.
- Always compare original deposit quantity with that obtained from the sum of segments.
- Re-evaluate deposit quantities/uncertainties as indicated by analysis results of segments.
- Retain original NDA quantity/uncertainty of intact equipment for a segment not measured.

5.5 Applying NDA data for NMC&A and D&D (NCS, DOT, WAC)

- Consider alternatives to the use of upper sensitivity limits of equipment nondestructively surveyed but not quantified by NDA to estimate this inventory.
- Maintain upper sensitivity limits for deposit quantities in equipment nondestructively surveyed but not quantified by NDA if alternatives are not implemented.
- Retain all (NDA) knowledge of deposits in equipment and track the information to disposal.
- Track holdup NDA quantities/uncertainties (or alternative NDA) to packages.

- Track package NDA quantities/uncertainties to containers.
- Sum deposit quantities and propagate uncertainties for sum of items loaded in containers.
- Propagate uncertainties on individual-item quantities to get uncertainty for transport container.
- Track upper limit of detection for nondestructive survey measurements of transported and stored/buried items not measured by quantitative NDA.
- Track container NDA quantities/uncertainties to disposal.
- Sum deposit quantities and propagate uncertainties for sum of items stored/buried as waste.

6.0 CONCLUSIONS AND PATH FORWARD

An independent review of the NDA measurements of holdup at the K-25 and K-27 facilities is complete. The independent review team investigated topics and communicated findings and recommendations in response to the charter provided to this team. This draft report incorporates the official response on the chartered topics.

A review of the draft report and input by DOE/OR is requested. A subsequent review by BJC will be beneficial to establish accuracy of the content.

Several recommendations for expert review appear in this report. Such reviews might be carried out by the BJC and USEC experts who participated in this review of NDA for K-25/-27. Consultation with outside experts – including the members of this review team but especially scientists and engineers who planned and implemented the original K-25/K-27 holdup measurements and others who designed and carried out the D&D at K-29/K-31/K-33 – is strongly encouraged.

Achievements in NDA at K-25 and K-27 to date represent a scope and process that is unique for such measurements. An expanded scope and more sophisticated process is required to apply the original NDA of holdup deposits and implement additional NDA for the D&D itself. The knowledge that comes from this work is useful to the NDA community in the design of measurements for imminent D&D projects and for operational facilities in anticipation of future D&D. The following topics relative to the work at K-25 and K-27 are precedents for NDA measurements of holdup whose communication – as reports or presentations – would benefit the NDA community.

- Exercise of measurement control in large-scale campaigns of holdup measurements.
- Maintaining long-term continuity of static-process holdup measurements for a future D&D.
- Use of multiple NDA measurement types to characterize holdup deposits.
- Use of Monte Carlo modeling of holdup to choose NDA measurement type and approach.
- Use of Monte Carlo modeling to determine complex systematic contributions to the uncertainty in holdup measurements.
- Implementing numerical approaches to obtain the total uncertainty in holdup measurements.
- Performing automated "quantitative survey" measurements of holdup in process piping.
- Comparison of holdup measurement results for K-25 and K-27 (or for K-25/K-27 and K-29/K-31/K-33).

Communicating results on these topics to the larger NDA community is encouraged.

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APPENDIX A

Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

Background

The K-25 and K-27 Buildings at the Oak Ridge Reservation (ORR) East Tennessee Technology Park (ETTP) were constructed during the Manhattan Project and placed into service in 1945. The facilities were designed and built to house full-gradient cascades to produce uranium enriched in the ^{235}U isotope up to the weapons grade. The cascade used the gaseous diffusion process that utilized uranium hexafluoride (UF_6) as the process gas. Various portions of the buildings operated through 1985, when all enrichment operations ceased at both buildings. There is no longer a mission for the facilities and they are slated for demolition by the end of Fiscal Year 2008.

In the late 1980's, non-destructive assay (NDA) measurements (over 17,000) located and quantified deposits of uranium in the cascade equipment. Since the 1990's, additional NDA measurements have been preformed to support the Verification/ Confirmation program - a statistically based NDA monthly measurement program that confirms whether there has been a diversion of Special Nuclear Materials from any process gas equipment or item.

The inventory of highly enriched uranium (HEU) in the K-25 Building not including NDA uncertainty is 1500 kg. The K-25 uranium mass is estimated assuming the entire 1500kg mass of HEU at ETTP as of December 31, 1993, as announced by the Secretary of Energy, exists in the K-25 process gas equipment. The enrichment ranges from 20 to 93% ^{235}U.

The inventory of uranium mass in the process gas equipment in the K-27 Building not including NDA uncertainty is 1409 kg. The enrichment ranges from 0.7 to 20% ^{235}U.

The uranium is mostly present as a generally uniform and diffuse layer. In areas where moist air in-leakage occurred, the UF_6 would react with water vapor to produce non-volatile UO_2F_2. Therefore, thicker deposits of uranium are expected in equipment near sites of air in-leakage.

Scope

Review the measurement protocols used for the 1980's – 1990's NDA surveys. Determine the conservativity of these measurements.

Evaluate the reliability and validity of existing data at specified confidence levels.

Determine if there are gaps in existing data (such as equipment not being measured) and, if so, what additional measurements are needed.

Evaluate current NDA technology being used and recommend alternative technology if needed.

