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MicroCT: X-Ray Radiograph Quality Assurance Through the Analysis of Copper Strip Data Using the Matlab CuStrip Analysis GUI

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Lawrence Livermore National Laboratory Global Security Principal Directorate **Livermore Explosive Development Program**	**Standard Operating Procedure**	
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MicroCT: X-Ray Radiograph Quality Assurance Through the Analysis of Copper Strip Data Using the Matlab CuStrip Analysis GUI

Concurrence MCT Technical Leader	Date
Approval LEDP Principal Investigator	Date
Approval LEDP QA Manager	Date

Contents

1.0 Purpose and Scope

This Standard Operating Procedure (SOP) supplements the LEDP data acquisition SOP [1] and reference material and specimen analysis SOP [2], and provides the specific procedural steps for analyzing copper strip (CuStrip) data using the Matlab CuStrip Analysis Graphical User Interface and preparing the tables and graphs to be used in the reporting of analytical results as required by the *LEDP Quality Assurance Plan for MicroCT Scanning* [3]. This procedure applies only to the analysis of two-slit data.

Although intended to apply primarily to MicroCT data acquired in the HEAFCAT Facility at LLNL, these procedures may also be applied to data acquired at other facilities with similar MicroCT systems [4] such as Tyndall Air Force Research Laboratory (TAFRL) from the YXLON cabinet and at Transportation Security Laboratory (TSL) from the HEXCAT system.

2.0 Precautions

There are no precautions from Integration Work Sheets or Facility Safety Plans and documents that are applicable to this work.

Work for this SOP is performed in project members' offices and does not present any high-risk safety situations. There are no operational safety boundaries such as set points or parameters that are applicable to this work.

3.0 Special Tools and Equipment

- Computer running Windows XP or above, with either Matlab version 2010a (or later) or the Matlab Compiler Runtime (MCR) version 7.14 installed. Other versions of MCR will not run the executable. Installations of Matlab require the inclusion of the image processing toolbox add-on.
- CuStrip GUI version 1.0 or later (the executable *CuStripGUI.exe* or the Matlab source code function *custrip_gui_split.m*) -- at present all versions are backwards compatible (for an outline of the files included in the GUI, see Appendix A). The CuStrip GUI includes a front-end graphical user interface used for facilitating the reduction and statistical characterization of x-ray radiographic projection data (see Appendix B). This code writes resulting data to output files, which are outlined in section 5.2 of this SOP. The internal mathematical details of the software are discussed in Appendix C.
- Microsoft Excel 2007 (or later).

4.0 Key Terms and Definitions

Copper Strip (CuStrip)	A strip of copper attached to the detector of a MicroCT system during scanning in order to provide a reference point from which to assess scan quality.
Experiment	The acquisition of CuStrip data, scanning a specimen with a specific x-ray source voltage (kV), with a specific source filter and collimation parameters.
GUI	Graphical User Interface.
kV	kilovolts (thousands of volts).
LAC	Linear Attenuation Coefficient – a quantity characterizing a material's x-ray attenuation.
LEDP	Livermore Explosive Detection Program
MicroCT	X-ray computed tomography system designed to scan small-quantity (~50ml) specimens.
QAP	Quality Assurance Plan.
QIP	Quality Implementing Procedure.
Scan set	The collection of all experiments for a single specimen.
SOP	Standard Operating Procedure.
TAFRL/Tyndall	Tyndall Air Force Base Research Lab.
Test	The collection of experiments scanning a particular preparation of specimen.
TSL	Transportation Security Laboratory.
μ	The mean value of the LAC over a volume of interest for a given x-ray source voltage, filtration and collimation.

