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Structural Integrity Assessments Modular – Probabilistic Fracture Mechanics
SIAM-PFM: User's Guide for xLPR

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ABSTRACT

This document provides an overview of the software structure and user instructions for the Structural Integrity Assessments Modular – Extremely Low Probability of Rupture (SIAM-xLPR) software tool under development at the Oak Ridge National Laboratory (ORNL), which supports the Nuclear Regulatory Commission's initiative for a new piping system assessment methodology. The new methodology will provide a tool for demonstrating compliance with the regulatory requirement that primary power plants water piping systems exhibit an extremely low probability of rupture (xLPR). SIAM-xLPR is a modular-based assessment tool that incorporates a prototype xLPR model assembled from new and existing fracture mechanics models and software. xLPR represents one of the four subsystems currently installed in the ORNL-developed SIAM Problem-solving Environment. The prototype SIAM-xLPR models and software modules are linked within a probabilistic framework fully developed using open-source languages and software libraries.

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ABBREVIATIONS

BWR	Boiling Water Reactor
DISFRAC	Dislocation-Based Fracture Model
EMC2	Engineering Mechanics Corporation of Columbus
EPFM	Elastic Plastic Fracture Mechanics
EPRI	Electric Power Research Institute
FAVOR	Fracture Analysis of Vessels – Oak Ridge
GUI	Graphic User Interface
ISI	In-Service Inspection
LBB	Leak-Before-Break
LEFM	Linear-Elastic Fracture Mechanics
LOCA	Loss-of-Coolant Accident
NPP	Nuclear Power Plant
US NRC	United States Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PFM	Probabilistic Fracture Mechanics
PNNL	Pacific Northwest National Laboratory
POND	Probability of Non-Detection
PRA	Probabilistic Risk Assessment
PRAISE	Piping Reliability Analysis Including Seismic Events
PTS	Pressurized Thermal Shock
PWR	Pressurized Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
RPV	Reactor Pressure Vessel
SC	Surface Crack
SCC	Stress Corrosion Crack
SCM	Software Configuration Management
SIAM-PFM	Structural Integrity Assessments Modular-Probabilistic Fracture Mechanics
SIAM-xLPR	the xLPR application as implemented into SIAM-PFM
SNL	Sandia National Laboratories
SRP	Standard Review Plan
SSE	Safe Shutdown Earthquake

TWC	Through-Wall Crack
xLPR	Extremely Low Probability of Rupture
WRS	Weld Residual Stress

1. Introduction

As described in Ref. 1, the U.S. Nuclear Regulatory Commission (USNRC) is working cooperatively with the nuclear industry to develop a new, modular-based, tool that incorporates a comprehensive assessment methodology for demonstrating compliance with regulatory requirements regarding primary piping systems in nuclear power plants. Specifically, that compliance is focused on the requirement of Title 10 Code of Federal Regulations, Part 50 (10CFR50), Appendix A, GDC-4 [2], that primary system pressure piping must exhibit an extremely low probability of rupture. The new tool, designated as xLPR (E**x**tremely **L**ow **P**robability of **R**upture), is being designed to numerically model the effects of the degradation mechanisms that are active in the system, as well as the relevant mitigation activities and the inevitable uncertainties associated with complex systems. The new initiative is a multi-year project, with an initial emphasis on methods and approaches for addressing the degradation mechanism of Primary Water Stress Corrosion Cracking (PWSCC) in the context of an assessment tool built on a modular-based framework.

To determine an appropriate architecture for such a modular-based system, the participants in this collaborative project are pursuing a pilot case study [3] that utilizes a prototype xLPR model [4]. That model draws upon new and existing fracture mechanics models and software modules that are linked within a probabilistic framework. The specific application of the prototype model in the pilot study is to assess the mechanism of PWSCC that is active in a pressurizer surge nozzle. Future development will extend the scope of xLPR to all primary piping systems in pressurized and boiling water reactors.

An important feature of this pilot study is the construction, in parallel activities, of two prototype xLPR assessment tools by two of the collaborating organizations. One of the prototype tools is based on a commercial software (i.e., GoldSim) framework, while the second tool under development at the Oak Ridge National Laboratory (ORNL) (i.e., Structural Integrity Assessments Modular- xLPR SIAM-xLPR) is strictly utilizing open-source software. These dual developments (and applications) will permit the project to assess advantages and disadvantages of each approach to the construction of a modular framework.

Below, the SIAM-PFM Problem-Solving Environment [5], in which SIAM-xLPR resides, is briefly described; the remainder of the manual provides an overview of the structure/user instructions for the SIAM-xLPR software tool.

1.1 The SIAM-PFM Problem-Solving Environment

The SIAM-PFM Framework [5] is a problem-solving environment being developed at Oak Ridge National Laboratory (ORNL) for the NRC. The acronym SIAM-PFM (or just SIAM for short) stands for Structural Integrity Assessments Modular – Probabilistic Fracture Mechanics. SIAM-PFM is intended to be an application framework within which a wide range of nuclear power plant safety issues can be addressed in a systematic and consistent way by using modern principles of probabilistic risk assessment. Probability techniques are applied to problems in fracture mechanics in order to predict fracture behavior and thus to assess the structural integrity of a variety of nuclear power-plant components that passively bear intense pressures over long periods of time. This new platform is intended to be readily extensible to different problem classes with the level and methods of user interaction to be determined by discussions with the U. S. Nuclear Regulatory Commission (NRC) and potential stake holders. A common feature of the different applications within SIAM-PFM will be that they are all the subjects of probabilistic risk assessment and will, therefore, represent "risk-informed" analyses.

At present, SIAM-PFM contains four applications; three have been developed at ORNL and one was developed elsewhere, as noted below. All of the modules can be operated independently as stand-alone applications, or they can be operated within the SIAM-PFM framework. The four modules include the following:

- **FAVOR – Fracture Analysis of Vessels Oak Ridge** . FAVOR **[6-7]** is a safety assessment tool for analyzing the effects of pressure and temperature loading due to normal and accident conditions on commercial nuclear reactor pressure vessels (RPVs). The FAVOR code, developed at ORNL for the U.S. Nuclear Regulatory Commission (NRC), addresses the potential for failure by through-wall cracking of the RPV wall when the vessel beltline is exposed to thermal-hydraulic transients, such as pressurized-thermal-shock (PTS) events, at specific points in time in the plant's operational history. Making use of finite element techniques and modern probabilistic risk assessment (PRA) methodologies, FAVOR calculates estimates for the probability of through-wall cracking of a nuclear reactor vessel due to pre-existing flaws in the wall of the vessel.
- **DISFRAC – Dislocation-Based Fracture Model with Extensions to Cleavage Initiation in Ferritic Steels**. DISFRAC is an implementation in code of a theoretical, multi-scale model currently under development for the prediction of fracture toughness of ferritic steels in the transition temperature region. The model accounts for temperature, irradiation, strain rate, and material condition (chemistry and heat treatment) effects. DISFRAC permits fracture safety assessments of ferritic structures with only tensile properties required as input.

- **PRAISE – Piping Reliability Analysis Including Seismic Events**. PRAISE, v04.2, [8,9] evaluates the reliability of welds in nuclear power plant piping systems. The PRAISE code was originally developed to provide a technical basis for the NRC to determine whether it could relax its requirements on the combination of a safe shutdown earthquake (SSE) event and a large loss-of-coolant accident (LOCA) for power plant piping components. In addition, PRAISE allows for an estimation not only of the probability of the simultaneous occurrence of a large LOCA and an earthquake, but also of the probability of a large LOCA caused by normal and abnormal loading without an earthquake. The original development of PRAISE provided a probabilistic treatment of the growth of crack-like weld defects in piping due to cyclic loading. This treatment of fatigue-crack growth was later expanded to include the initiation and growth of stress corrosion cracks (SCCs) found in boiling water reactors (BWRs). Additional development for PRAISE, v04.2 [9], expanded the capabilities of the code to include a probabilistic treatment of fatigue-crack initiation.
- **xLPR –** E**x**tremely **L**ow **P**robability of **R**upture, the subject of this user's guide, is the latest addition to the SIAM-PFM suite**.** SIAM-XLPR will refer herein to the xLPR application as implemented into SIAM-PFM.

1.2 The xLPR Model

xLPR is a methodology for assessing the integrity of nuclear power plant piping systems. xLPR's goal is to demonstrate a system's compliance with the NRC Standard Review Plan (SRP) 3.6.3 and Leak-Before-Break (LBB) assessment procedure. Specifically, xLPR aims to demonstrate compliance with the 10CFR50 Appendix A, GDC-4 [2] requirement, which states that primary pressure piping systems must exhibit an extremely low probability of rupture.

xLPR is being implemented as a software tool that predicts how nuclear power plant piping systems degrade over time; it also models the uncertainties or probabilities of degradation and predicts the probable effects of mitigation efforts on the system. The implementation that ORNL presents in this manual corresponds to the v1.0 version, which concentrates on the initiation and growth of primary water stress corrosion cracks (PWSCC) in a dissimilar metal pressurizer surge nozzle weld (see Fig. 1). Hence, the degradation mechanism and materials are fixed, but the operating conditions, pipe geometry, weld residual stress characterization, mitigation effects, material properties, and uncertainty characterizations of the inputs to the model can be modified by the user.

Fig. 2 presents the basic flow of xLPR. Both epistemic and aleatory trial records are sampled according to pre-defined parameters related to load, leaks, and crack initiation. The term "epistemic" uncertainties refer to uncertainties that reflect a lack of knowledge; i.e. the information is not present or available, but in principle could be acquired with enough study or expert judgment. "Aleatory" uncertainties refer to uncertainties that cannot be determined or resolved. The green block at the center of Fig. 2 represents the core of the execution: the "Execute Time Loop" module. The Time Loop module executes the trials for each new set of variables.

The details of the Execute Time Loop flow are depicted in Fig. 3, which presents a sequence of modules that model the crack progression in piping systems: crack initiation, crack growth, degree of crack stability, and leakage. The figure also shows the progression of mitigation efforts: inspection, detection, and mitigation of PWSCCs. During each time step the number of active cracks is determined, and the decision is made whether inspection and/or mitigation will be performed. If any crack has initiated within a given time step, its location is identified. If coalescence or merging with another crack or cracks is detected, the new combined crack's size and location are also determined. All new cracks initiate as internal surface cracks (SCs). Over time they may grow through the wall of the pipe and transition to through-wall cracks (TWCs). In the case of TWCS, the crack-opening displacement and the leakage rate are calculated. TWCs can be detected by this system when the leakage rate is larger than a user-specified LOCA leakage rate; the system also records the predicted time of the failure. For those cracks identified as surface cracks, the system calculates the Probability of Non-Detection (POND), and completes the current time step.

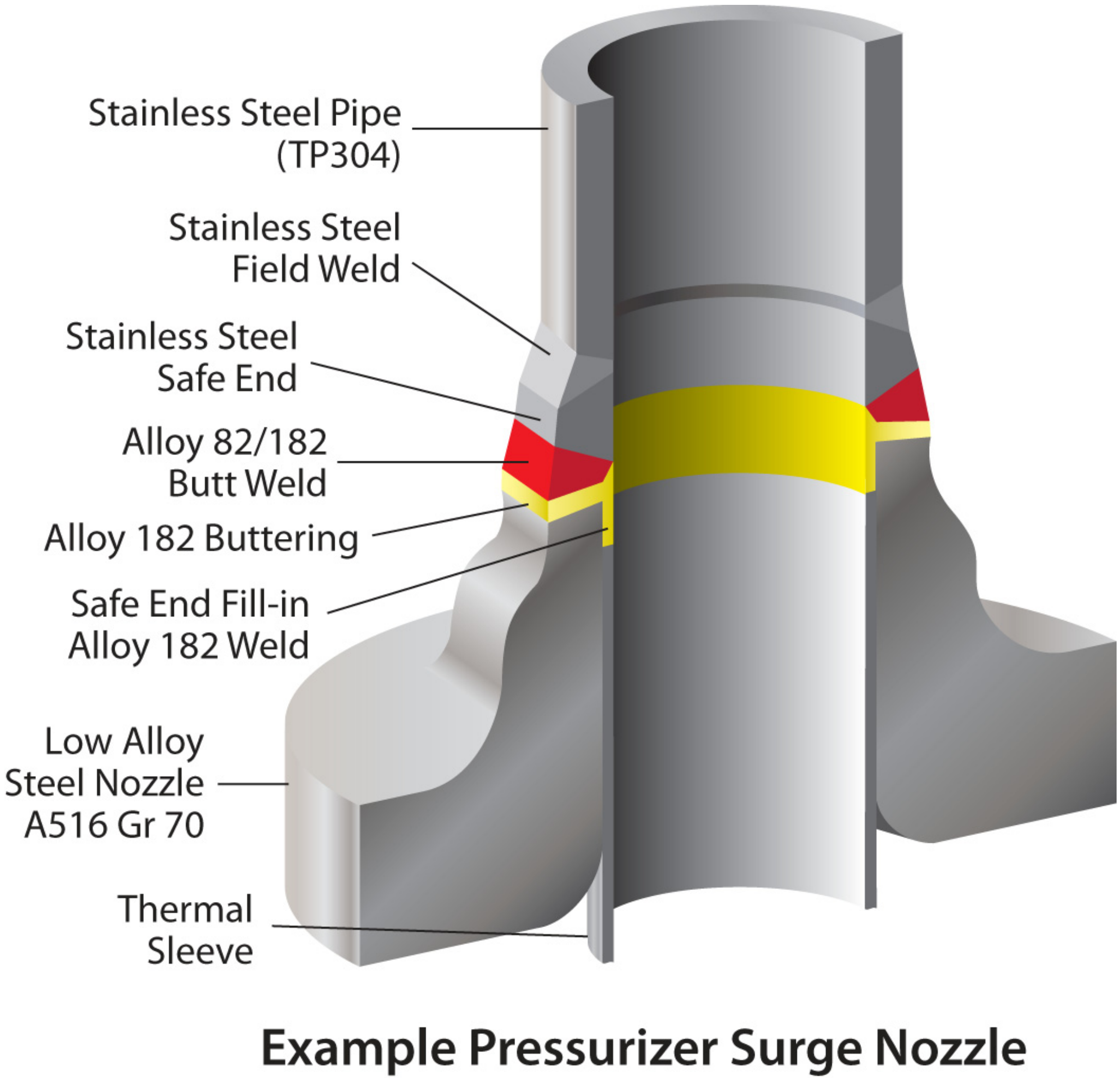


Fig. 1 Dissimilar metal pressurizer surge nozzle weld geometry schematic.

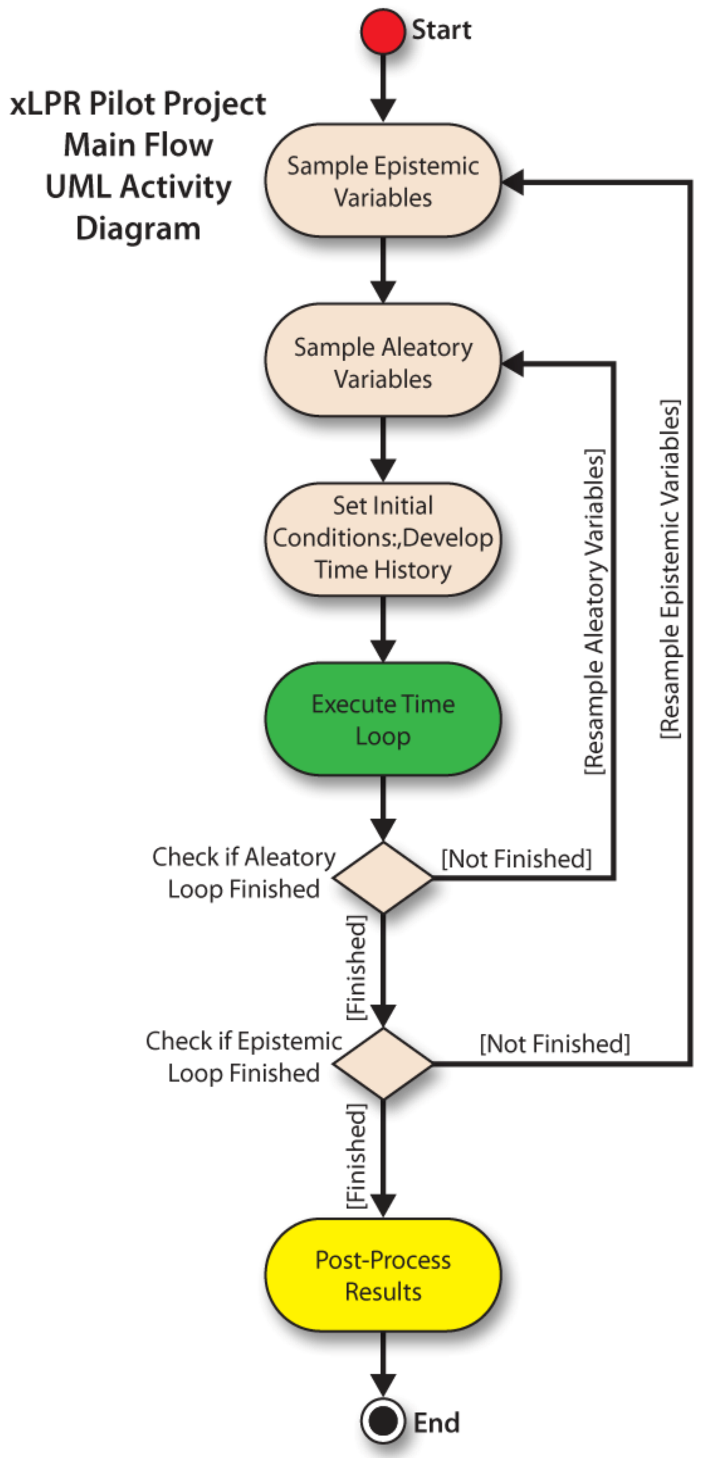


Fig. 2 xLPR's High-Level Execution Flow.