Evaluate the usefulness of existing NDA data for Nuclear Material Control and Accountability as well as critical D&D activities such as: Nuclear Criticality Safety evaluations and controls during the removal and handling of process gas equipment; Department of Transportation requirements for transportation and disposal; and Waste Acceptance Criteria (WAC) requirements for disposal facilities.

APPENDIX B

Technical Team Members and Participants

Name	Role, Discipline, and Affiliation	Telephone and E-mail Address
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APPENDIX C

NDA Independent Review
East Tennessee Technology Park
Oak Ridge, Tennessee
November 30 – December 3, 2004

DRAFT Agenda

Tuesday, November 30
K-1580, Conference Room

Time	Presentation	Presenter
8:00 – 8:05a	Introductions	Texas Chee
8:05 – 8:15a	Welcome, Objectives, Site Overview	Donna Perez
8:15 – 8:45a	GDP Overview – Past and Present	Wendy Cain
8:45 – 9:15a	Past NDA Technologies and Approach	Kevin Meyer
9:15 – 9:45a	Planned use of old and new NDA data	Chad Brown
9:45 – 10:00a	Break	
10:00 – 10:30a	BJC Independent Review Results	Joe Alvarez
10:30 – 10:45a	NMC&A	Karen Shaffer
10:45 – 11:30a	Q&A, Logisitics	All
11:30a – 12:30p	Lunch at Oliver's	
12:30p – 5:00p	Classified Document Review	

Wednesday, December 1
8:00a – 4:00p RRAS Team Review
4:00p – 5:00p RRAS Team meeting with Donna Perez, K-1580

Thursday, December 2
8:00a – 5:00p RRAS Team Review

Friday, December 3
8:00a – 1:30p RRAS Team Review
1:30p – 4:00p RRAS Team Outbriefing to McCracken and Senior Management

APPENDIX D

Request for Technical Solution

Tracking Number:		(assigned by EM-HQ)
Request Title:	Methodology to Correlate Historic NDA Data	
Requesting Organization:	K25/K27 D&D Project	

Contacts: Greg Eidam, phone 865 576-3393, fax 865 576-6946, o98@bjcllc.org
Robert Johnson, phone 865 576-1952, fax 865 576-6946, rj9@bjcllc.org
Paula Kirk, phone 865 241-2259, fax 865 574-9646, kirkpg@ornl.gov

Scope of Work

What is the problem that needs to be addressed?

In order to meet the closure schedule, over 10,000 piece of gaseous diffusion equipment and over 4 million linear feet of piping must be characterized for disposition by September 2005. Characterization is a major cost and schedule driver for the D&D of the K-25 and K-27 buildings. While volumes of NDA data collected over the past 40 years are available, the technologies, methodologies, assumptions, and drivers have varied greatly. In order to minimize the time and cost of characterization, a regulatory methodology is need to validate and correlate the past data.

How is this problem impeding site closure?

Characterization is a major cost and schedule driver for the D&D of the K-25 and K-27 buildings. If this phase of the D&D is not completed by September 2005, the closure schedule may be impacted.

What is the current baseline approach and estimated cost and schedule?

If the project is required to perform 100% NDA on all equipment and piping prior to disposal, the cost could be in the tens of millions of dollars and the schedule delay could be 9 – 12 months.

What are the potential benefits of solving this problem (cost, schedule, safety, etc.)?

The benefits of finding an efficient and cost-effective methodology for using existing data include:
Reducing the cost of characterization
Expediting the disposition of equipment and associated process materials
Facilitating meeting the closure schedule

What type of assistance is requested (analysis and report, develop/modify technology, etc.)?

Assistance is needed to review and analyze the existing data and recommend a methodology to validate past data that will be acceptable to the regulators.

What are the anticipated major tasks/activities, start/end dates, milestones, and/or deliverables?

August 2004
Compare/analyze past NDA data and new NDA data.
Determine if past data can be defensibly used (possible development of a correlation algorithm). Identify if additional NDA readings are needed. If so, where and how many
Evaluate current NDA technology being used and recommend alternate technology if needed.
Final report detailing and justifying the approach.

What is the estimated cost?

2 people for 10 days plus travel ~$20,000

Submitted by:

Name	Date

Authorized by:

Signature (for DOE Site)

Stephen H. McCracken	
Assistant Manager for Environmental Management	Date

Signature (for Site Contractor)

Greg Eidam	
Manager of Projects, K25/K27 D&D Project, Bechtel Jacobs	Date

APPENDIX E

Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project*

OUTBRIEF PRESENTATION

November 30-December 3, 2004

Oak Ridge, TN

* Sponsored by the US Department of Energy, Office of Core Technical Group, EM-23

December 3, 2004 Oak Ridge, TN

Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

Team

Anthony Belian	LANL	Team member
Phyllis Russo	LANL	Team leader
Denny Weier	PNNL	Team member
Roger Bartholomay	BJC	Participant
Chad Brown	BJC	Participant
Kevin Kimball	BJC	Participant
Paula Kirk	ORNL	Participant
Wendy Cain	DOE/ORO	Participant
Texas Chee	DOE/EM-21	Participant
Richard Mayer	USEC	Participant

December 3, 2004 Oak Ridge, TN

Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

Review Process

- Topics/charter provided to team.
- Advanced material sent prior to visit
- Overview presentation given at entrance session.
- Specific and classified presentations and discussions held.
- Observations/findings and recommendations are reported herein.