Note *Within this document, the adopted coordinate system is such that the x-axis is the horizontal axis in the radiographic projection image plane, the y-axis is the vertical axis in the radiographic projection image plane.*

5.0 Procedure

Notes *Assure applicable data and test dates are current and correct by comparing the dates provided in acquisition notes text file with the dates of radiographic projection data files. If no such file is available, contact the radiographer for these data. The radiographic data files should have a filename structure "**specimen_#**.sdt," where* **specimen** *denotes the specimen name, and* **#** *is an integer value omitting leading zeros identifying the radiographic projection* *number of each scan file. The directory structure of the test directory will be outlined below in section 5.2.*

Stop the procedure immediately and notify the Technical Leader if there are any unusual discrepancies, failures, or abnormalities as noted in this SOP.

5.1 Preliminary Steps

This process begins when the analyst is notified that data are available for processing and is given the location of the data to be analyzed.

Verify the following:

5.1.1.1 The acquisition SOP has been followed (i.e., the data have been acquired with the dual-level carousel, the reference materials on the lower level of the carousel and the specimen(s) on the upper carousel, and every rotational view acquired includes either the reference materials or the specimen(s) in the field of view). This step should be completed in accordance with the directions outlined in the Data Acquisition SOP [1].

5.1.1.2 The data has been acquired for at least the following two source-filtration and collimator settings (Data taken at these two settings is **required**. Data taken at additional settings will not be processed):

a. 160 kV AlCu, 2 slits, known as "Exp1"
b. 100kV Al, 2 slits known as "Exp2"

5.1.1.3 If files with mismatching dates are observed within an experiment set of 400 radiographic data files (suggesting a data copying error), stop work and notify the Technical Leader.

5.1.1.4 The latest version of analysis software is located on a local disk drive.

At LLNL, both source code and executable files can be found on TeamForge (sourceforge.llnl.gov) under the project “**DHS Image Database**,” at the path: “**/Automate_MicroCT_Analysis_GUI/tags/Copper_Strip_Release_1/**.”

End users must download this directory to disk before analyzing radiographic data files. The location that the software is downloaded to can be determined at the end user’s convenience.

5.2 Data Analysis

5.2.1 Locate Radiographic Data Files from Each Energy Spectrum

5.2.1.1 Locate the radiographic data files for each energy level. Do not copy these to a local machine, as the number of files and file size would make this process prohibitively slow. For each experiment of each test present, both the radiograph data files (of the form ***specimen_#****.sdt*) and the corresponding parameter files (of the form ***specimen_#****.spr*) should be present for every value of **#**, where **#** is an integer value from 0 to 399 (for a total of 400 radiographic projection data files) formatted to exclude leading 0's, and **specimen** represents the specimen name. Also make sure that ***specimen****bak.sdt* and ***specimen****bak.spr* files are present at each energy level. These sets of files must be present for proper operation of the CuStrip GUI.

5.2.2 Run Data Analysis

5.2.2.1 Load the CuStrip GUI

If loading from source code:

To load the GUI, set Matlab's path to include the directory where custrip_gui.m is located.

a. To add this folder to the path, within Matlab go to **File→Set Path…**
b. Within the Set Path GUI window, click on **Add Folder…**
c. Find the location of the CuStrip GUI files locally, select the folder and click OK.
d. Within the Set Path GUI window, click Close, and save changes if desired.
e. At the prompt, enter "custrip_gui."

If loading from the executable:

Find the directory in which the executable "CuStripGUI.exe" sits, and double-click to execute (this is left up to the user to store the software in a convenient location).

5.2.2.2 Assign a destination directory.

For setting the destination directory within the CuStrip GUI window (see Appendix B), click on the "Browse for Directory" Browse button for "Destination" the top of the window. This selection should be any directory where you would like the reduced data to be placed.

When placed locally, response time for the software package is faster, and thus data reduction will complete more quickly. For each test folder analyzed, the GUI will generate a new folder with the same name as the test folder within the destination directory. All reduced data will be saved within this new folder.

5.2.2.3 Using both the "Source – 160kV AlCu" and "Source – 100kV Al" browse buttons (see Appendix B), form a list of test folders to process.