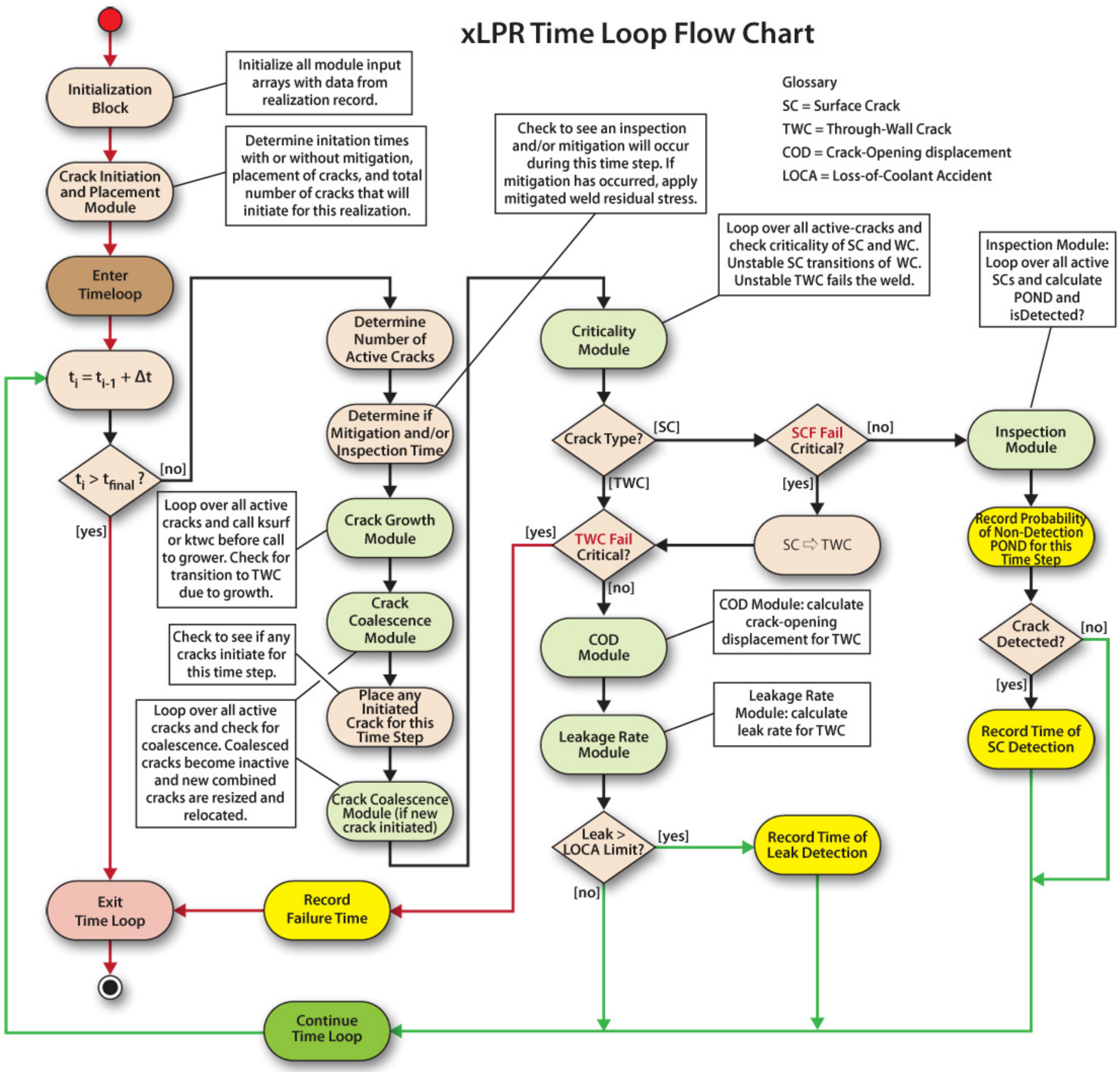


Fig. 3 xLPR's Time Loop Execution Diagram.

1.3 Scope – How This Manual Is Organized

This user's manual is organized as follows: first, the hardware and software requirements to run the SIAM-PFM xLPR application are presented. Second, the reader is introduced to the basics of using SIAM-PFM and the creation of new projects and the opening of existing projects. Then, the graphical user interface (GUI) of SIAM-xLPR is explained to familiarize the reader with how to use and modify the input data to the xLPR model. After that, instructions are given for running the application and analyzing the results. Finally, we present the reference list, and two appendixes: one for the installation instructions and another one with the list of input parameters, descriptions and references.

2. Getting Started

A few requirements need to be satisfied before the SIAM-xLPR stand-alone application can be installed and run. In this section, SIAM-xLPR's hardware and software requirements are presented and the steps for installing and starting the program are outlined. Finally, we explain how to create new SIAM projects and open existing ones.

2.1 Hardware Requirements

To install SIAM-xLPR, the target computer must have at least the following available memory and free hard-drive space:

- 2 Gbytes of available RAM (above that used by the operating system) to run the probabilistic base case in SIAM-xLPR. Additional RAM is required to run larger cases.
- 250 Mbytes of free hard-drive space for SIAM-xLPR
- 350 Mbytes of free hard-drive space for Python 2.6 and its 3rd party packages
- 1.5 Gbytes of free hard-drive space for the SIAM-xLPR workspace to hold project data. This requirement will depend on how many individual projects and cases have been created by the user.
- To be able to navigate through the GUI, the minimum resolution requirements of the display is 1200x800 pixels.

2.2 Software Requirements

To install SIAM-xLPR, the target computer must be running one of the following 32 or 64 bit Microsoft Windows operating systems: Windows XP, Windows Vista, or Windows 7. Deployment packages are still under development for executing SIAM-PFM under Linux, Unix, and Mac OSX operating systems.

2.3 Installing SIAM-xLPR on Windows OS Computers

SIAM-xLPR follows standard Windows installation procedures:

1. Download the three binary Windows installer files: (1) SIAM_XLPR_<version>.exe, (2) SIAM_Dependencies1.exe, and (3) SIAM_Dependencies2.exe.

2. Follow the detailed instructions given in Appendix A of this report.

3. An icon with the name SIAM_XLPR_<version> will appear on your desktop and in your "All Programs" Menu.

2.4 Uninstalling SIAM-xLPR

In the Windows Operating System Start Menu, look for the folder called 'Oak Ridge National Laboratory'. There, you will find the sub-folder 'SIAM_xLPR_<version>'. Within it, you will find shortcuts to 'Uninstall' as well a shortcut to start the application. Users can go through this route as a shortcut and to avoid going to the Control Panel to uninstall the application.

2.5 Starting SIAM-xLPR from Your Desktop

To start SIAM-xLPR, click the SIAM_XLPR_<version> icon on your desktop. The window shown in Fig. 4 will appear.

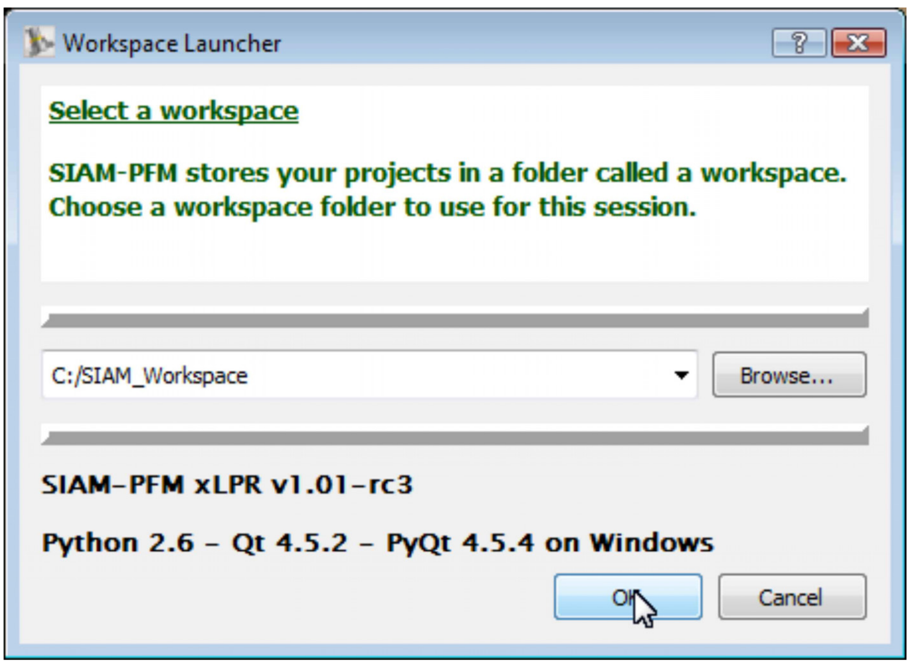


Fig. 4 Selecting a workspace.

2.6 Setting Your Workspace

SIAM-PFM stores your projects in a folder called a workspace. When starting SIAM-PFM, the dialog in Fig. 4 will prompt you to specify where this workspace folder is located. On the initial startup of the program, this selection will be blank. Click the "Browse…" button and navigate to the area where you wish to store your projects for this session and either select an existing folder or create a new one. On subsequent sessions, the selections that you have made in the past will be available for you to select an existing workspace or to again create a new one. It is important that the user has write privileges for the newly created workspace folder. If in doubt, check with your System Administrator about selecting an appropriate location on your file system. After selecting or creating your workspace, the SIAM-PFM main window will appear as shown in Fig. 5. The main window consists of a menu bar, a tool bar, a Project Explorer window on the left side, a project window on the center-right, and a Python console at the bottom. The Project Explorer (see Fig. 6) provides a view of all of the existing projects currently in your workspace. At any time, you can right-click in the Project Explorer and either refresh the current view or switch to a different workspace.

Fig. 5 The SIAM-PFM problem solving environment.

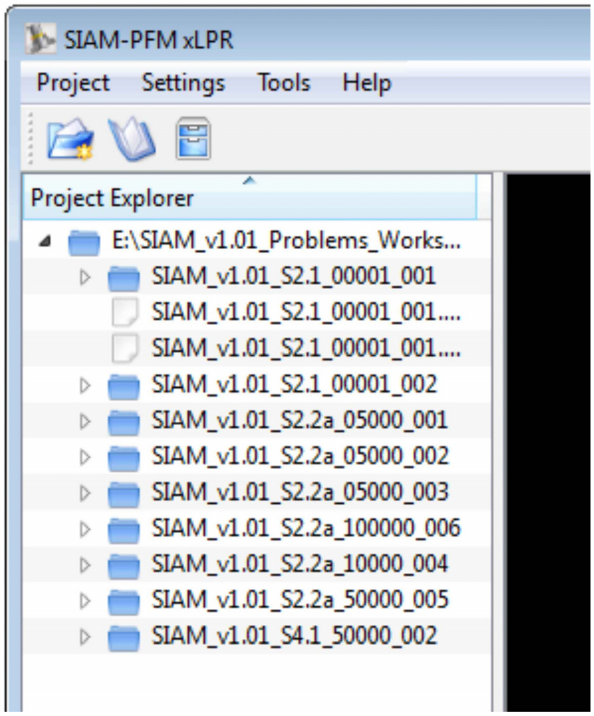


Fig. 6 The Project Explorer panel.

2.7 Creating a New Project

This action can be accomplished by any of the following three actions:

(1) Select "New", from the Project menu,

(2) Click on the "Create a new project" icon in the tool bar, or

(3) Use the "Ctrl+N" keyboard shortcut.

When the "Create new SIAM project" dialog appears (Fig. 7), type in the name of the new project name and click OK.

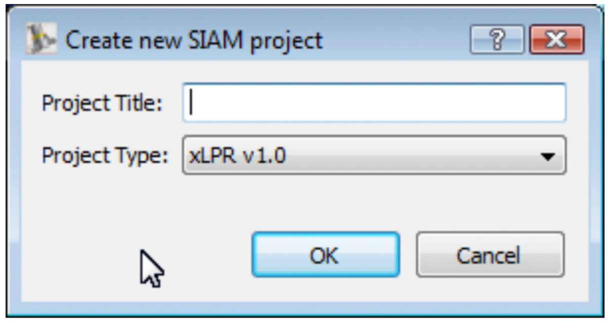


Fig. 7 Creating a new project.

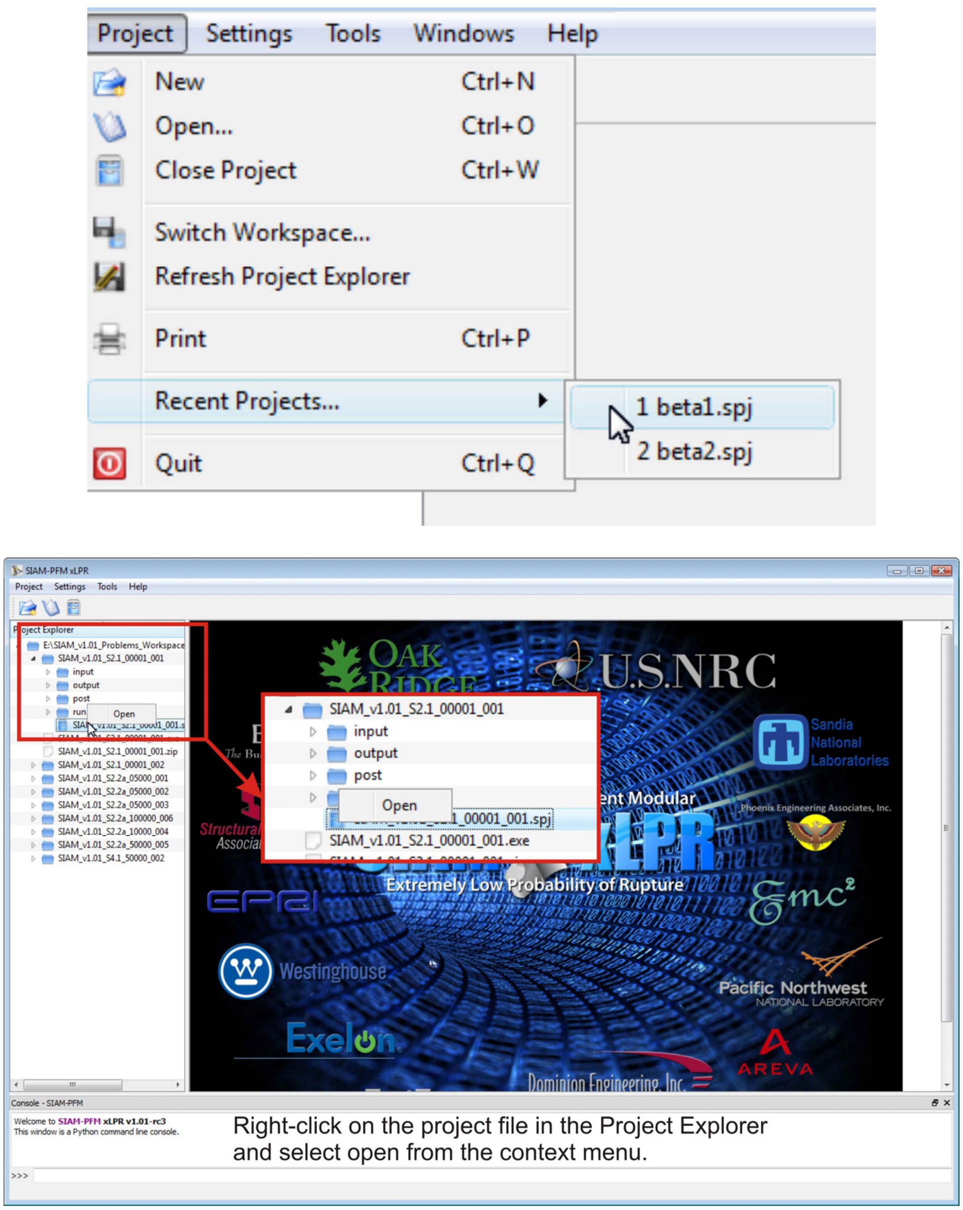


Fig. 8 Opening existing projects.