December 3, 2004 Oak Ridge, TN

Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

Review Topics

Observations and Findings

1. Measurement protocols and priorities for 1980-1990's portable NDA measurements of holdup
2. Validity of existing holdup data within specified confidence intervals
3. Gaps in existing data and possible additional measurement needs
4. Current and possible alternative NDA technology.
5. Usefulness of existing NDA holdup data for
   - Nuclear Material Control and Accountability
   - Essential D&D components: Nuclear Criticality Safety
DOT requirements
WAC for disposal

Recommendations

December 3, 2004 Oak Ridge, TN

Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

1. Measurement protocols and priorities for 1980-1990's portable NDA measurements of holdup

- Conservative
  - determinations/assignments of ^{235}U mass.
  - estimates (empirical) of measurement uncertainty
  - coverage of process equipment at K-25 facility
- Portable gamma spectroscopy and neutron counting with
  - rigorous measurement control
  - stabilization or intrinsically stable detectors
  - accessible and clear archives of measurement results
- Consistent NDA confirmation of selected items over time
- Scheduled segmentation/NDA of high-mass items

December 3, 2004 Oak Ridge, TN

Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

1. continued
Conservative aspects of measurement protocols and priorities for 1980-1990's portable NDA measurements of holdup

- All process equipment at the K-25 facility is measured.
- Determinations/assignments of ^{235}U mass:

  Analysis of data uses the credible deposit model that tends to maximize the measured quantity (*e.g.*: converters)
- Estimates of measurement uncertainty:

  Use holdup results for diverse collection of HEU reference materials (rods, plates, powder, foils, filter media…) to define a conservative measurement uncertainty (± 50%).

December 3, 2004 Oak Ridge, TN

1. continued

Reliability in measurement protocols and priorities for 1980-1990's portable NDA measurements of holdup

- Measurement control demanding reproducibility of HEU check-source rate periodically (twice per hour) guarantees proper performance of equipment .
- Stabilized gamma spectroscopy electronics automatically compensate for gain drift.
- Helium-3 neutron detectors are intrinsically stable.
- The accessible and complete archive of measurement results assures their longevity through the D&D.

1. continued

Robust follow-up to measurement protocols and priorities for 1980-1990's portable NDA measurements of holdup

- Monthly NDA of selected items using original methodology preserves options for analytical upgrades if necessary to improve results (*e.g.*: the self-attenuation corrections for piping) without the need to repeat the measurements.
- Mechanical segmentation of high-mass items and NDA of segments in the early phases of the D&D will assure greater reliability of the original NDA and support determination that neutron readings are more accurate.

Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

2. Validity of existing holdup data within specified confidence intervals

- Equipment:
  - Converters (~ 3000 items, each ≤ 2 kg ^{235}U)
  - Compressors (~ 5500 items, each ≤ 0.7 kg ^{235}U)
  - Piping segments (~ 5000 items, each ≤ 0.4 kg ^{235}U)
  - Surge tanks (~ 20 items, each ≤ 3 kg ^{235}U)
  - Cold traps (~ __ items, each ≤ 3 kg ^{235}U)
- The items above represent > 95% of ^{235}U inventory.

December 3, 2004 Oak Ridge, TN

Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

2. continued

Validity of existing holdup data for **converters** (~ 3000 items, each ≤ 2 kg ^{235}U)

- Gammas measured at 4 positions (#1-2 converters)
- Neutrons measured at two locations for high-mass converters*.
- Observed trend for high gamma results, relative to neutron.
- Expectation is that gamma may incur negative bias or neutron may incur positive bias, *contrary to observation*.
- The systematics of these observations follow. (Denny Weier)

*Neutron measurements are not applicable for low ^{235}U masses.