In order for the GUI to accept a scan directory for processing, both the 160kVAlCu and 100kVAl data must be present.

a. Click on the "Browse for Directory" browse button for 160kV AlCu data. Using this browse window, select the folder directly containing radiographic data files for 160kV AlCu scans of the specimen and references. If the radiographic data files or background file are missing, the selection will throw an error.
b. Click on the "Browse for Directory" browse button for 100kV Al data. Using this browse window, select the folder directly containing radiographic data files for 160kV AlCu scans of the specimen and references. If the radiographic data files or background file are missing, the selection will throw an error.
c. Ensure that the strip height and width values are correct in the text boxes within the GUI (see Appendix B). For Tyndall data, use 60 for width and 7 for height. For LLNL and TSL data, use 80 for width and 7 for height.
d. Ensure that the lab selection is correct. Each lab has its copper strip placed in a different (but consistent) location, which requires different subroutines for extraction of the copper strip area during analysis.

Once all of these selections are made, click on the “Add Directory” button to add the folders to the data reduction listbox (see Appendix B). In the list, this will show up as: “**lab**: **specimen_W**x**H,**” representing the **lab** the data is from, the name of the **specimen** being analyzed, and the width (**W**) and height (**H**) of the copper strip region. Make sure that all values are correct.

If a test has been added that the user does not wish to process, that test may be selected in the data reduction listbox and removed by clicking **Remove**. Currently, any test can be represented only once in the processing list.

5.2.2.4 Click the **Run** button (see Appendix B) in the GUI to begin data analysis. Upon completion, the reduction process will post the message “Data reduction for all materials is complete” (the run time averages between 15−20 minutes per test on an Intel Xeon 2.67-GHz PC).

Notes *The data reduction process saves results in a file structure that mirrors the input format: a folder is generated with the same name as the test folder (which generally includes the name of the specimen and date of data acquisition) within the destination directory. Within this results folder, an experiment folder with the name format "Exp#" is generated for each experiment run. A summary statistics excel file (.xlsx) is saved within the results folder with copper strip mean values for each radiographic projection, along with another aggregate statistics excel file.*

There are two data formats for saved data during the data analysis process: Matlab-compatible .mat files, and ASCII text. The data files saved are:

1. *ASCII text files are formatted with one line per radiographic projection. The ASCII line includes the radiographic projection number and copper strip mean value, in that order. The radiographic projection numbers are integer values, while the mean values are stored as floating-point format. All numeric values on each ASCII line are separated by spaces (data is space-delimited). These files are not critical to the automated Matlab code analysis process.*

2. *Matlab files for saved data contain 2-dimensional arrays representing the copper strip regions from each radiographic projection and from the background projection. These are saved in a subdirectory named by copper strip dimensions (Example: “60x7”) within each experiment directory. There is one file saved for every radiographic projection analyzed. Each data file contains an extracted copper strip region used in the analysis calculations.*

5.3 Quality Assurance

5.3.1 Inspection of Radiographic Data

5.3.1.1 Upon completion of scanning and processing a set of data, the CuStrip GUI will generate an image of radiographic projection ***specimen***_0.sdt, with the copper strip and postage stamp regions highlighted (see Figure B-3 in Appendix B). There should be one image for each energy level. Check the images to make sure that the copper strip is properly centered to within visual sensitivity, and the postage stamp is properly located on the upper slit next to the copper strip region. If the copper strip regions are not properly placed, check that the settings used to run the data are correct, or notify the technical lead.

5.3.1.2 Inside the analysis folder where the results are saved, open the spreadsheet containing statistics. Add the following data points to current copper strip QA spreadsheet plots: (1) 100kV lower slit mean attenuation versus 100kV lower to upper mean ratio, (2) 160kV lower slit mean attenuation versus 160kV lower to upper mean ratio, and (3) 160kV lower slit mean attenuation versus 100kV lower slit mean attenuation. Be sure that the specimen name is clearly marked for these plot points.