2.8 Opening an Existing Project

To open an existing project use one of the following methods:

(1) Select “Open…” from the Project menu,

(2) Click on the “Open an existing project” icon on the toolbar,

(3) Use the “Ctrl+O” keyboard shortcut,

(4) Right-click on the project file in the Project Explorer and select “Open” from the context menu (Fig. 8),

(5) Double-click on the project file in the Project Explorer, or

(6) Select a project from the “Recent Projects…” dropdown menu in the Project menu.

When using options 1-5 navigate to the desired project folder in the workspace folder, open the folder and select the project file “<project_name>.spj”.

Note that projects created on older versions of SIAM-xLPR may not be compatible with newer versions and will not be able to function as expected. In this case, users need to create new projects in order to be able to work on the deterministic and probabilistic base cases [10].

3. How SIAM-xLPR Works

This section explains how to use SIAM-xLPR. It will familiarize the user with setting up a case definition, modifying input values, running the application, and viewing the results.

The first task in using SIAM-xLPR is to define the case conditions. The SIAM-xLPR main graphical user interface (GUI) frame has seven tabs (see Fig. 9). Input data can be entered in the first six tabs, in no particular order. Default input values have been provided and can be modified as needed. The last tab displays the SIAM-xLPR Execute Utility window that presents a command line view of the run-through in which realizations are created and executed according to the flows presented in Fig. 2 and Fig. 3. The tabs presented in the main GUI frame include the following:

1. **Problem Setup tab** (Fig. 10): In this tab, users can define values related to the number of aleatory and epistemic realizations, respectively; initial seed values for the random generator number utility [11]; properties related to the plant, such as the expected number of years of operation, time increment for analysis and mitigation schedule; and, properties related to the pipes, such as outer diameter and wall thickness.

2. **Material Properties tab** (Fig. 11): In this tab, users can specify input related to the dissimilar metal weld materials; in this project the materials are: A516 Gr 70, TP 304, and Alloy 182 [3].

3. **Crack Initiation and Growth tab** (Fig. 12): In this tab, users can specify input related to crack-dependent initiation and crack growth properties [12, 13].

4. **Operating, Loading and Mitigation tab** (Fig. 13): In this tab, users can define values related to operating conditions, loading conditions, Normal WRS State and Mitigation WRS state [14].

5. **In-service Inspection (ISI) tab** (Fig. 14): In this tab, users can input data related to probabilities of detection and inspection [15].

6. **Post-processing Options tab**: In this tab, users can define values of the Transformers and Expectation modules [16, 17]. Basically, to post-process output variables to take into account effects from leak rate detection and crack inspection, as well as averaging data for an uncertain variable and estimate statistics (mean values).

7. **Execution tab** (Fig. 22): In this tab, users control the execution of the case as defined in the other tabs, monitor the progress of execution, and view the resulting output files.

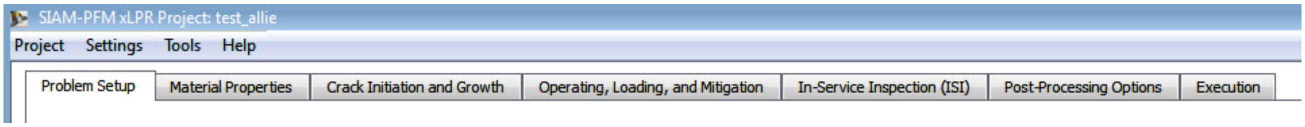


Fig. 9 SIAM-xLPR user interface organization tabs.

3.1 Using and Modifying Input Values

This section explains the purpose of each of the tabs in Fig. 9. A complete list of parameter names, descriptions and references related to each parameter can be found in Appendix B SIAM-xLPR input parameters.

3.1.1 Problem Setup Tab

The Problem Setup tab is designed to allow the user to enter and modify the input data shown in Fig. 10. There are seven main sections: Source of Flaws, Problem Specification- Monte Carlo Setup, Surface Crack Failure Criteria, Through-Wall Crack Failure Criteria, Setup Plant Time Horizon, Time Increment for Analysis, and Mitigation Schedule, Pipe/Weld Geometry and Setup Analysis Methods. Each of these sections' input values are outlined below.

Source of Flaws section: In this version of SIAM-xLPR, PWSCC-initiated source flaws are assumed. Problem Specification- Monte Carlo Setup section: Here, the user specifies how many times the system will run the two nested loops shown in Fig. 2 by entering the number of desired aleatory and epistemic realizations. And the user can specify the seeds for the Random Number Generator [11].

Surface Crack Failure Criteria section: The criterion of surface-crack failure used in this version of SIAM-xLPR is net-section plastic collapse. Through-Wall Crack Failure Criteria section: the criterion applied for through-wall crack failure is net-section collapse or LBB ENG2 elastic plastic fracture mechanics EPFM.

The methodology for net-section collapse of circumferential surface cracks is described in detail in [18]. The LBB.ENG2 estimation method proposed by Brust and Gilles [19] for evaluating the J-integral of cracked tubular members subjected to combined tensile and bending loads is used for assessing the stability of through-wall cracks. In future versions of SIAM-xLPR, it is expected that other types of crack-initiation mechanisms as well as other surface and through-wall crack failure criteria will be specifiable; for the present, however, those sections are disabled.

Setup Plant Time Horizon, Time Increment for Analysis, and Mitigation Schedule section: here the user specifies the number of years that the power plant is expected to operate, i.e. the plant time horizon, and the time at which mitigation actions for the weld under analysis are scheduled to occur; the time step used for time integration, or the time interval used for analysis in each time step in Fig. 3. Pipe/Weld Geometry section: the outer diameter and wall thickness can be specified here. Finally, Setup Analysis Methods section includes entries to specify the COD, initiation and scfail methods.

A complete list of parameter names, descriptions and references related to each parameter can be found in Appendix B SIAM-xLPR input parameters.

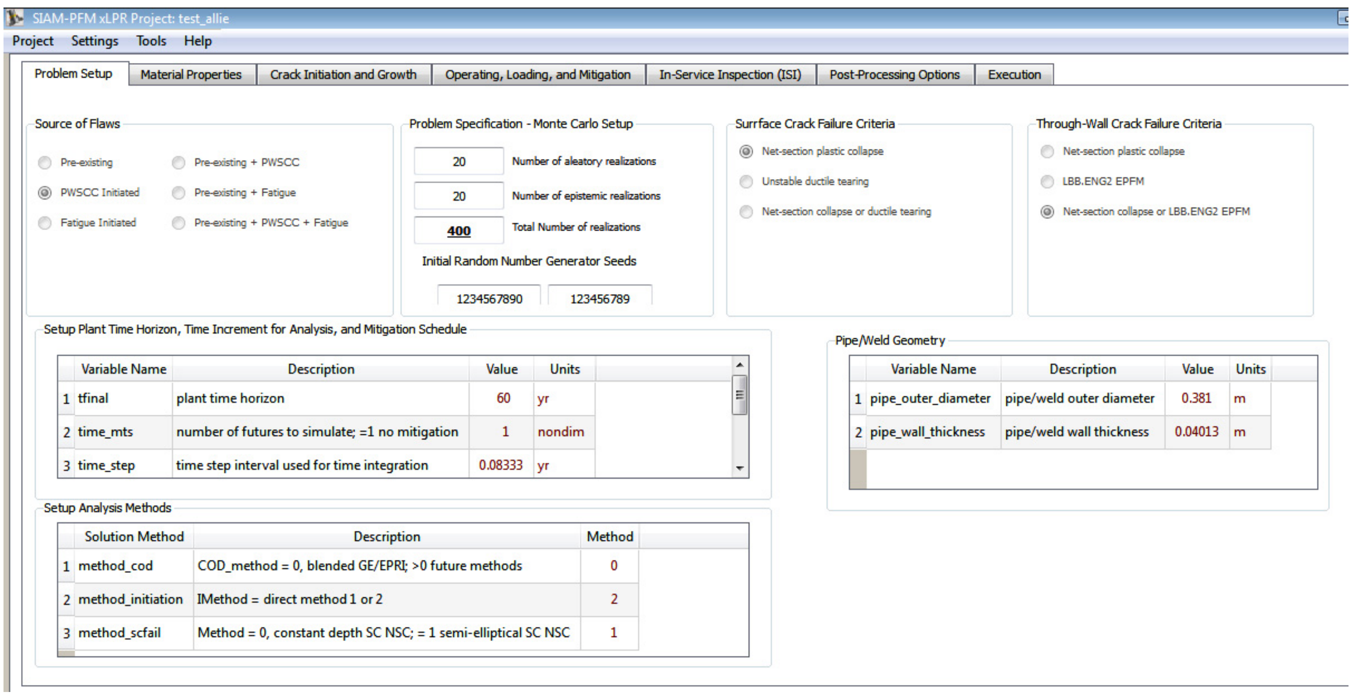


Fig. 10 Problem Setup tab.

3.1.2 Material Properties Tab

The Material Properties Tab (see Fig. 11) is designed to define the values related to materials used in the specific model problem. For the pressurizer surge nozzle weld these materials are A516 Gr 70 ferritic steel, TP 304 stainless steel, and Alloy 182 weld [see Fig. 1]. As can be seen in Fig. 11, the selection of one of the vertical tabs (A516 Gr 70, TP 304 and Alloy 18) displays the properties for the various varieties of that material in a table format. Specified properties include yield strength, ultimate strength, elastic modulus, factor (F) and the exponent (n) for the elastic-plastic Ramberg-Osgood constitutive model; ductile-tearing and PWSCC model properties specifically for the Alloy 182 weld material. The given default values for each material property can be changed by the user. There is a way to get the default values back if the user changes his/her mind after they have been changed; by pressing the 'Reset to defaults' button underneath the tabs section (see Fig. 21).

A complete list of parameter names, descriptions and references related to each parameter can be found in Appendix B.

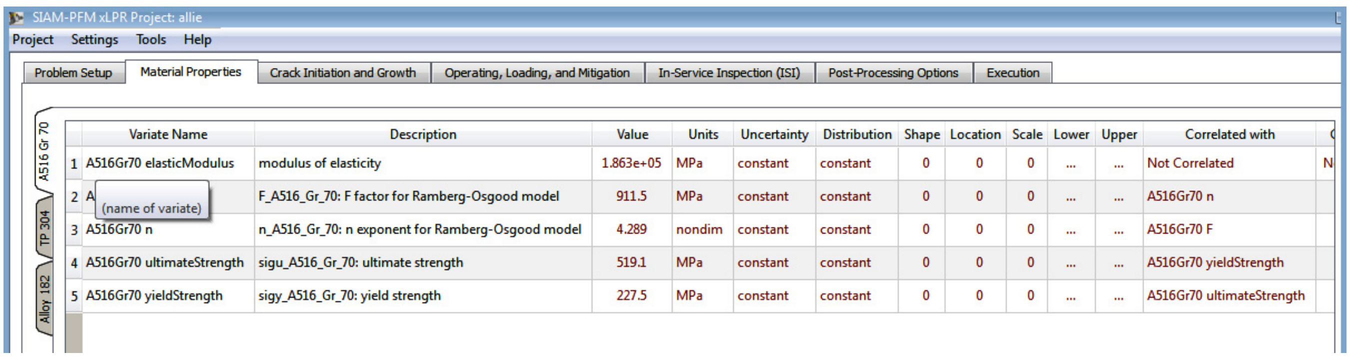
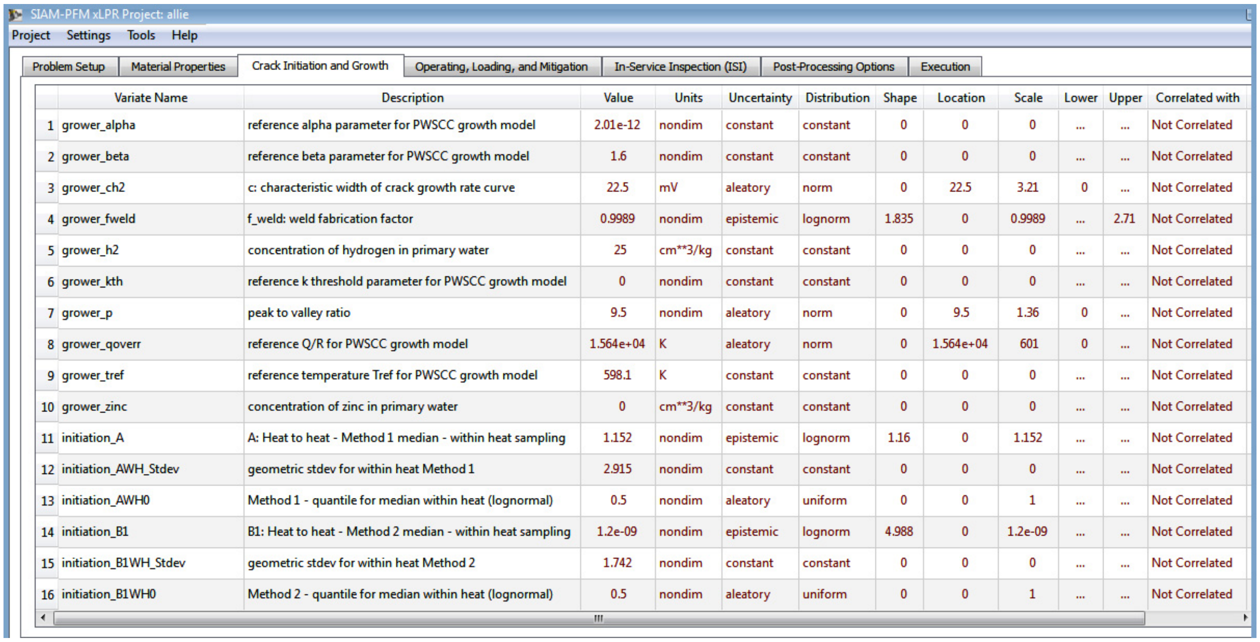


Fig. 11 Material Properties tab

3.1.3 Crack Initiation and Growth Properties Tab

In the Crack Initiation and Growth Properties tab (see Fig. 12), the user can define parameter values that will be sampled for each initiated crack, such as the initial crack depth and half-length of the initiated surface crack, sampled values for the probability of detection, and random numbers required for the crack initiation and inspection models. Moreover, values related to the grower module can also be entered.

A complete list of parameter names, descriptions and references related to each parameter can be found in Appendix B.