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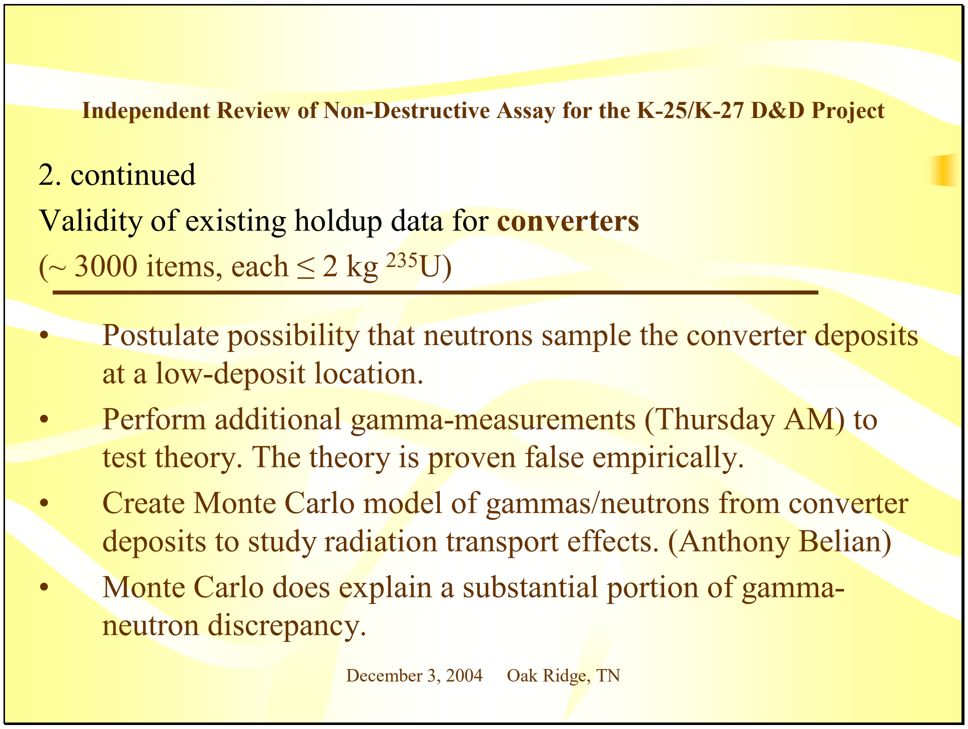
Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project
2. continued
Validity of existing holdup data for converters
(~ 3000 items, each ≤ 2 kg 235U)
• Postulate possibility that neutrons sample the converter deposits at a low-deposit location.
• Perform additional gamma-measurements (Thursday AM) to test theory. The theory is proven false empirically.
• Create Monte Carlo model of gammas/neutrons from converter deposits to study radiation transport effects. (Anthony Belian)
• Monte Carlo does explain a substantial portion of gamma-neutron discrepancy.
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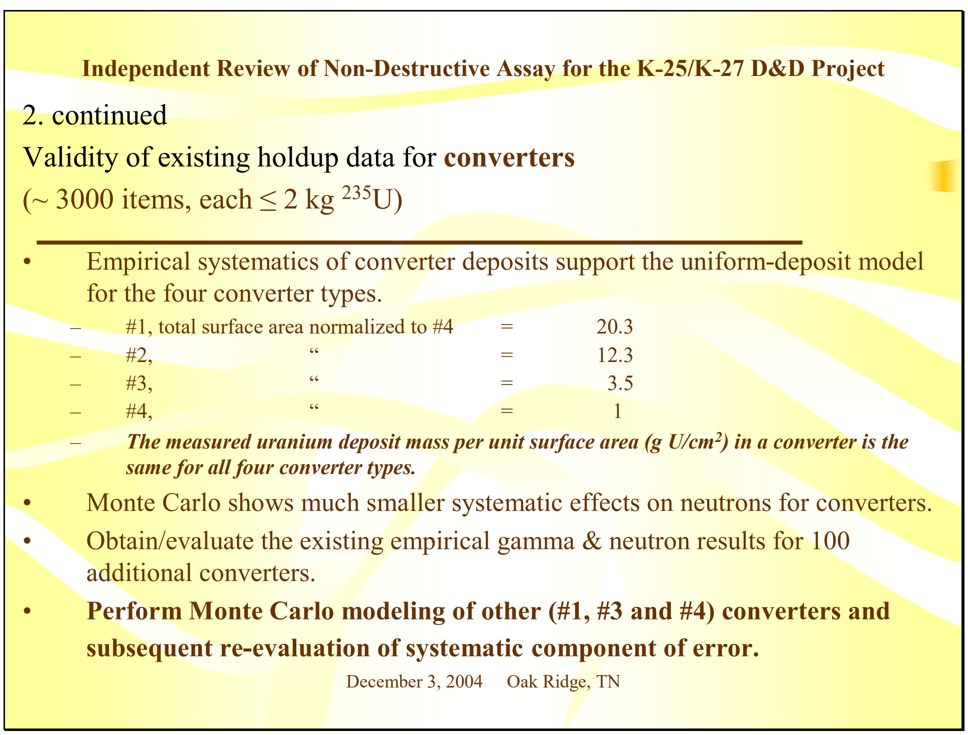
Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project
2. continued
Validity of existing holdup data for converters
(~ 3000 items, each ≤ 2 kg 235U)
• Empirical systematics of converter deposits support the uniform-deposit model for the four converter types.
– #1, total surface area normalized to #4 = 20.3
– #2, “ = 12.3
– #3, “ = 3.5
– #4, “ = 1
– The measured uranium deposit mass per unit surface area (g U/cm2) in a converter is the same for all four converter types.
• Monte Carlo shows much smaller systematic effects on neutrons for converters.
• Obtain/evaluate the existing empirical gamma & neutron results for 100 additional converters.
• Perform Monte Carlo modeling of other (#1, #3 and #4) converters and subsequent re-evaluation of systematic component of error.
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2. continued

Validity of existing holdup data for **compressors**

(~ 5500 items, each ≤ 0.7 kg ^{235}U)

- Neutrons measurements are performed on all compressors because equipment is too dense and thick for gamma.
- Calibration is empirical.
- Consider Monte Carlo models to evaluate systematic effects of changing deposit distribution on results that use a fixed calibration.

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2. continued

Validity of existing holdup data for **piping segments**

(~ 5000 items, each ≤ 0.4 kg ^{235}U)

- Gamma measurements of line deposits are calibrated empirically with HEU standards.
- Self attenuation corrections are applied to measured results.
- This correction algorithm is being applied incorrectly, causing negative bias in measured results.
- The assumption on surface area is incorrect, causing additional negative bias.
- Examination of deposit thickness in a sampling of pipes shows that bias incurred from incorrect application and assumption is very small because deposits in these cases are very thin.