5.3.1.3 For each plot, check the location of the current sample relative to established QA boundary regions. If any of the plots is out of bounds, contact the technical lead.

5.3.2 Computation of QA boundaries

5.3.2.1 Computation of QA boundary regions for each of the three types of plots is done according to the specifications provided in [5] for computing a tolerance interval with both upper and lower limits, using parameters of 0.95 **proportion** and 0.95 **confidence**.

5.3.2.2 The QA boundary regions shall be recomputed whenever the hardware of the MicroCT undergoes any known change in configuration, or at the discretion of the technical lead.

5.3.2.3 In the event that QA boundary regions must be recomputed, consult with the principal investigator or his designee to determine the set of data points to be used to compute new QA boundaries.

5.4 Summarizing Results

5.4.1 Generate Excel Spreadsheet

5.4.1.1 The Matlab GUI generates an excel file with the reduced data displayed in Sheets 1 through 3, and renames these sheets ‘Lower Slit,’ ‘Upper Slit’ and ‘Ratio’.

5.4.2 Archive the Results on the Server

5.4.2.1 Create a subdirectory in the *Analyses* subdirectory for the specimen with the name

a#a#_miscID_acqdate_custrip_**INIT_date**

where **a#a#** is the specimen name, **acqdate** is the date of data acquisition in the form yymmdd, **miscID** is any other identifying information that might be available (such as batch number, set number if there were multiple data sets taken in a day, etc.), **INIT** are the initials of the person who analyzed the data, and **date** is the date the analysis took place.

5.4.2.2 Copy everything generated during the analysis (including the directory structure and Excel spreadsheets) into this subdirectory. Refer to the LEDP Records Management QIP [6] for responsibilities in the handling of generated data.

5.5 Post-Procedure Checks and Notifications

5.5.1.1 Notify the LEDP Records Librarian that the data are available for archival. Copy the LEDP Technical Leads, PI, Deputy Project Leader, and others as requested on the notification.

5.5.1.2 Contact the team member responsible for writing of reports once analyzed data are available on the server.

6.0 Records

Analysis results generated from this SOP shall be managed per the LEDP Document Management QIP [7] and the LEDP Project Data Management Plan [8].

7.0 Review Interval

This SOP shall be called for periodic review at an interval not to exceed 1 year from its issue.

8.0 Document Revision History

Date	Revision	Author	Responsible Manager	Comments
2/14/2011	0	Isaac Seetho	Bill Brown	
8/13/2012	0	Isaac Seetho	Harry Martz	Updated to address comments
10/22/2012	0	Isaac Seetho	W. Travis White, III	Updated to address comments

9.0 References

1. *MicroCT: Acquisition of CT Data of Home Made Explosive Matierials*, LEDP Standard Operating Procedure, IDD-MCT-SOP-003, latest revision.
2. Isaac Seetho, *MicroCT: Analysis of CT Reconstructed Data of Home Made Explosive Materials Using the Matlab MicroCT Analysis GUI*, Lawrence Livermore National Laboratory, IDD-MCT-SOP-007, January 13, 2011.
3. Lawrence Livermore National Laboratory, “IDD Quality Assurance Plan for MicroCT Scanning,” IDD-MCT-QAP, latest revision, LLNL-AM-463479.
4. Jerel A. Smith, Daniel J. Schneberk, Jeffrey S. Kallman, Harry E. Martz, Jr., David Hoey, *Documentation of the LLNL and Tyndall Micro-Computed-Tomography Systems*, Version 091216, Lawrence Livermore National Laboratory, LLNL-TR-421377, December 17, 2009
5. “Tolerance Intervals for a Normal Distribution,” 2007, NIST Engineering Statistics Handbook, NIST, 10 January 2012, <http://www.itl.nist.gov/div898/handbook/prc/section2/prc263.htm>.
6. *Records Management*, LEDP Quality Implementing Procedure, IDD-QIP-002, latest revision.
7. *Document Management*, LEDP Quality Implementing Procedure, IDD-QIP-001, latest revision.
8. *IDD Data Management Plan*, IDD-DAMA-Plan, latest revision.