	Variate Name	Description	Value	Units	Uncertainty	Distribution	Shape	Location	Scale	Lower	Upper	Correlated with
1	grower_alpha	reference alpha parameter for PWSCC growth model	2.01e-12	nondim	constant	constant	0	0	0	...	...	Not Correlated
2	grower_beta	reference beta parameter for PWSCC growth model	1.6	nondim	constant	constant	0	0	0	...	...	Not Correlated
3	grower_ch2	c: characteristic width of crack growth rate curve	22.5	mV	aleatory	norm	0	22.5	3.21	0	...	Not Correlated
4	grower_fweld	f_weld: weld fabrication factor	0.9989	nondim	epistemic	lognorm	1.835	0	0.9989	...	2.71	Not Correlated
5	grower_h2	concentration of hydrogen in primary water	25	cm**3/kg	constant	constant	0	0	0	...	...	Not Correlated
6	grower_kth	reference k threshold parameter for PWSCC growth model	0	nondim	constant	constant	0	0	0	...	...	Not Correlated
7	grower_p	peak to valley ratio	9.5	nondim	aleatory	norm	0	9.5	1.36	0	...	Not Correlated
8	grower_qoverr	reference Q/R for PWSCC growth model	1.564e+04	K	aleatory	norm	0	1.564e+04	601	0	...	Not Correlated
9	grower_tref	reference temperature Tref for PWSCC growth model	598.1	K	constant	constant	0	0	0	...	...	Not Correlated
10	grower_zinc	concentration of zinc in primary water	0	cm**3/kg	constant	constant	0	0	0	...	...	Not Correlated
11	initiation_A	A: Heat to heat - Method 1 median - within heat sampling	1.152	nondim	epistemic	lognorm	1.16	0	1.152	...	...	Not Correlated
12	initiation_AWH_Stdev	geometric stdev for within heat Method 1	2.915	nondim	constant	constant	0	0	0	...	...	Not Correlated
13	initiation_AWH0	Method 1 - quantile for median within heat (lognormal)	0.5	nondim	aleatory	uniform	0	0	1	...	...	Not Correlated
14	initiation_B1	B1: Heat to heat - Method 2 median - within heat sampling	1.2e-09	nondim	epistemic	lognorm	4.988	0	1.2e-09	...	...	Not Correlated
15	initiation_B1WH_Stdev	geometric stdev for within heat Method 2	1.742	nondim	constant	constant	0	0	0	...	...	Not Correlated
16	initiation_B1WH0	Method 2 - quantile for median within heat (lognormal)	0.5	nondim	aleatory	uniform	0	0	1	...	...	Not Correlated

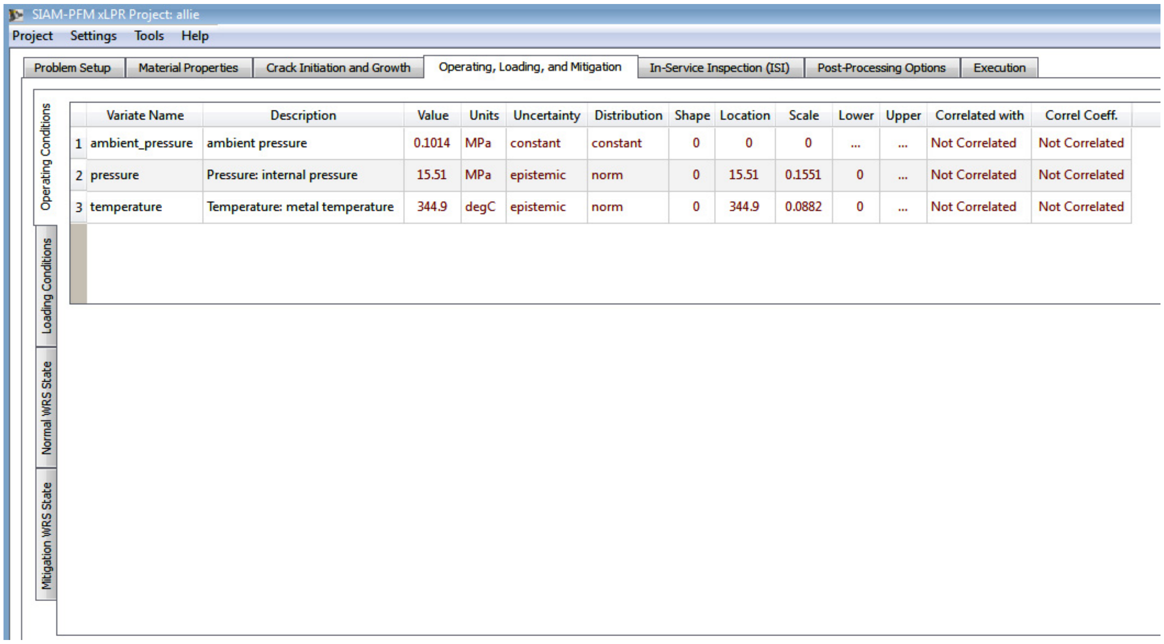
Fig. 12 Crack Initiation and Growth Properties tab.

3.1.4 Operating, Loading and Mitigation Tab

The Operating, Loading, and Mitigation tab (see Fig. 13) allows the user to define parameter values related to:

1. Operating Conditions: ambient pressure, internal pressure and metal temperature.
2. Loading Conditions: axial forces and moment components.
3. Normal Weld Residual Stress (WRS) parameters, and
4. Mitigation WRS State parameters.

A complete list of parameter names, descriptions and references related to each parameter can be found in Appendix B.

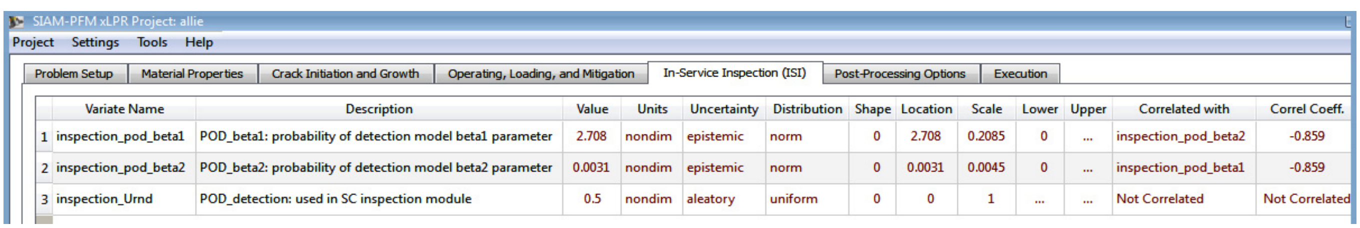


	Variate Name	Description	Value	Units	Uncertainty	Distribution	Shape	Location	Scale	Lower	Upper	Correlated with	Correl Coeff.
1	ambient_pressure	ambient pressure	0.1014	MPa	constant	constant	0	0	0	...	...	Not Correlated	Not Correlated
2	pressure	Pressure: internal pressure	15.51	MPa	epistemic	norm	0	15.51	0.1551	0	...	Not Correlated	Not Correlated
3	temperature	Temperature: metal temperature	344.9	degC	epistemic	norm	0	344.9	0.0882	0	...	Not Correlated	Not Correlated

Fig. 13 Operating, Loading and Mitigation Tab

3.1.5 In Service Inspection (ISI) Tab

The In-Service Inspection Tab (see Fig. 14) allows the user to input values related to the probability of detection and to the detection used in SC inspection module. A complete list of parameter names, descriptions and references related to each parameter can be found in Appendix B.



	Variate Name	Description	Value	Units	Uncertainty	Distribution	Shape	Location	Scale	Lower	Upper	Correlated with	Correl Coeff.
1	inspection_pod_beta1	POD_beta1: probability of detection model beta1 parameter	2.708	nondim	epistemic	norm	0	2.708	0.2085	0	...	inspection_pod_beta2	-0.859
2	inspection_pod_beta2	POD_beta2: probability of detection model beta2 parameter	0.0031	nondim	epistemic	norm	0	0.0031	0.0045	0	...	inspection_pod_beta1	-0.859
3	inspection_Urnd	POD_detection: used in SC inspection module	0.5	nondim	aleatory	uniform	0	0	1	...	...	Not Correlated	Not Correlated

Fig. 14 In-Service Inspection (ISI) tab

3.1.6 How to Edit Input Parameters

SIAM-xLPR,as shown from Fig. 15 through Fig. 20, provides the user with the ability to change the displayed units for individual inputs, the uncertainty type, statistical distributions and their parameters characterizing the uncertainty, and correlation attributes between bivariate pairs. Throughout SIAM-xLPR, the user can modify units of measurement by selecting (double click or hit F2 in the selected Units cell) a different unit in the Units menu (see Fig. 15). The unit conversion is performed automatically when focus is moved outside of the selected Units cell. Input data can be viewed in user-selected units systems including US Customary, SI, and mixed units. Internally, the code uses SI units and the required conversions are performed transparently to the user.

The following notes apply to the individual columns in the User-Interface tables on the Material Properties, Crack Initiation and Growth, Operating, Loading, and Mitigation, In-Service Inspection (ISI), and Post-Processing Options tabs:

- The variable in the "Value" column is only used when the uncertainty type is set to constant. When the uncertainty type is set to either *aleatory* or *epistemic*, the number in this column is ignored.
- When the uncertainty type is set to either *aleatory* or *epistemic*, then the numbers input in the "Shape", "Location", and "Scale" columns represent the parameters required to fully define the continuous distribution specified by the selection from the drop-down comboBox in the "Distribution" column. The definitions of the shape, location, and scale parameters follow the conventions accepted in the statistical literature (see for example ref. [20]) and applied in the scipy.stats statistical library. These definitions depend on the selected distribution, where the three distributions used in the xLPR Pilot Project are:
    - *Lognormal distribution* (requires two parameters): shape parameter is the geometric standard deviation, the location parameter is not used, and the scale parameter is geometric mean which is equal to the median of the distribution.
    - *Normal distribution* (requires two parameters): the shape parameter is not used, the location parameter is the arithmetic mean, and the scale parameter is the square root of the variance (commonly known as the standard deviation) of the normal distribution.
    - *Uniform* (or rectangular distribution) (requires two parameters): the shape parameter is not used, the location parameter is the left boundary of the uniform distribution, and the scale parameter is the value at the right boundary minus the left boundary (or location parameter).
- The values input in the "Lower" and "Upper" columns are the lower and upper truncation boundaries applied to the sampling protocol for this variate. An ellipsis "…" in either column signifies that there is no prescribed truncation boundary. SIAM-xLPR applies a rescaling procedure to ensure that no values sampled from the distribution extend beyond these truncation boundaries.
- The "Correlated with" and "Correl Coeff." columns allow the user to specify bivariate correlation relationships with two variates. Both pairs must be specified explicitly in the "Correlated with" column using the dropdown comboBox. For example on the Material Properties/TP 304 tab, the TP 304 yield strength is correlated with the TP 304 ultimate strength as prescribed by the Pearson's correlation coefficient of 0.6066 input in the "Correl Coeff." column. This bivariate relationship must be specified for both variates.

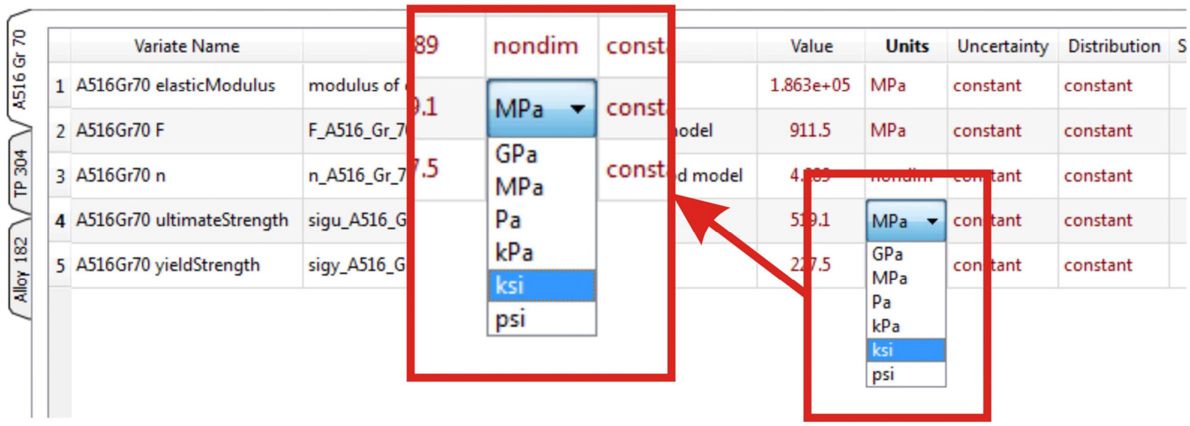


Fig. 15 Modifying units.

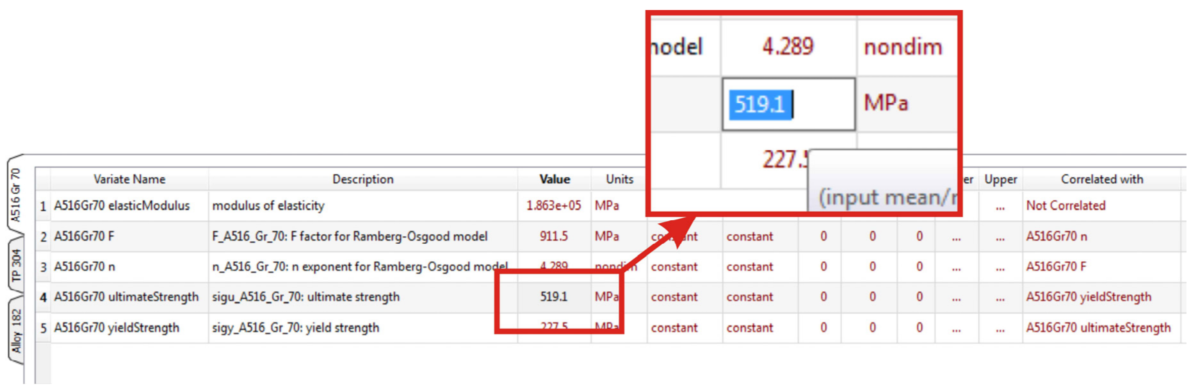
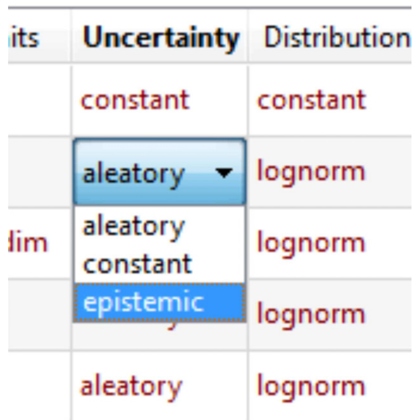
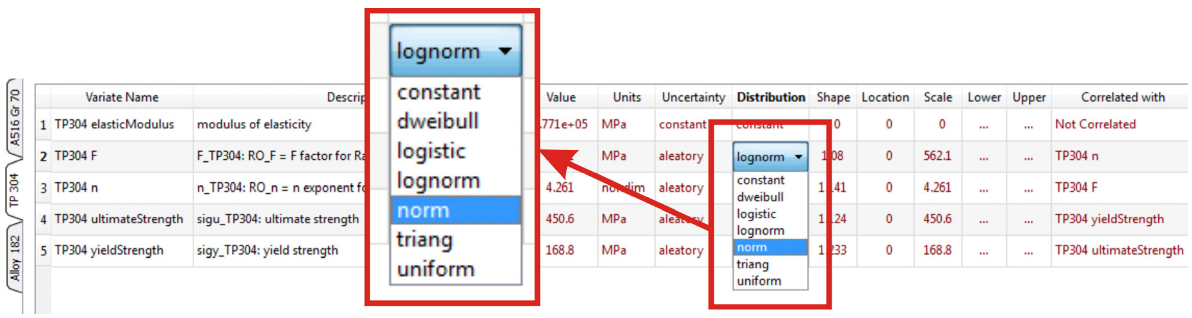


Fig. 16 Modifying values including statistical distribution parameters shape, location, scale, and lower/upper truncation boundaries.



(a)



(b)

Fig. 17 Modifying statistical distributions characterizing uncertainty (a) uncertainty type and (b) statistical distribution.

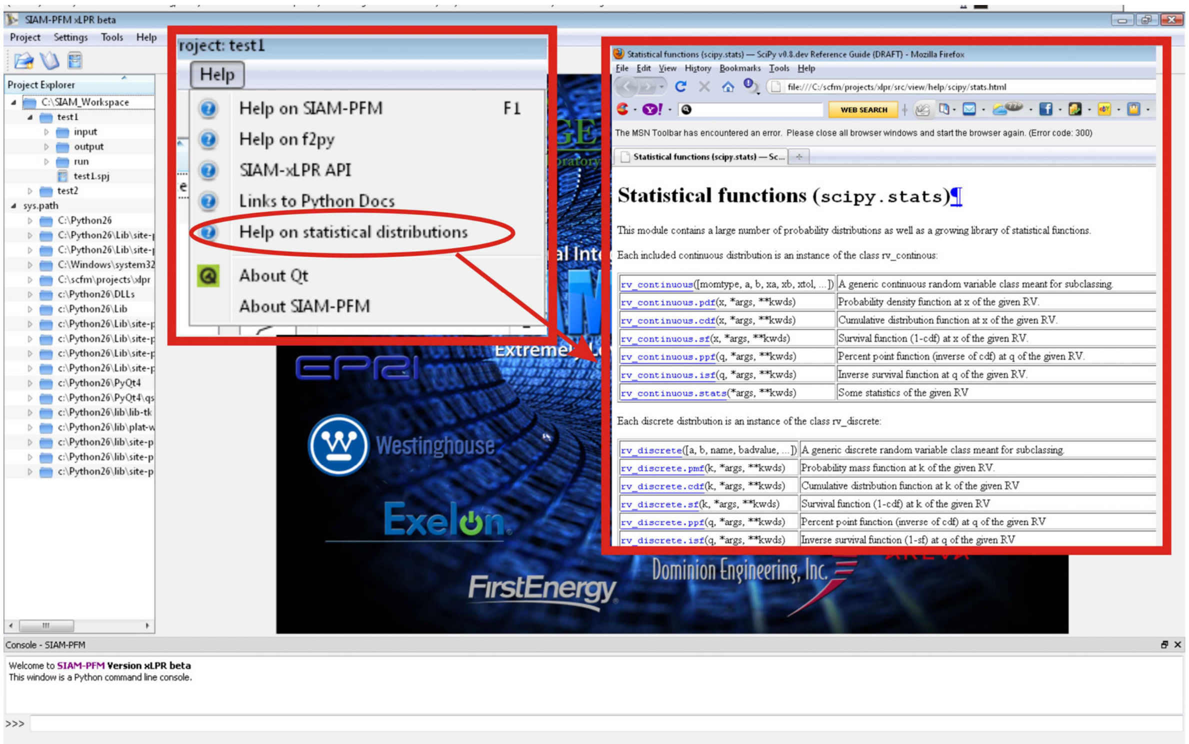


Fig. 18 Online help for the statistical distributions available to characterize uncertainty.