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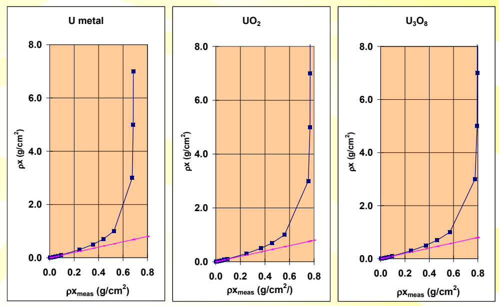
2. continued

Validity of existing holdup data for **piping segments** (~ 5000 items, each ≤ 0.4 kg ^{235}U)

- Consider surveying historic measurement file for deposits > 0.1 g U/cm^2.
- Recompute the self-attenuation using the algorithm and geometry correctly for these cases.



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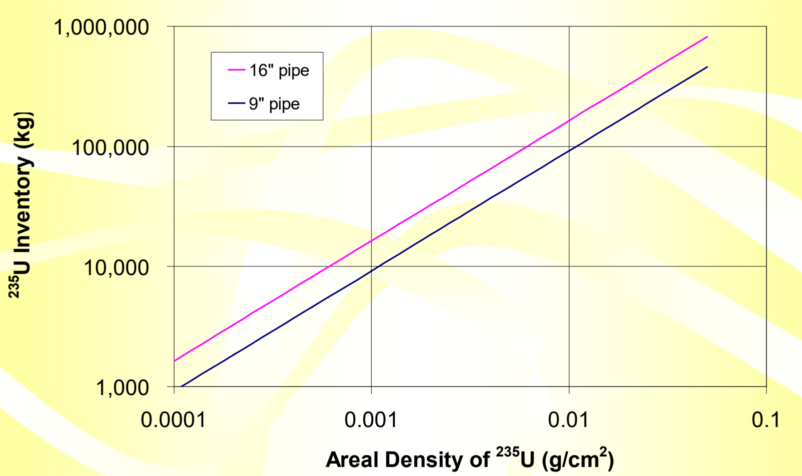
Total Pipe Inventory in 4.2 Million linear-feet of Process Piping

Small deposits add to some high masses



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2. continued

Validity of existing holdup data for **surge tanks**
(~ 20 items, each ≤ 3 kg ^{235}U)

- Gamma-ray measurements (20 measurement locations)
- Neutron measurements (2 measurement locations)
- Agreement between gamma and neutron is reasonable for those cases examined.
- Obtain/evaluate the existing empirical gamma & neutron results for ~12 additional converters.
- Consider Monte Carlo models to evaluate systematic effects of changing deposit distribution on results that use a fixed calibration.

Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

2. continued

Validity of existing holdup data for **cold traps**
(~10 items, each ≤ 3 kg ^{235}U)

- Neutron counting, multiple (up to ~10) measurement positions
- Empirical calibration is amenable to Monte Carlo modeling.
- Multiple measurements indicate distribution of deposit.
- Consider Monte Carlo models to evaluate systematics of changing deposit distribution on results that use a fixed calibration. Empirical determination of distribution can support corrections to measurement result when deposits are non-uniform throughout equipment.

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Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

3. Gaps in existing data & additional measurement complements

- Add graphics to Nuclear Criticality Safety Report[1]:
  - Spatial maps of measurement results (mark those monitored).
  - Monitoring data (measured mass* *vs*. time) for each item.
  - Use graphics and inventory information to locate possible gaps (see 18).
- Complement empirical calibrations with models.
  - Note systematics in response vs. mass, geometry, composition, *etc*.
  - Postulate subsets of items affected significantly.
  - Re-evaluate measurement uncertainties accordingly.
  - Identify possible additional candidates for segmentation/NDA.

[1] NCSR-ET-K25/K27-0019, R. W. Bartholomay, September 2004

* Include both gamma and neutron results.

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Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

3. Gaps in existing data & additional measurement complements

- Consider the possible gaps in process measurements. A simple example is process piping:
  - There are ~ 5 million linear feet of process piping.
  - A total of 5,000 piping segments were measured by NDA.
  - Therefore, average segment length is ~ 1000 feet. This is large.
  - *Use the graphics and inventory information to locate important gaps.*

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4. Current and possible-alternative NDA technology

- Retain and support portable measurement capability (including trained teams) throughout D&D.
- Perform package measurements at site of crating (*e.g.*: gamma-isotopics and neutron measurements with slab detectors)
- Consider active neutron assay (plus gamma isotopics) of packaged/crated items/materials as a referee technique on any questionable quantity.

Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

5. Usefulness of existing NDA holdup data

- Nuclear Material Control and Accountability

  BJC should consider any possible security requirements and, if applicable, adjust present plans accordingly
- Essential D&D components:
  - Nuclear Criticality Safety
    - Deposit-removal project addressed deposits of greatest concern.
    - Vent/purge/drain mitigates unexpected issues with deposits.
    - Conservative uncertainties applied to NDA of deposits reduces concerns about unsafe deposits.
    - Segmentation/NDA of remaining high-mass items reduces quantities in individual packages.

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Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

5. Usefulness of existing NDA holdup data (continued)

- Essential D&D components (continued):
  - DOT requirements
  - WAC for disposal

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Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

Recommendations

- Supplement Nuclear Criticality Safety Report (slide 17) with graphic spatial mapping and monitoring.
- Compare and evaluate gamma and neutron results when these exist for any items. *Make use of all such data opportunities.*
- Perform Monte Carlo modeling when effects such as deposit distribution can cause systematic effects in applications of a fixed calibration.