Appendix A: Automated CuStrip Analysis GUI File Structure

In **source code** form, the Automated CuStrip Analysis GUI contains three types of Matlab files:

- **GUIDE Figure Files** (*custrip_gui_dlg.fig*)

  These files are generated automatically by the GUIDE GUI development toolbox within Matlab. These files specify graphical user interface layout and assign labels and types to all GUI elements. One file is required for each corresponding GUI window.

- **Dialog Box Control Files** (*custrip_gui_dlg.m*)

  These files are used to specify GUI functionality by supplying code connecting each GUI element with the corresponding callback functions.

- **Function Definition Files** (*custrip_gui_split.m, custrip_xls_gui.m*)

  These files contain functional definitions for all Matlab callback functions, and define the state variables stored by the corresponding GUIs.

In **executable** form, the Automated CuStrip Analysis GUI contains the following file:

- ***CuStripGUI_1.0.exe***

  This is the main executable, which will run the Automated CuStrip Analysis GUI.

Appendix B: GUI Operation and Capabilities

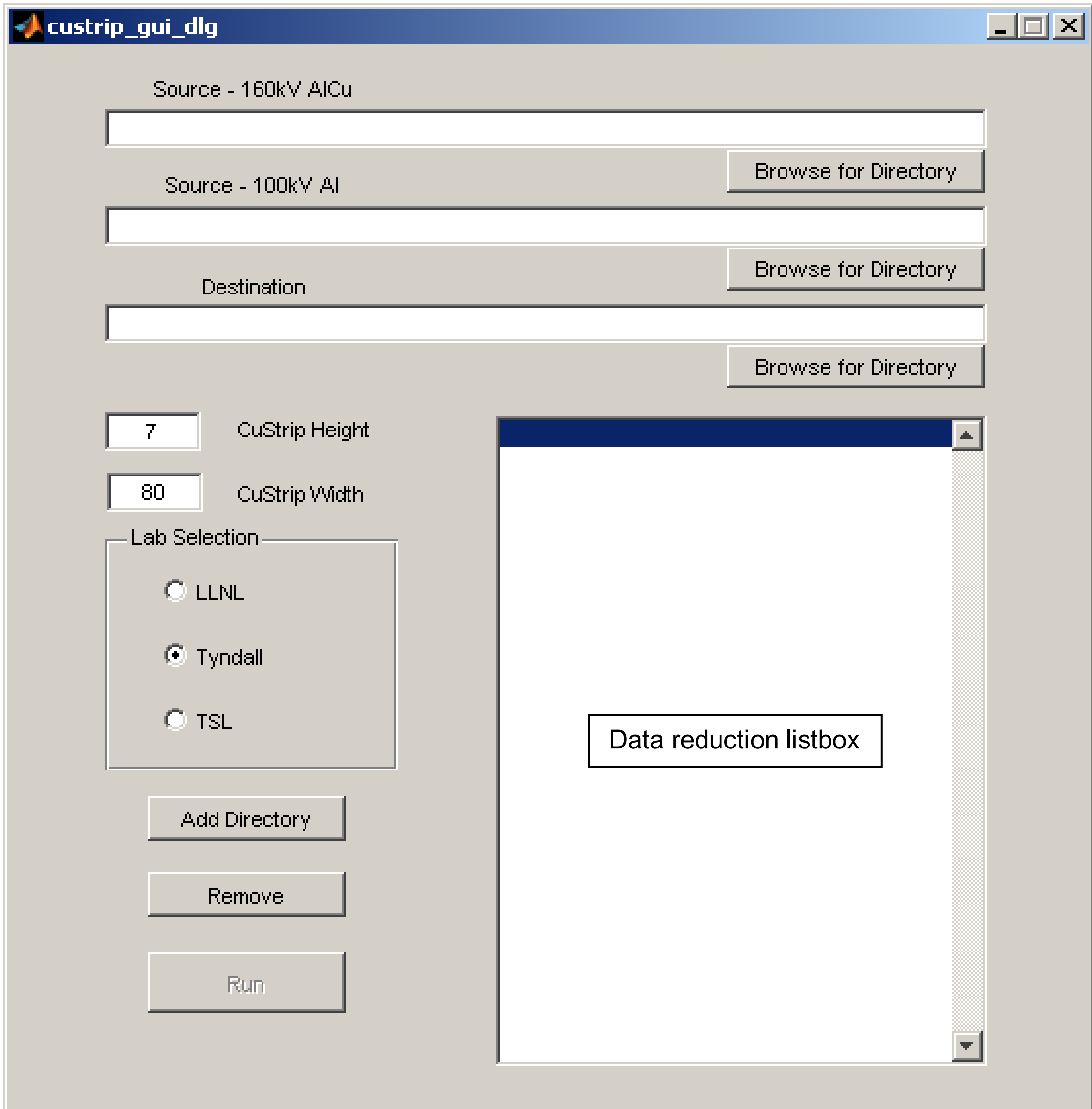

Figure B-1. Initial graphical user interface of the Automated CuStrip Analysis program.

Main Automated CuStrip Analysis GUI Window

The main window of the Automated CuStrip Analysis GUI contains the following fields and functions:

- **Browse for Directory (Source - 160kV AlCu).** Clicking on this Browse button will bring up a browse window (see Fig. B-2) allowing the user to set a directory to scan for an appropriate set of radiographic data files. The GUI assumes the directory is valid if both ***specimen****_0.sdt* and ***specimen****bak.sdt* are present, where ***specimen*** is the specimen name. If the directory does not exist, the edit box will revert to its last valid value (includes the empty string). At this point, the GUI does not check that any .sdt files are specifically for 160kV AlCu data – it is up to the user to ensure the correct directory is chosen.

- **Browse for Directory (Source - 100kV Al).** Clicking on this Browse button will bring up a browse window (see Fig. B-2) allowing the user to set a directory to scan for an appropriate set of radiographic data files. The GUI assumes the directory is valid if both ***specimen**_0.sdt* and ***specimen**bak.sdt* are present, where ***specimen*** is the specimen name. If the directory does not exist, the edit box will revert to its last valid value (includes the empty string). At this point, the GUI does not check that any .sdt files are specifically for 100kV Al data – it is up to the user to ensure the correct directory is chosen.