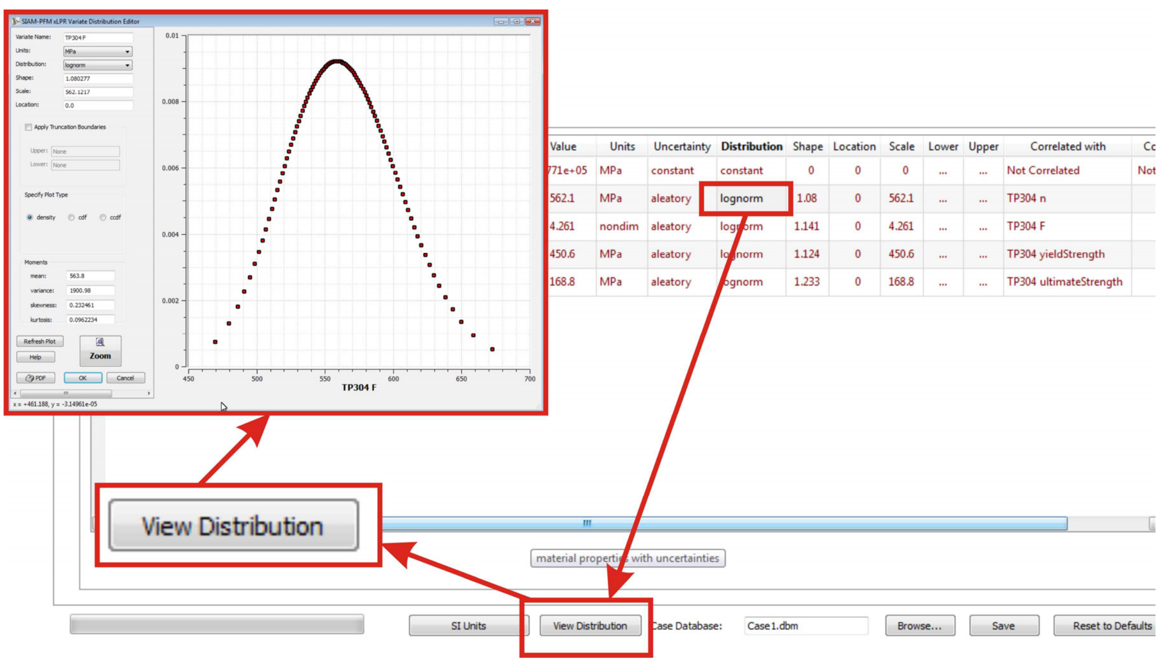


Fig. 19 Statistical distribution viewer/editor.

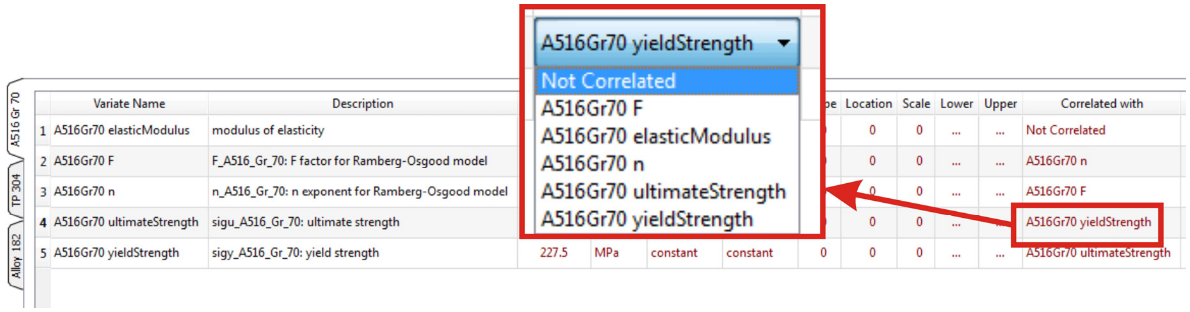


Fig. 20 Specifying bivariate correlations.

3.1.7 Button Toolbar

A set of buttons and other widgets, which apply for all of the tab forms, is located in the main window, below the tab forms are, as shown in Fig. 21. Each of these items is discussed below.

Progress Bar: When a task, such as saving the project to a file, is expected to take more than a second, the bar to the left of the labeled buttons tracks the progress of the task with a moving green highlight.

Customary Units button: Selection of this button toggles back and forth between displaying all parameter values in US Customary or SI units. Please note that no matter what the units selection is, SIAM-xLPR handles consistently the units in SI internally. Before the code executes and sends trials to the timeloop (see Fig. 3), all input values are automatically converted to the units required by the individual modules (in other words SI units). This conversion is transparent to the user, allowing the user to enter input data in either US Customary or SI units. The correct conversion is then taken care of internally.

View Distribution button: When the input focus is on any table row corresponding to an input parameter which has a non-constant distribution, selection of this button displays a popup window with a variate distrbution graph for that parameter.

Case Database textbox: The name of the current project database file is displayed in this textbox. The user can change the name of the file, however, the file is not saved under the new name until the Save, Browse, or Reset to Defaults button is selected.

Browse button: Selection of this button displays a dialog asking the user to select an existing input database file to load into the project. The user can select a file in the current project input folder from the list box or browse to the desired directory folder and file.

Save button: Selection of this button displays a dialog asking the user for confirmation before saving the input data to the file named in the Case Database textbox.

Reset to Default button: Selection of this button restores all of the parameter values to their default values.

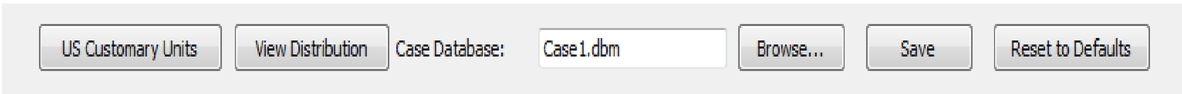


Fig. 21 US Customary Units and Reset to Defaults Buttons.

3.1.8 Execution Tab

The Execution tab is shown on Fig. 22. The program can be executed in one of two ways: either a probabilistic analysis or a deterministic calculation of a model problem used in verification and benchmarking studies [10]. The method of execution can be specified by the user; however, a probabilistic analysis will be the most common mode of execution. More information about the execution is given in the following section.

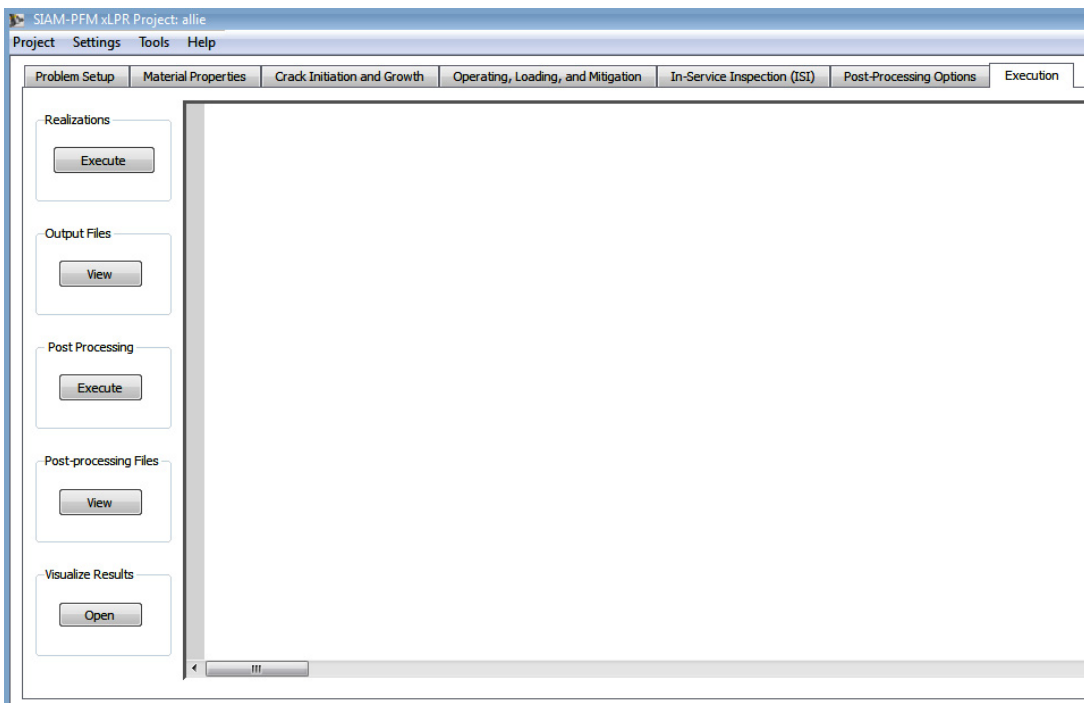


Fig. 22 The Execution tab.

3.2 Running the program

Click on the Execute button in the Execution tab (see Fig. 23) to start execution of the numerical calculations. When the Execute button is clicked, the user is first asked if the project changes should be committed to the input database file.

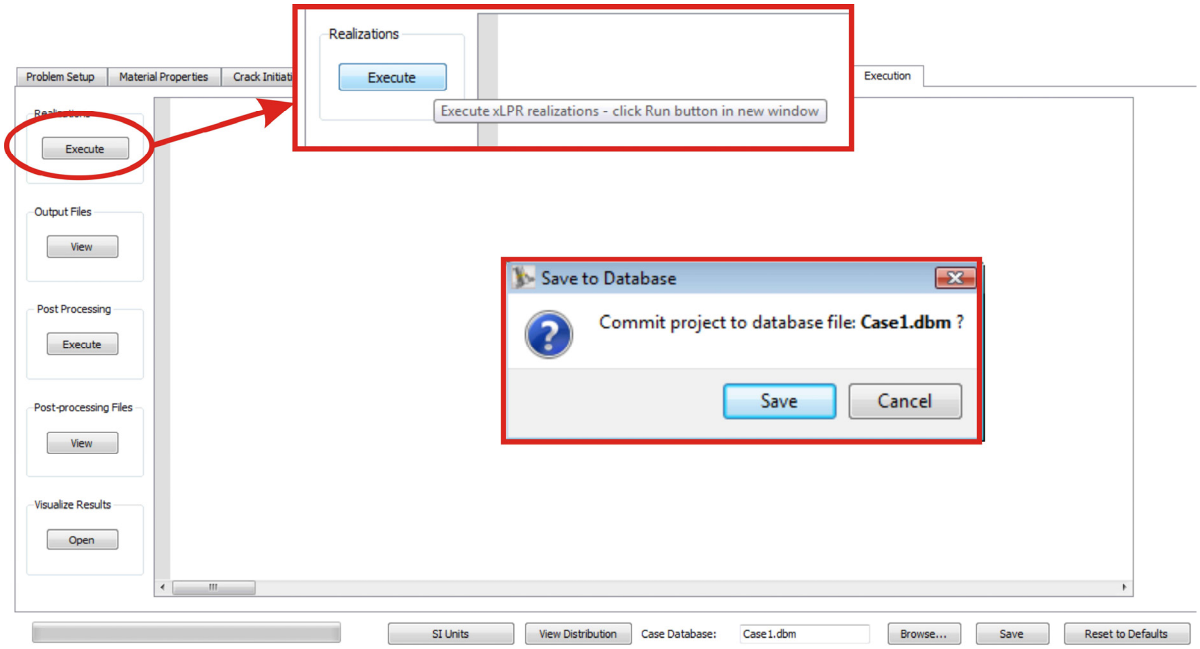


Fig. 23 Start the case execution.

When the SIAM-XLPR Execute Utility window comes up, click on the "Run" button (see Fig. 24) to display the "Run SIAM-xLPR" window. Parameters on this window are displayed in five data group boxes:

Epistemic Sampling Procedure: select either Random Sampling or Latin Hypercube Sampling (LHS) radio button (for a probabilistic analysis) to specify the sampling procedure [4].

Execution Mode: select one of three execution modes: Monte Carlo with uncertainties, Deterministic Baseline Case #1 or Deterministic Baseline Case #2 [10].

Output Options: Check "debug mode" if detailed debugging information should be included in the execution output database file.

Number of Realization Trials: The numbers of trials are read only values presented only as a reminder to the user. They can only be changed in the Problem Setup Tab.

Random Number Generator Initial Seeds: The random generator seeds are read only values presented only as a reminder to the user. They can only be changed in the Problem Setup Tab [11].

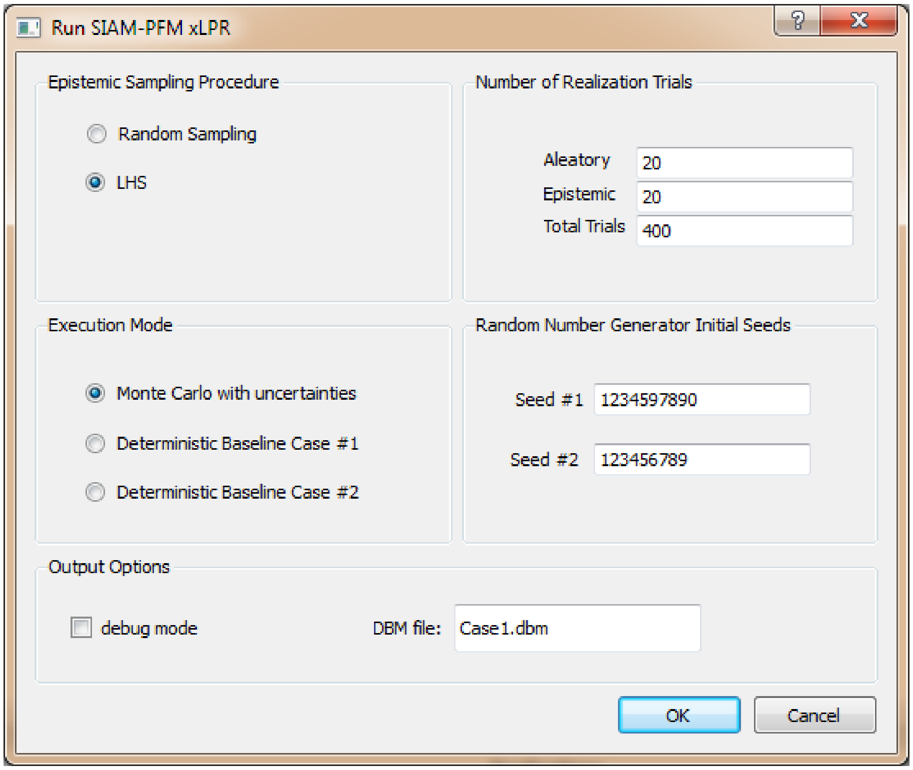


Fig. 24 Specify the Execution Mode and number of realization trials.

Click "OK" in "Run SIAM-xLPR" window to start the execution [Fig. 24]. During execution, run-time information for each realization is displayed in the "SIAM-xLPR Execute Utility" window (see Fig. 25), allowing the user to monitor progress of the calculations. For each epistemic and aleatory realization trial executed, the CPU time, in milliseconds, for the trial and the number of cracks initiated are displayed. When all the realizations have been completed, a summary of the execution time will be presented (see Fig. 25), as well as the size of the binary output file generated by the analysis. A summary popup window will also display the execution termination codes where exitcode=0 and exitstatus=0 indicate a successful run.