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Independent Review of Non-Destructive Assay for the K-25/K-27 D&D Project

Conclusion

- Review team addressed topics and provided findings and recommendations.
- Draft review report will be provided to ORO for comments by TBD.
- Final review report will follow.

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APPENDIX F

Converter Models, OUTBRIEF DETAIL

A. P. Belian

Use MCNPX to simulate detection of neutrons and gammas from holdup deposits in Type-2 converters. Use alternative models for the distribution of the holdup deposit.

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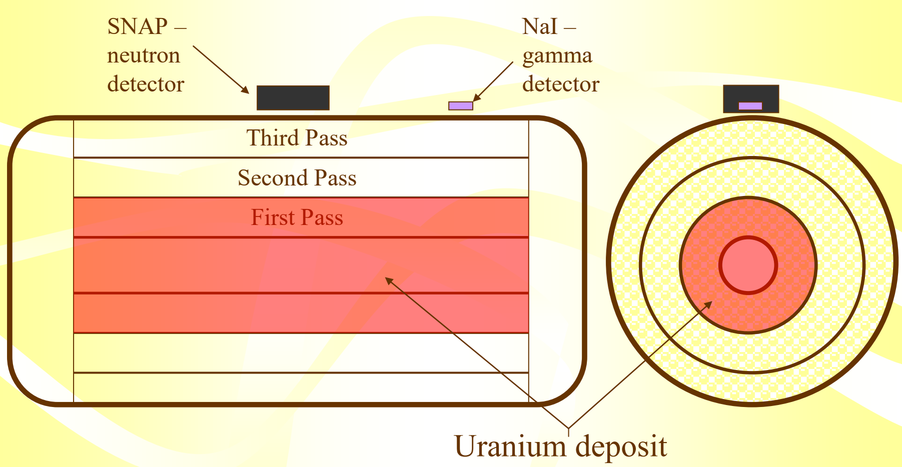
Converter Models

First Pass Model



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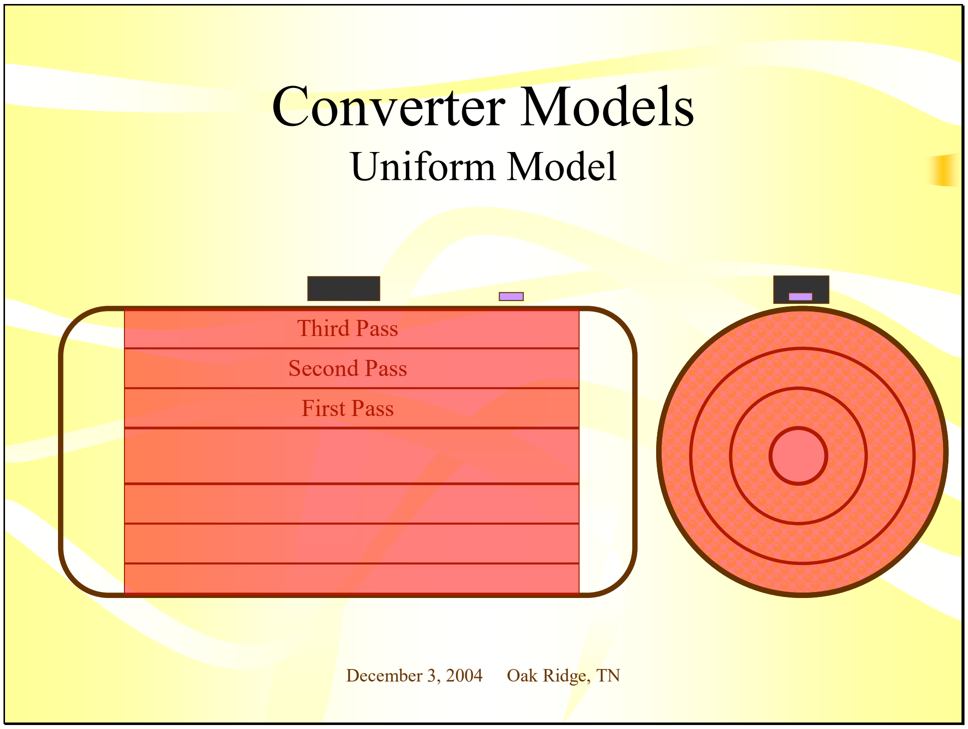
Converter Models
Uniform Model
Third Pass
Second Pass
First Pass
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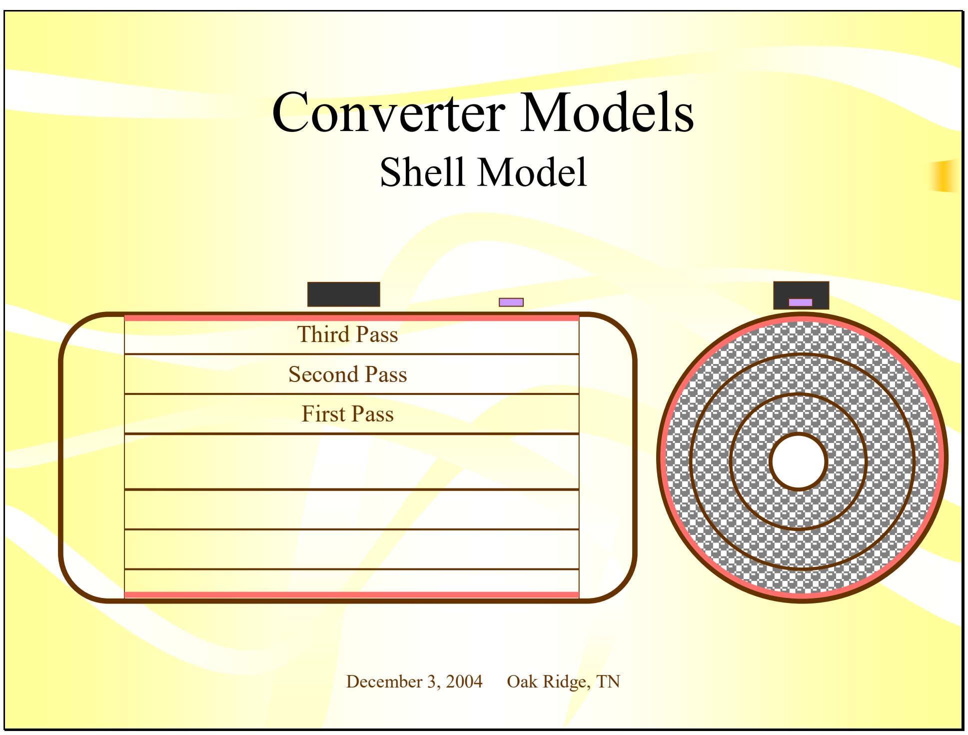
Converter Models
Shell Model
Third Pass
Second Pass
First Pass
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Ratio of Model Responses