- **Browse for Directory (Destination).** Clicking on this Browse button will bring up a browse window (see Fig. B-2) allowing the user to set the destination directory for saved data. The program generates a new subdirectory within the destination directory for each test reduced (named to match the specimen name) and saves files in the format identified in section 5.2.2 of this SOP. Alternatively, the user can edit the text in the accompanying edit box manually. Any manually entered directory will be checked for existence. If the directory does not exist, the edit box will revert to its last valid value (includes the empty string).
- **Lab Selection Radio Buttons.** These buttons allow the user to specify which lab the scans are from. Depending on where the data was scanned, the GUI will look in a different region of each radiographic projection for the copper strip.
- **Data Reduction Height & Width Edit Boxes**. These editable text boxes allow the user to specify the width and height of the copper strip region to extract from each radiographic projection during the analysis process. For LLNL and TSL data, the width should be 80. For Tyndall data, the width should be 60. For all labs, the height should be 7. The values used are recorded as subdirectory names as identified in section 5.2.2 of this SOP.
- **Data Reduction Listbox.** If the user has added specimens to be analyzed through the data reduction process, they will be displayed in this listbox.
- **Add Directory.** Clicking on the **Add Directory** button once the source directories are both specified will add the selected test to the “Data Reduction Listbox.” Data to be analyzed are displayed in the “Data Reduction Listbox” in the format: **Lab**: **specimen_W**x**H**, where **W** and **H** correspond to width and height of the copper strip region to be extracted, **Lab** indicates the lab where the data were taken, and **specimen** is the specimen name.
- **Remove.** Clicking on a specimen in the “Data Reduction Listbox,” and then clicking the **Remove** button will remove the selected specimen from the “Data Reduction Listbox,” removing it from the list of data to be analyzed.