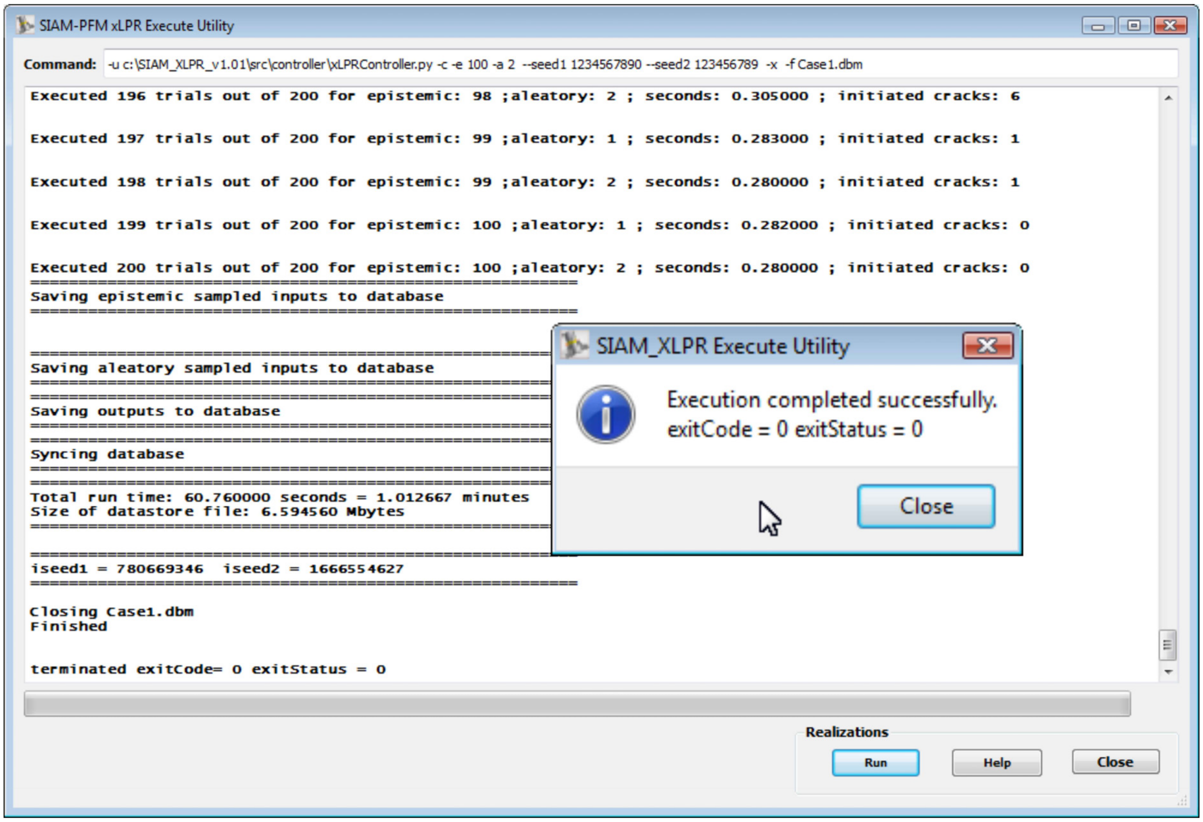


Fig. 25 Monitor the progress of the execution.

3.2.1 Output files

SIAM_xLPR generates several output files. The output files are located at <workspace>/<project_name>/output directory. The following output files are created during execution (e.g., the case database name is "Case1.dbm"):

- Case1_aleatory.log – a listing of all aleatory inputs with details on distributions
- Case1_epistemic.log – a listing of all epistemic inputs with details on distributions
- Case1_constants.log – a listing of all variates with uncertainties set to "constant"
- Case1_aleatory_inputs.log – a listing of sampled aleatory inputs for all trials
- Case1_epistemic_inputs.log – a listing of sampled epistemic inputs for all trials
- Case1_returnCodes.log – a listing of return codes from individual modules for all realizations
- Case1_summary.log – a summary of selected results for all realizations (see from Fig. 26 to Fig. 31).
- Case1_time.log – a listing of execution times (in seconds) for each module for all realizations
- Case1_TL_input.log – a descriptive file of sampled input data for each realization
- Case1_TL_output.log – a descriptive file of results from the execution of the timeloop module for each realization
- Case1_variables.log – a listing of all input variables (they have no uncertainty type assigned)

- Case1_variables_calculated.log – a listing of input variables showing calculated values after the execution of the timeloop.

3.3 Post-Processing custom plots

Fig. 26 through Fig. 31depict the current process for post-processing of the computational results and creation of custom plots using Microsoft Excel. The steps to create custom plots follow:

1. After completion of the run, click on the "Output Files – View" button (Fig. 26) to open the "Open File" dialog (Fig. 27), and select the "Case1_summary.log". Click "Open" and the contents of this file will be displayed in the output files Browser window.

2. Right-click in the Browser (Fig. 28) and pick "Select All" from the popup context menu.

3. Right-click again and copy the file's contents to the computer's clipboard (Fig. 29).

4. Copy the provided Excel workbook (Fig. 30) ("SIAM_xLPR_beta_template.xlsx" or "SIAM_xLPR_beta_template.xls"), from the \SIAM_XLPR_v1.0\docs folder into the project folder. Open this copy, click on the "Summary Template" worksheet tab, select cell A1 (contains "itrial"), and paste the contents of the clipboard to the template (Fig. 31).

5. If necessary, convert the data from "Text to Columns" using the "delimited" option with a "space" as the delimiter.

6. Select the data in Columns A through P and carry out a "custom sort" using the column of interest (for example the "time_at_rupture[yr]" Column K) as the sorting key.

7. The total number of trials should then be entered in cell S1.

8. Finally, plot the required results as shown in Fig. 31.

   Note: The other worksheets will not be automatically updated as they do not point to this data.

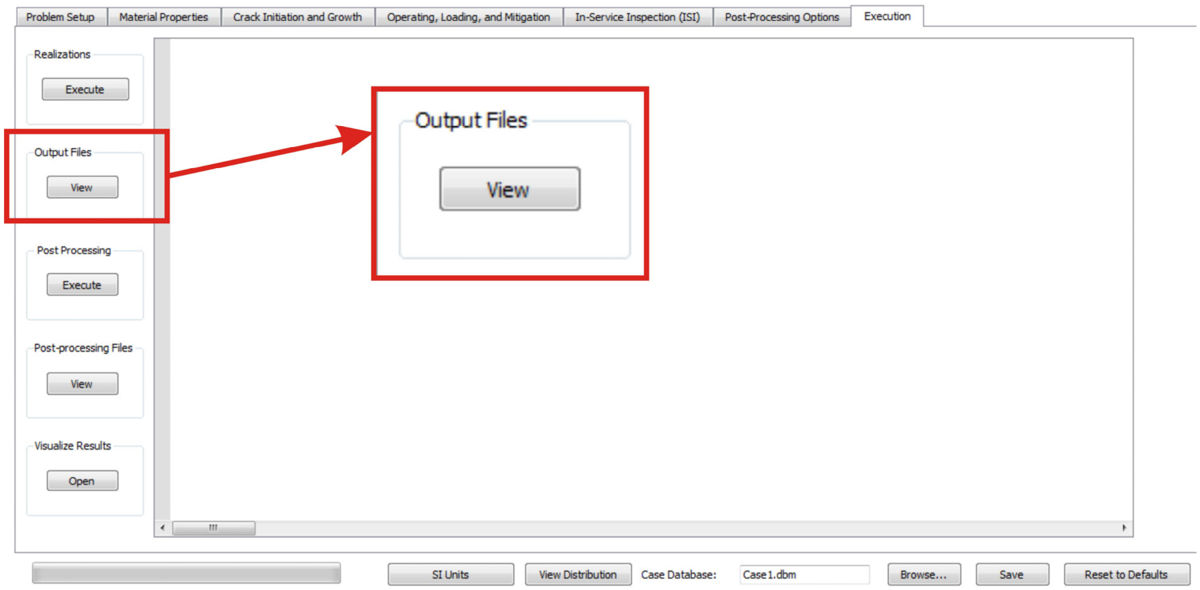


Fig. 26 Viewing output files.

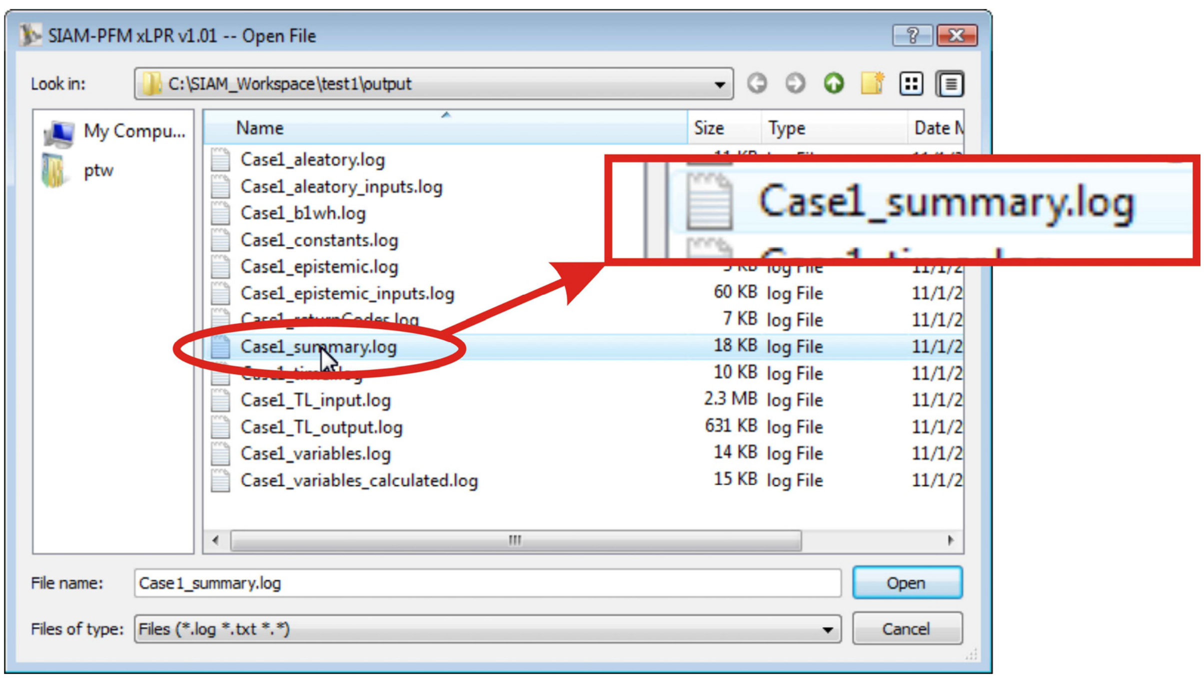


Fig. 27 Select the "Case1_summary.log" file for a summary of selected results.

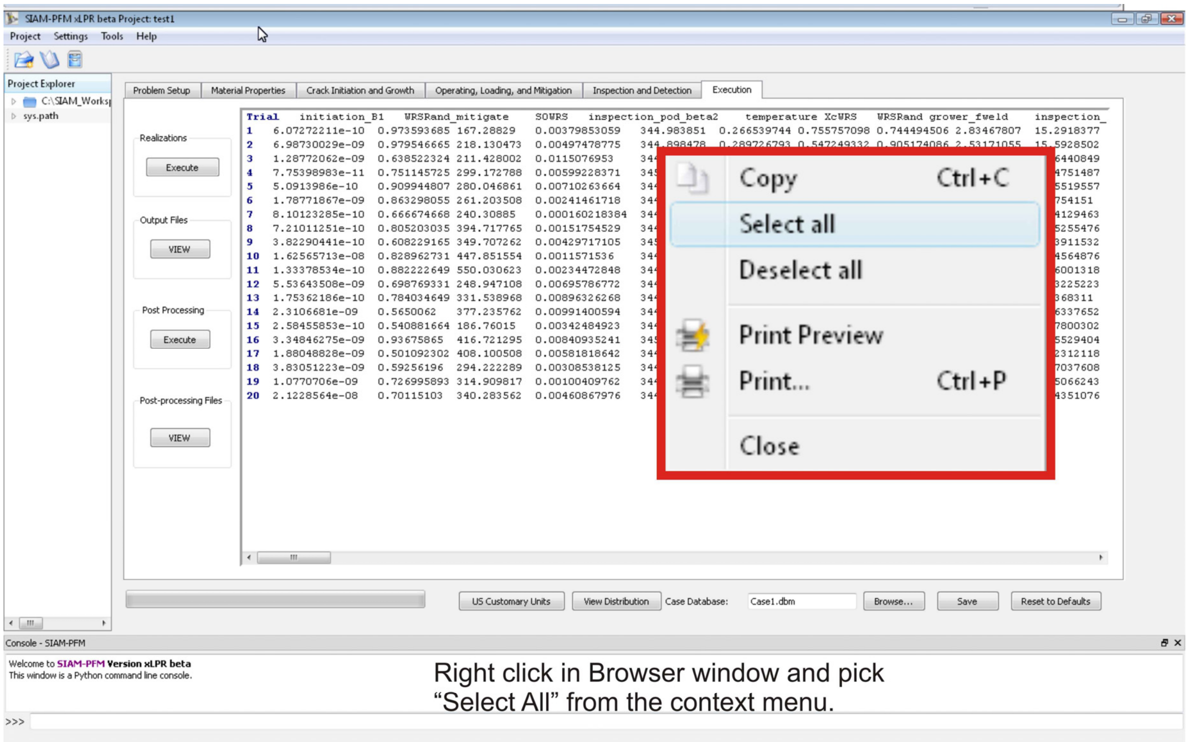


Fig. 28 Select all in the browser window or copy individual records.

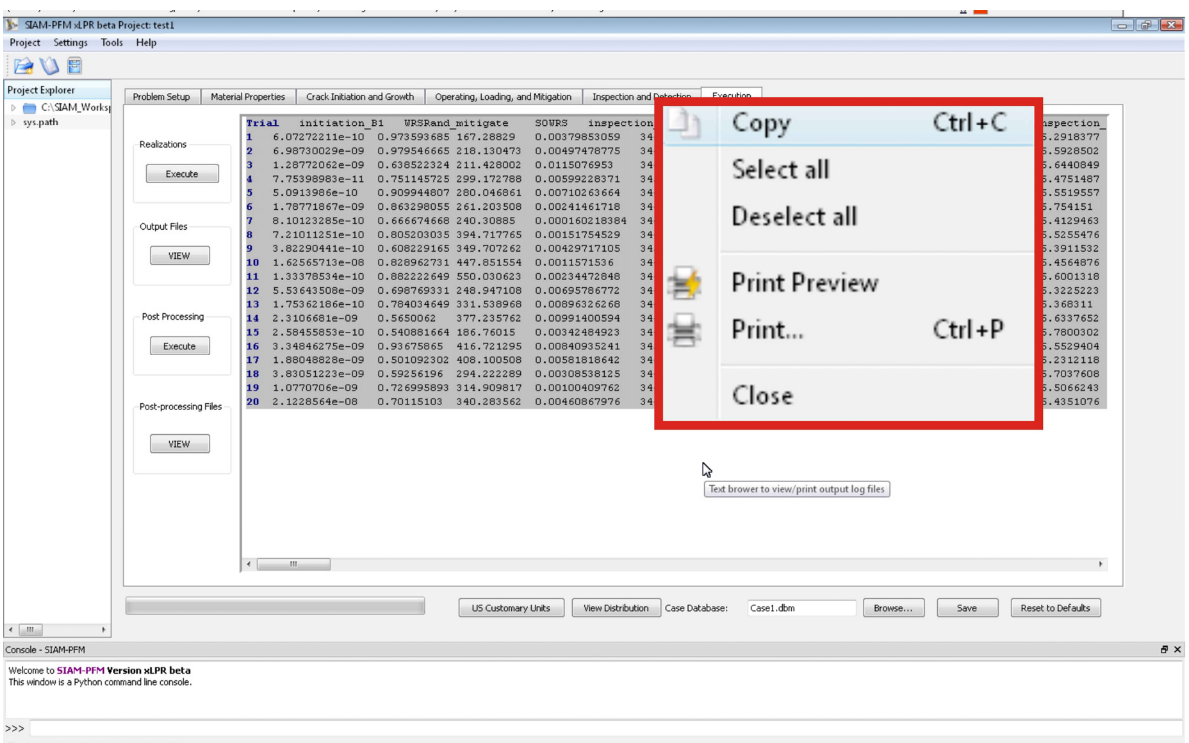
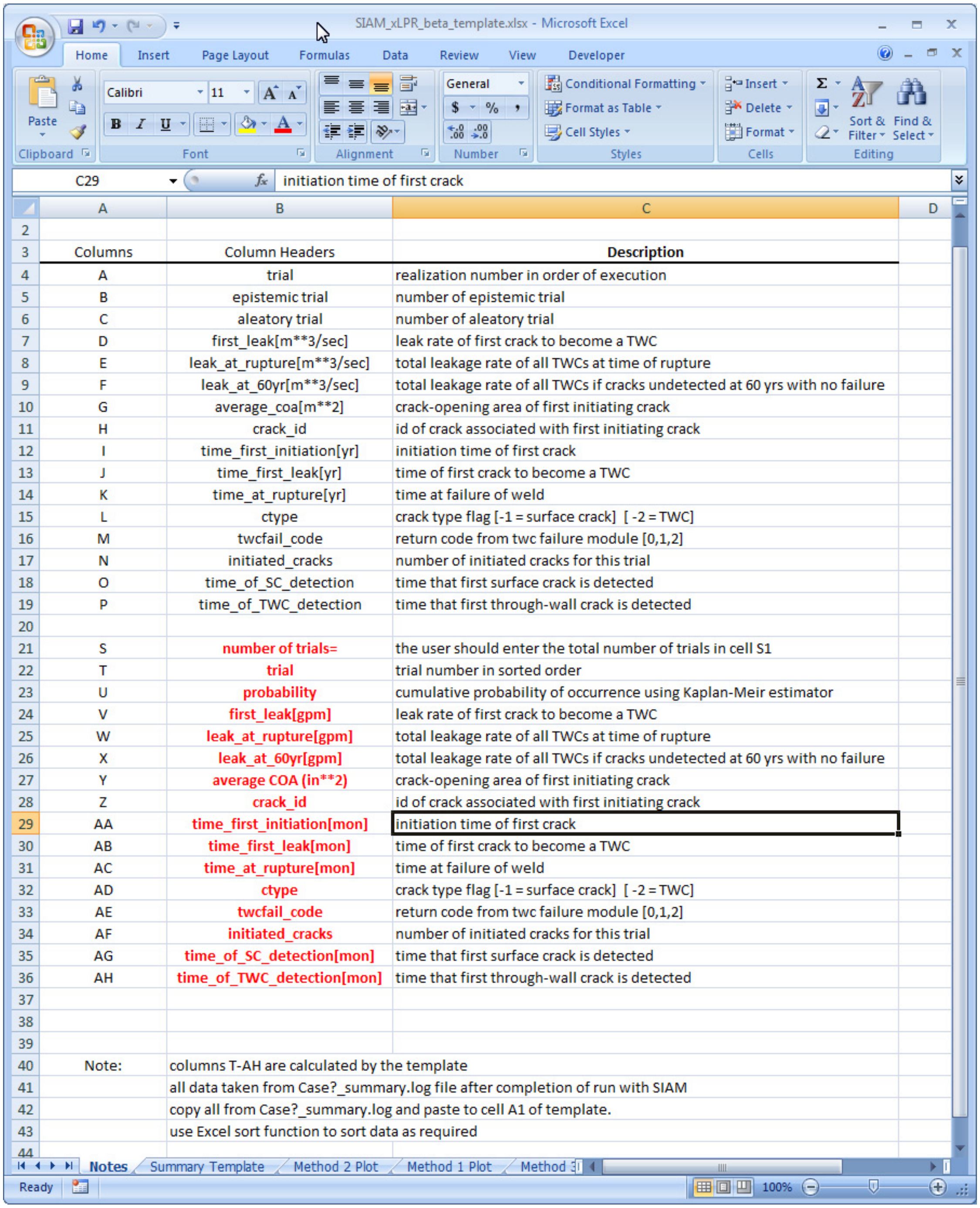