Neutron		Gamma-ray	
Ratio Uniform/First Pass	**1.16**	**Ratio Uniform/First Pass**	**2.63**
Ratio Shell/First Pass	**1.37**	**Ratio Shell/First Pass**	**5.87**

Mass = CR * K K = 1/(detector response)

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Adjusted Masses

Mass = CR * K K = 1/(detector response)

Gamma (g)	Unif/First Pass	Shell/First Pass	Neutron (g)	Unif/First Pass	Shell/First Pass	G/N	G/N Unif	G/N Shell
3725	1527	685	771	665	563	4.83	2.30	1.22
3499	1434	643	417	359	304	8.39	3.99	2.11
1056	433	194	233	201	170	4.53	2.15	1.14
959	393	176	171	147	125	5.61	2.67	1.41
877	359	161	126	109	92	6.96	3.31	1.75
864	354	159	352	303	257	2.45	1.17	0.62
853	350	157	558	481	407	1.53	0.73	0.38
728	298	134	143	123	104	5.09	2.42	1.28
690	283	127	114	98	83	6.05	2.88	1.52
663	272	122	119	103	87	5.57	2.65	1.40
657	269	121	260	224	190	2.53	1.20	0.64
571	234	105	1950	1681	1423	0.29	0.14	0.07

"First Pass" model was chosen to be conservative

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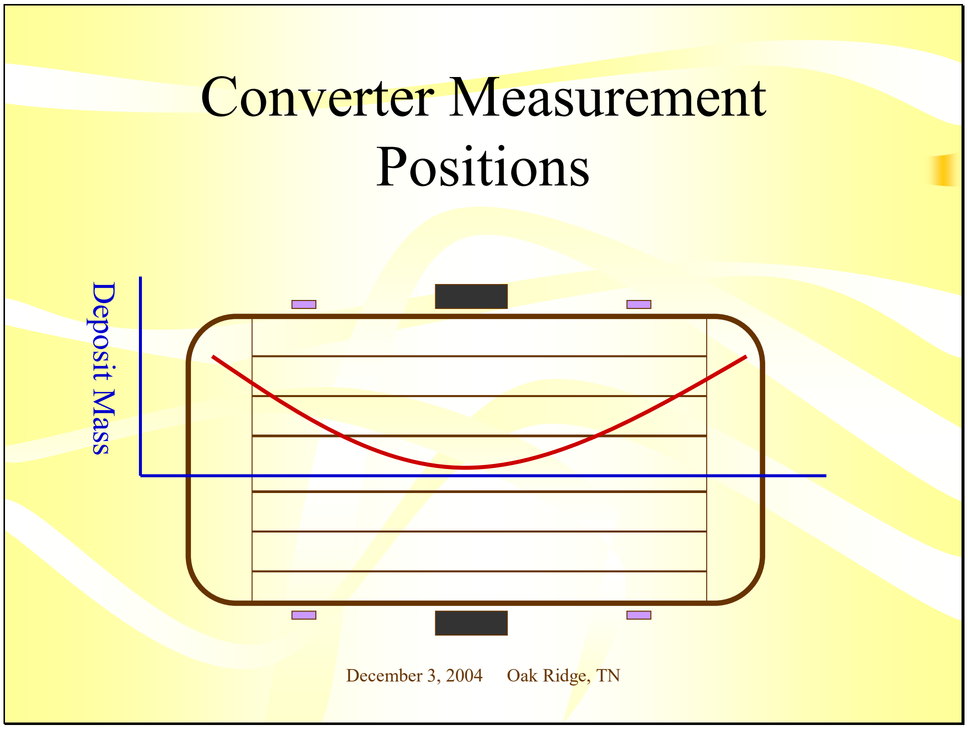
Converter Measurement Positions
Deposit Mass
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APPENDIX G