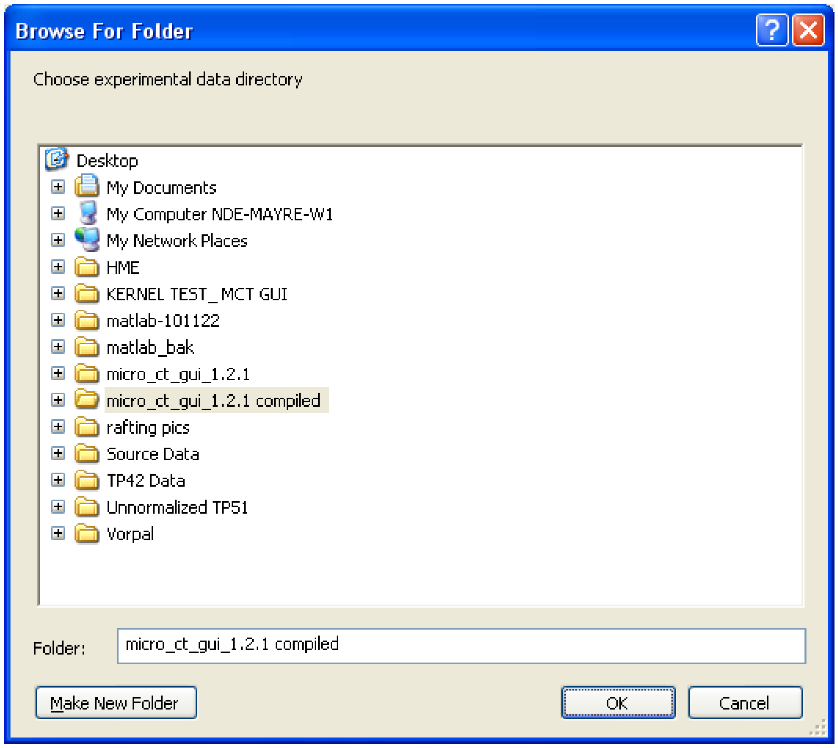

Figure B-2. The dialog box that appears whenever a Browse button is selected.