Fig. 29 Copy the selected results to the computer’s clipboard.



Columns	Column Headers	Description
A	trial	realization number in order of execution
B	epistemic trial	number of epistemic trial
C	aleatory trial	number of aleatory trial
D	first_leak[m**3/sec]	leak rate of first crack to become a TWC
E	leak_at_rupture[m**3/sec]	total leakage rate of all TWCs at time of rupture
F	leak_at_60yr[m**3/sec]	total leakage rate of all TWCs if cracks undetected at 60 yrs with no failure
G	average_coa[m**2]	crack-opening area of first initiating crack
H	crack_id	id of crack associated with first initiating crack
I	time_first_initiation[yr]	initiation time of first crack
J	time_first_leak[yr]	time of first crack to become a TWC
K	time_at_rupture[yr]	time at failure of weld
L	ctype	crack type flag [-1 = surface crack] [-2 = TWC]
M	twcfail_code	return code from twc failure module [0,1,2]
N	initiated_cracks	number of initiated cracks for this trial
O	time_of_SC_detection	time that first surface crack is detected
P	time_of_TWC_detection	time that first through-wall crack is detected
S	**number of trials=**	the user should enter the total number of trials in cell S1
T	**trial**	trial number in sorted order
U	**probability**	cumulative probability of occurrence using Kaplan-Meir estimator
V	**first_leak[gpm]**	leak rate of first crack to become a TWC
W	**leak_at_rupture[gpm]**	total leakage rate of all TWCs at time of rupture
X	**leak_at_60yr[gpm]**	total leakage rate of all TWCs if cracks undetected at 60 yrs with no failure
Y	**average COA (in**2)**	crack-opening area of first initiating crack
Z	**crack_id**	id of crack associated with first initiating crack
AA	**time_first_initiation[mon]**	initiation time of first crack
AB	**time_first_leak[mon]**	time of first crack to become a TWC
AC	**time_at_rupture[mon]**	time at failure of weld
AD	**ctype**	crack type flag [-1 = surface crack] [-2 = TWC]
AE	**twcfail_code**	return code from twc failure module [0,1,2]
AF	**initiated_cracks**	number of initiated cracks for this trial
AG	**time_of_SC_detection[mon]**	time that first surface crack is detected
AH	**time_of_TWC_detection[mon]**	time that first through-wall crack is detected

Note: columns T-AH are calculated by the template
all data taken from Case?_summary.log file after completion of run with SIAM
copy all from Case?_summary.log and paste to cell A1 of template.
use Excel sort function to sort data as required

Fig. 30 Paste to a spreadsheet program using provided template (see notes on first tab).

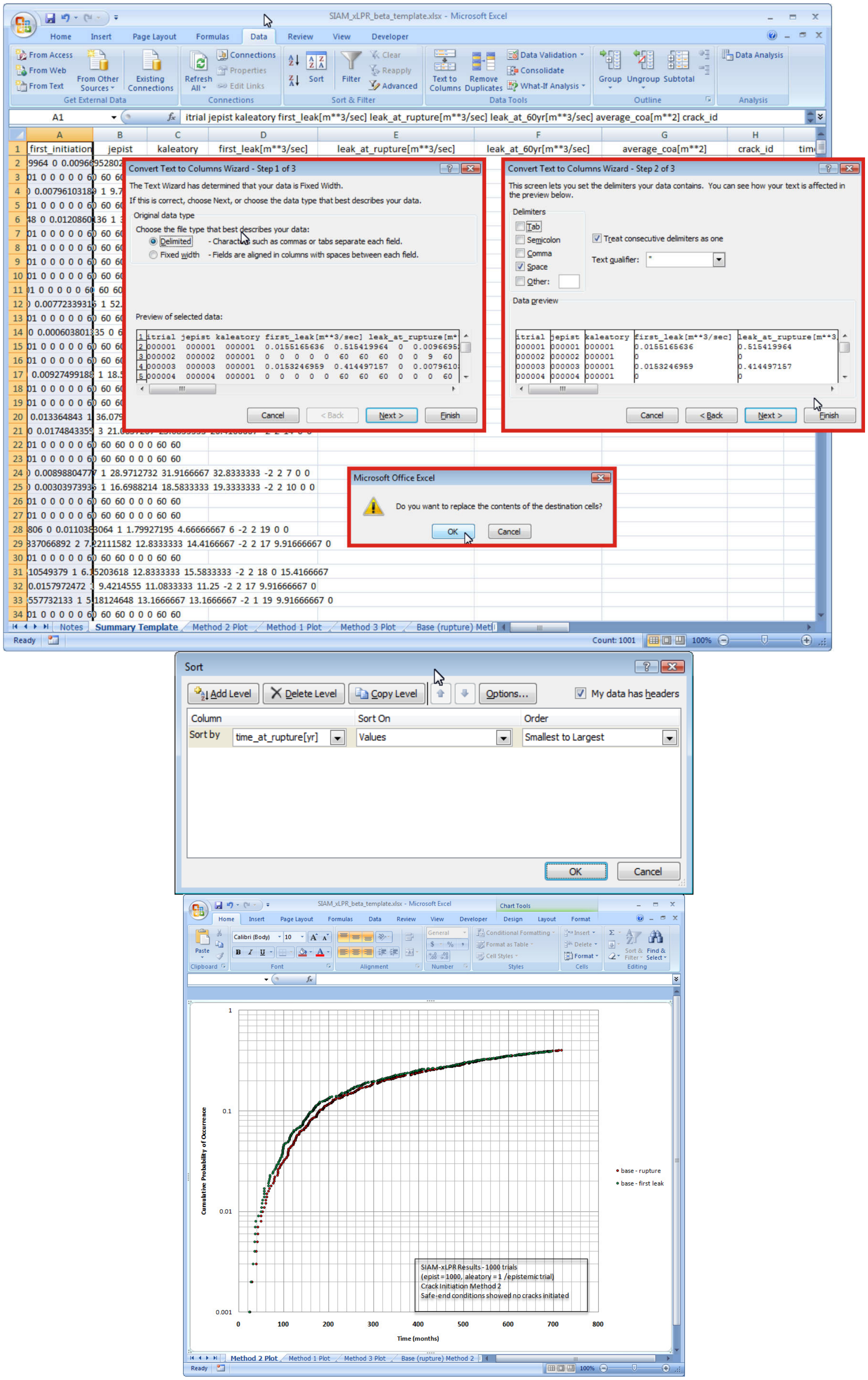


Fig. 31 Paste to a spreadsheet program and proceed to sort and plot the results.

3.4 How to visualize deterministic results

In this section, we explain how to visualize results for the deterministic base case defined in the xlPR Pilot Study Problem Statements [10].

Step 1. Select the deterministic case to run at the Run SIAM-PFM xLPR dialog as shown in Fig. 32.

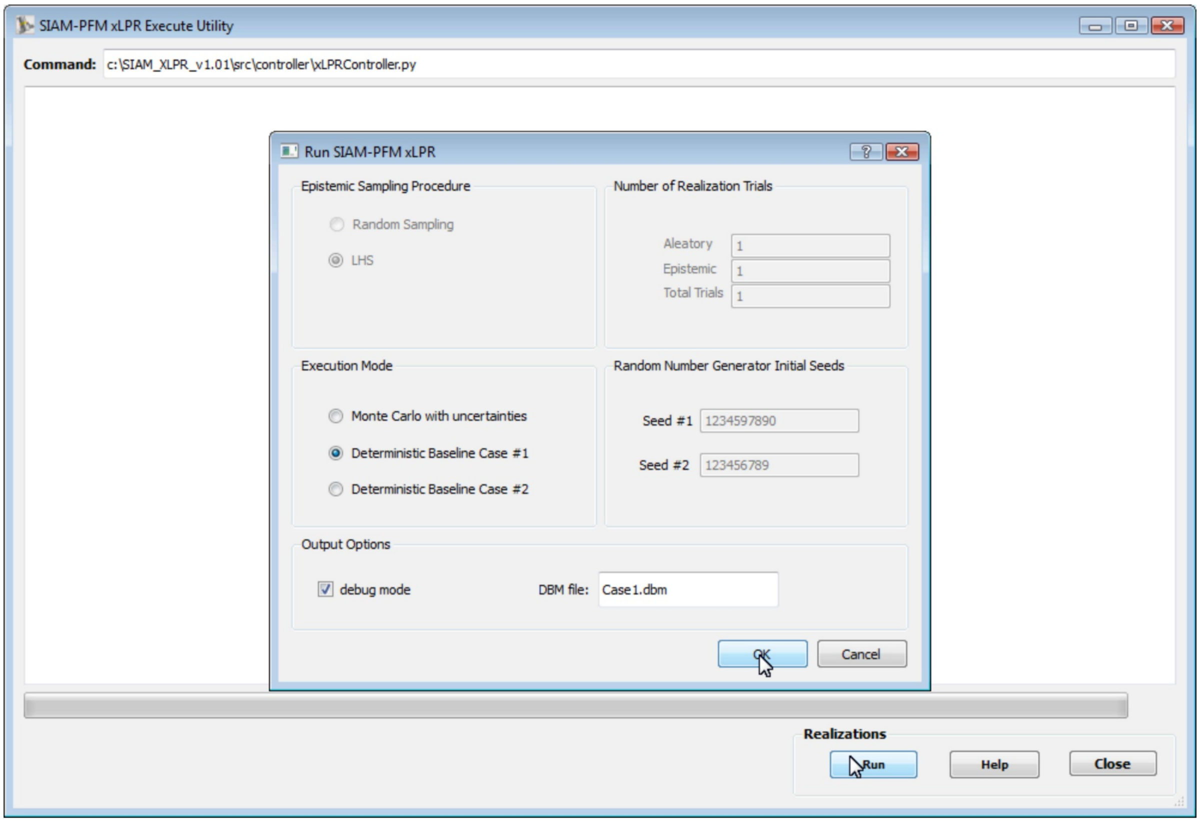


Fig. 32 Open the Run SIAM-PFM xLPR dialog and select a deterministic case to execute.

Step 2. Once the run completes (see Fig. 33), there are two possible alternatives Open the <work_space>/<project_name>/run/<case#>_timeloop_details.out file as shown below in Fig. 34:

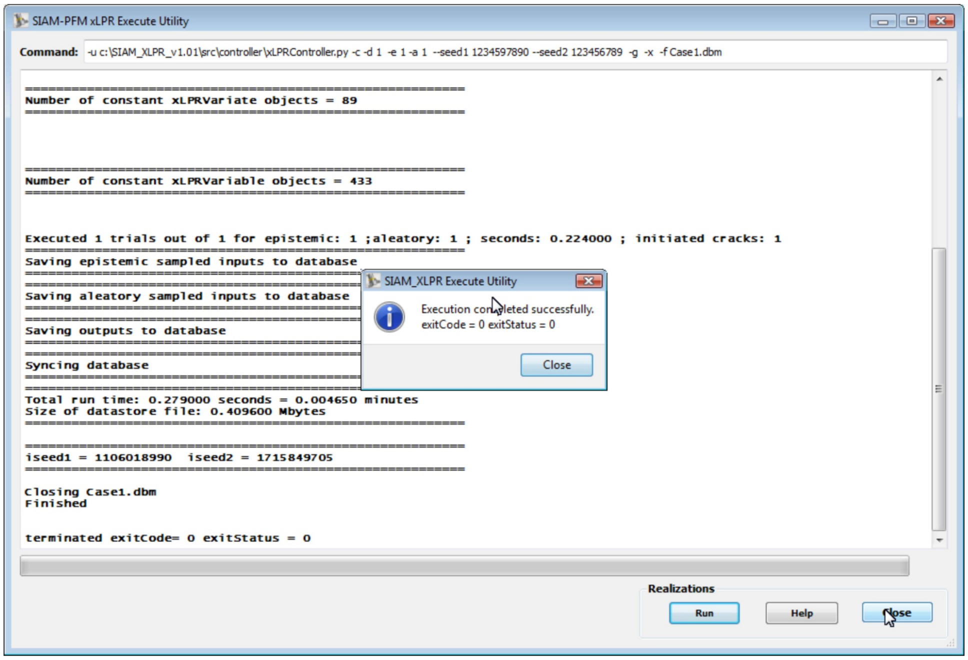


Fig. 33 Deterministic Run Complete.