Statistical Topics, OUTBRIEF DETAIL

D. R. Weier

- Typical environmental/D&D activities are concerned with the "quantity" of data required
  - DQO (Data Quality Objectives) process can be used to derive a sampling plan than sufficiently characterizes a potential remediation site
  - The more "sample" measurements made to estimate a site "population" average or percentile, the more the measurement uncertainty is reduced and confidence level increased
- For the K-25/K-27 D&D project, the issue is more the "quality" of the measurements than the "quantity"
  - 17,000+ measured deposits are already on the NMC&A books
  - While this quantity might be questioned as being sufficient (e.g. for example, were all piping deposits located?), most of the questions are in regard to the quality of some of these measurements

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Statistical Topics (continued)

- The measurement "quality" issues are more NDA-related than statistical in nature
  - Are assumed material geometries used in the NDA algorithms sufficiently close to the actual holdup disposition to obtain accurate estimates?
  - If gamma and neutron results differ, which is likely the "better" approach?
- Opportunities will likely arise in which material removal and measurement will provide the opportunity to statistically evaluate the methodologies
  - Measure a unit before and after with NDA methods and measure material removed to determine NDA accuracy

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Statistical Topics (continued)

- Assumed 50% and 100% measurement uncertainties are "experience-based" rather than statistically derived
  - Repeated measurements over years in NMC&A program suggest random sources (e.g. counting errors or device placement) and short-term systematic sources (e.g. particular device, calibration, operator) generate much less uncertainty than the 50%/100% level
  - But the uncertainty magnitude due to long term systematic sources (e.g. material disposition, assumed geometries) are difficult to determine and likely of considerably greater magnitude
  - Comparison of gamma and neutron methods suggest such long term biases might be of lesser magnitude than the 50%/100% for surge tanks, but of greater magnitude for converters.
  - Material removal and measurement might provide better systematic uncertainty characterization

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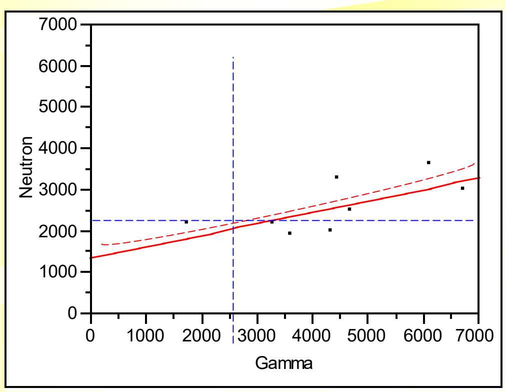
Mass Results for Non-Converters



Linear Fit
Neutron = 1336.1911 + 0.2764121 Gamma

Summary of Fit

RSquare	0.474729
RSquare Adj	0.387184
Root Mean Square Error	493.77
Mean of Response	2551.333
Observations (or Sum Wgts)	8

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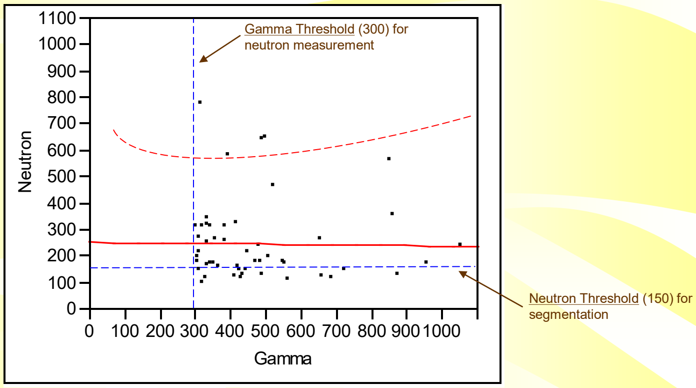
High Mass Results for Converters



Linear Fit
Neutron = 251.32697 - 0.0138356 Gamma

Summary of Fit

RSquare	0.000269
RSquare Adj	-0.02013
Root Mean Square Error	155.9597
Mean of Response	244.7255
Observations (or Sum Wgts)	51

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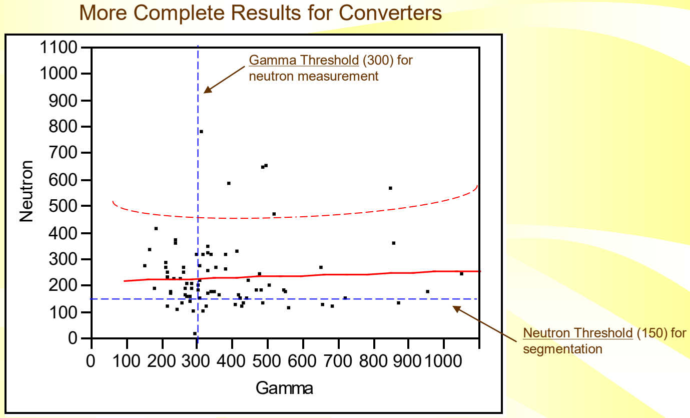
More Complete Results for Converters



Linear Fit
Neutron = 214.71239 + 0.0374001 Gamma

Summary of Fit

RSquare	0.002652
RSquare Adj	-0.00982
Root Mean Square Error	134.2061
Mean of Response	229.303
Observations (or Sum Wgts)	82

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