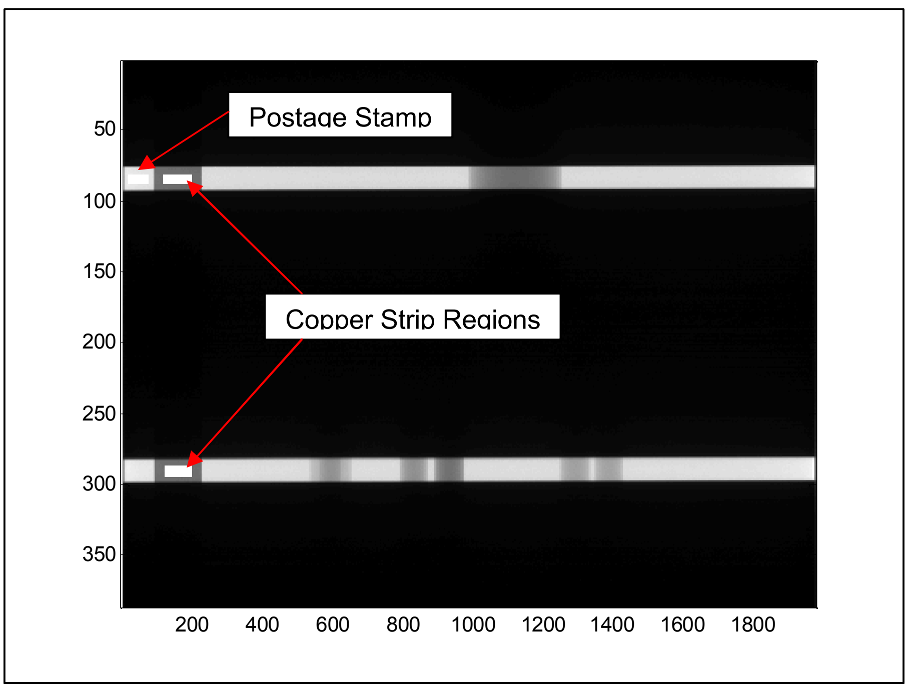

Figure B-3. Example output image of the Copper Strip analysis GUI analyzing LLNL data. White regions mark the copper strip and postage stamp regions.

Appendix C: CuStrip Data Reduction Algorithm Overview

The CuStrip Matlab GUI operates on linearized (calibrated) radiographic data files, and generates statistics from MicroCT scans as follows:

For each series of interest (160kV AlCu and 100kV Al), the GUI loads the file tagged as projection 0 from the series. Within this file, the row locations of the upper and lower slits are determined by summing up the values over each row, and finding the contiguous regions with row sums higher than half of the maximum value. There should be exactly two contiguous sets of rows that pass this threshold, one corresponding to the lower slit and one corresponding to the upper slit.

Depending on the lab at which a set of radiographic data files was scanned, the GUI then proceeds to locate the copper strip within a preset region of columns. At TSL, the copper strip Is located at the right edge of the projection image. At Tyndall, the copper strip is located at the left edge of the projection image. At LLNL, the copper strip is located within the first 200 columns.

The left and right boundaries of the copper strip region are determined through the use of gradient methods, since attenuation inside of the strip region is much lower than to the left or right of the strip, where there is no obstruction between the source and detector.

Once the strip has been localized, its midpoint is determined and a rectangular ***W***x***H*** region is extracted from the middle of the strip region, where **W** indicates width (columns), and **H** indicates height (rows). For LLNL and TSL, 80x7 is used. For TAFRL, 60x7 is used.

In order to account for variability in the output of the source due to flux or current, a "postage stamp" region is also extracted. The coordinates of this region are determined by performing the same kind of row centering described above, on the upper strip. At LLNL, the postage stamp region is centered between the end of the copper strip region and the left edge of the projection image. For TSL, the postage stamp region begins 50 pixels to the left of the copper strip region. For Tyndall data, the postage stamp begins 50 pixels to the right of the copper strip region. For all three labs, the postage stamp size is 59x7.

The data are converted into attenuation values using the following formula:

$LAC(x,y) = ln(I_o(x,y)/[I_n(x,y)*A_o/A_n])$, where the subscript "*o*" denotes data are taken from the background file ***specimen****bak.sdt*, the subscript "*n*" denotes data are taken from numbered radiographic projection data files ***specimen_#****.sdt* (where **specimen** is the specimen name and **#** is the radiographic projection number between 0 and 399), "*A*" denotes postage stamp average value, and "*I(x,y)*" denotes pixel value at image coordinates (x,y).

From these LAC values, statistics such as mean, standard deviation, and low-to-high energy mean ratio per radiographic projection are obtained and saved in Matlab data files (.mat format). Mean value statistics are also saved in a summary spreadsheet named *Custrip_**specimen**_W**W**xH**H**.xls*, where **specimen** indicates the specimen name, **W** is the number of columns of the region of interest in the copper strip, and **H** is the number of rows of the region of interest.