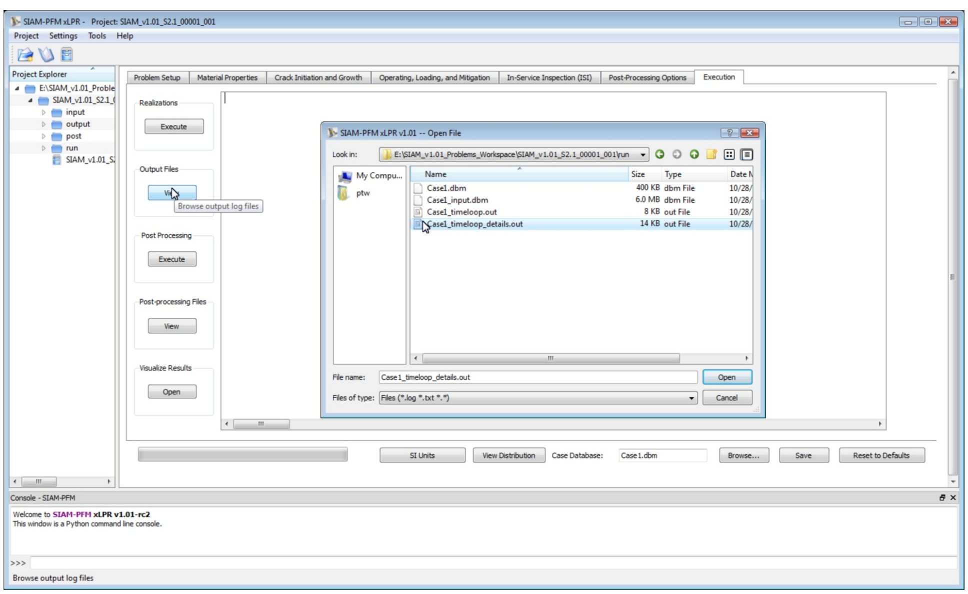


Fig. 34 Open *_timeloop_details.out file

Select all (see Fig. 35)

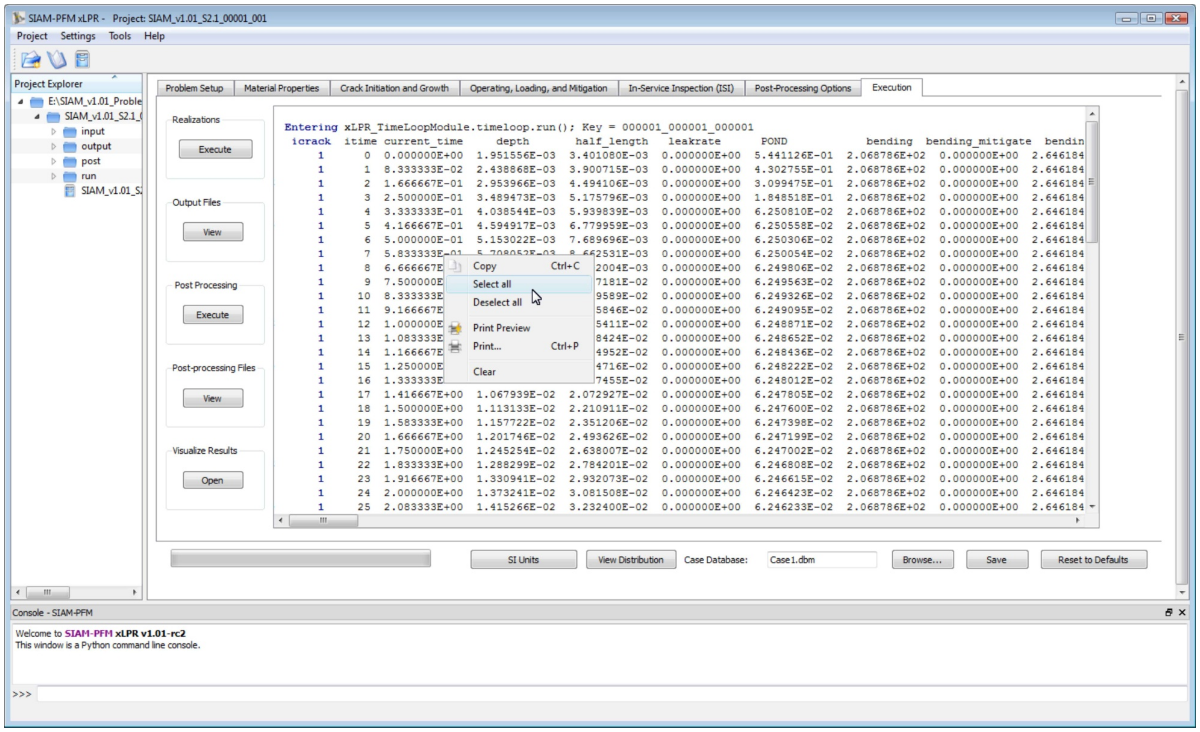


Fig. 35 Select all contents of the *timeloop_details.out file

And copy it to a MS Excel worksheet as shown in Fig.36.

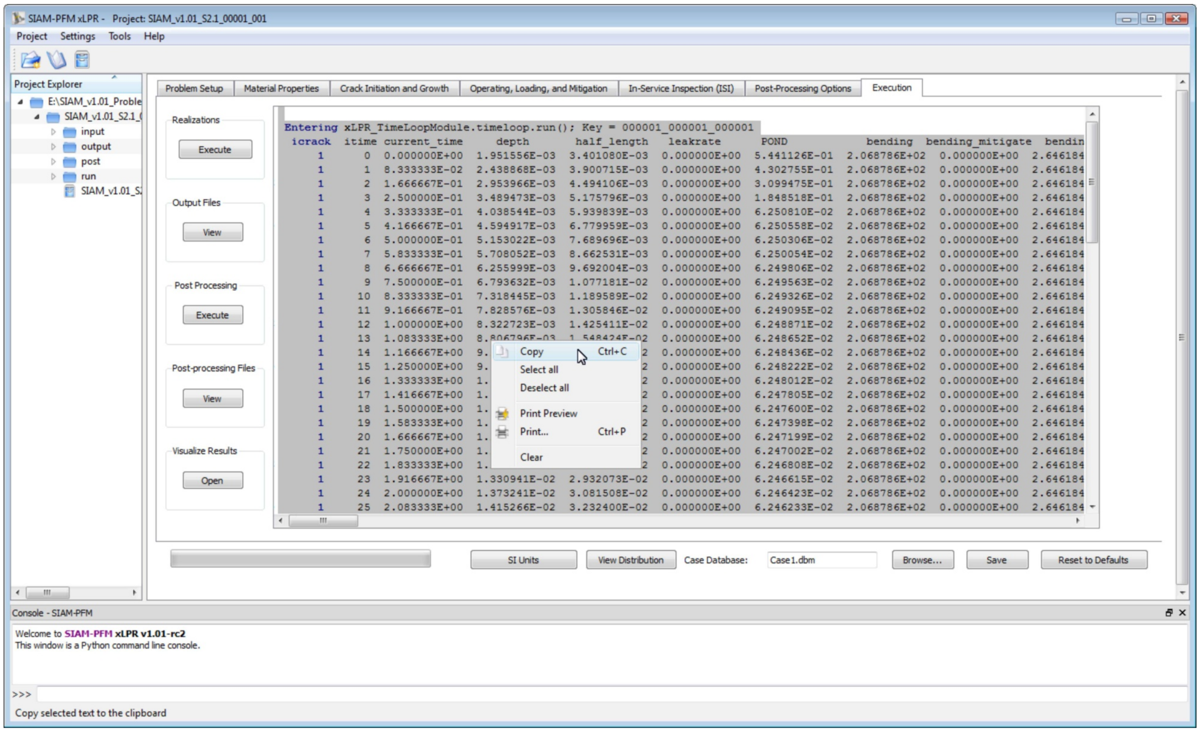


Fig. 36 Copy contents of the *timeloop_details.out file

Option #2:
Execute the post-processing utility: (see Fig. 37)

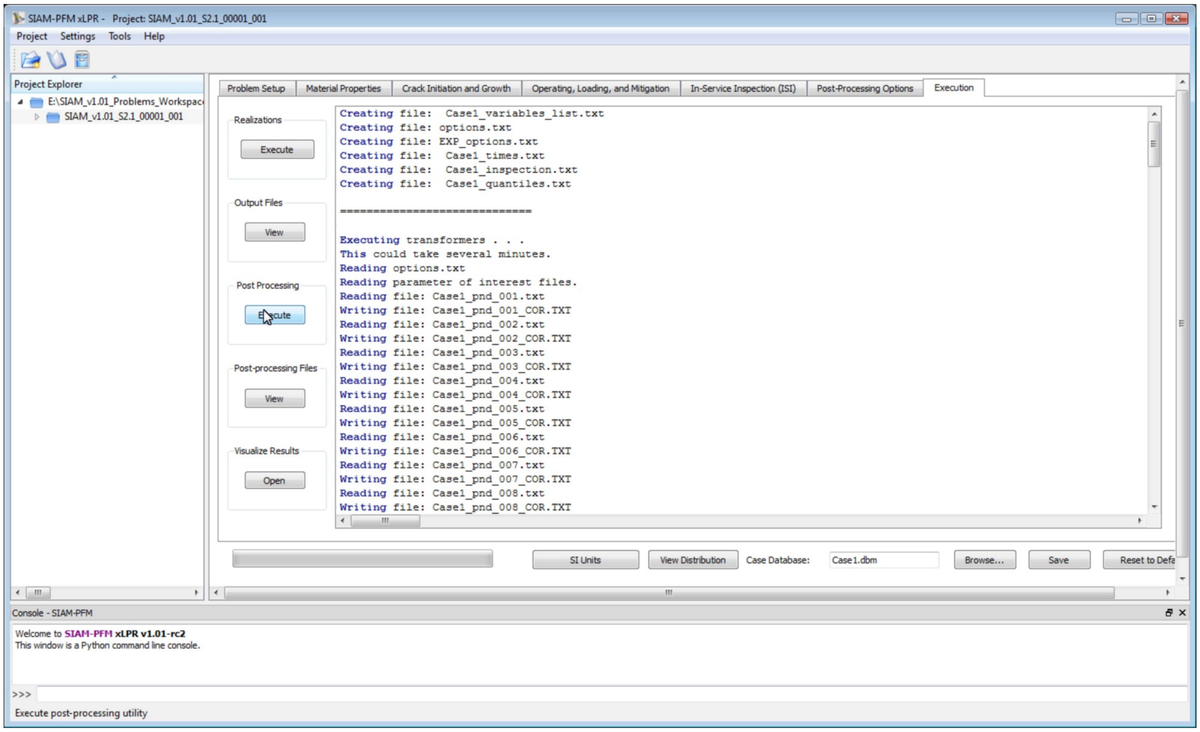


Fig. 37 Post-processing execution.

Click in the Post-processing Files, 'View' button, and open the <case#>_depth_001_COR_exp.txt file (see Fig. 38), which is an output from the Transformers and Expectation modules.

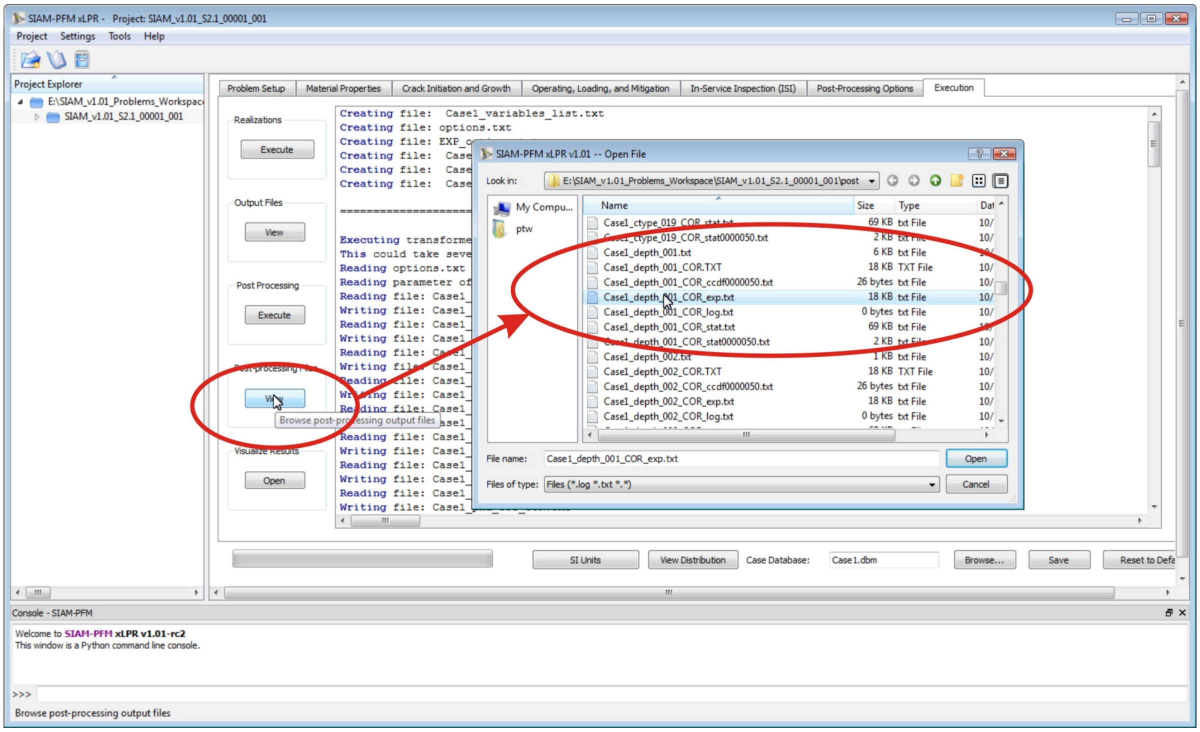


Fig. 38 Open *depth_001_COR_exp.txt file.

Open that file and copy and paste its contents in a MS Excel spreadsheet

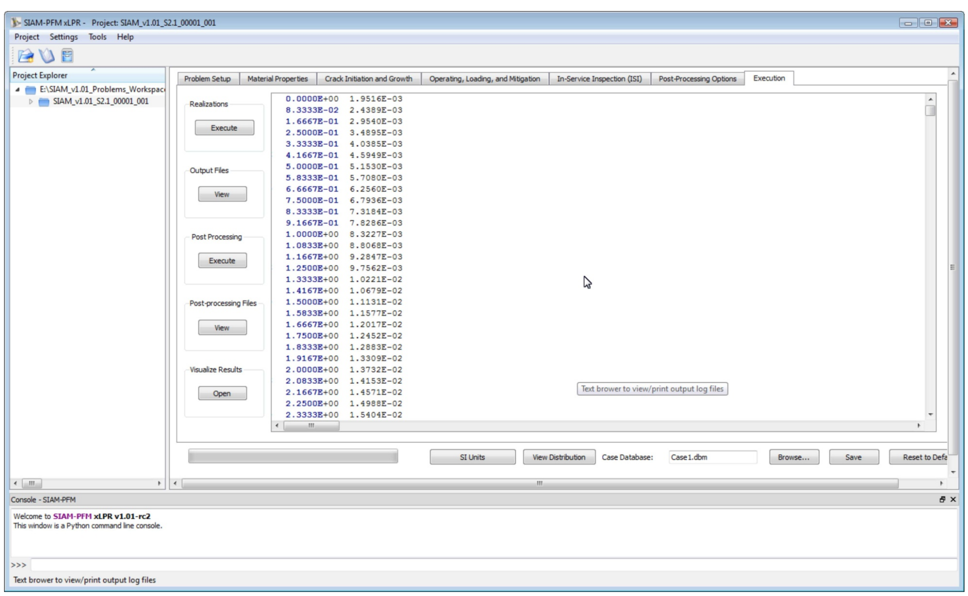


Fig. 39 Contents of *depth_001_COR_exp.txt file

Finally, another option is to use SIAM-xLPR Post-Processing Utility, by clicking the "View Results, Open" button.

3.5 SIAM-xLPR Post-Processing Utility

The "View Results – Open" button will open three windows, one for each of the two uncertainty types (aleatory inputs and epistemic inputs) and one to aid in visualizing selected output parameters.

3.5.1 Aleatory Inputs

The results of sampling all aleatory inputs can be visualized in the Aleatory Input window. Use the drop-down comboBox to select the aleatory variate and click on the Refresh Plot button. The imposition of correlation restrictions for correlated bivariate parameters can be checked by using the scatter plot option after selecting the correlated pair with the second drop-down comboBox and then refreshing the plot.

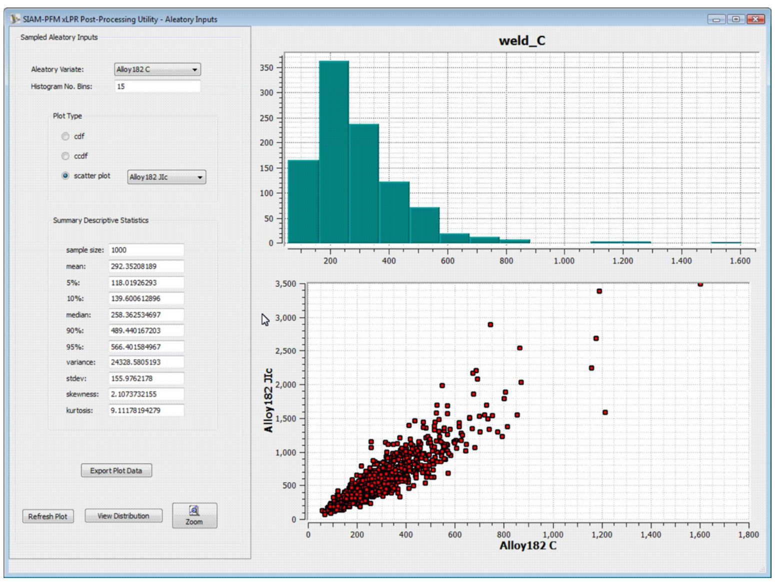


Fig. 40 Aleatory inputs window to check sampling of aleatory variates.

Additional functionality is provided in the buttons on the lower right-hand corner of the dialog as shown in Fig. 41.

Fig. 41 Additional functionality include export plot data to text file, view input distribution, and zoom plot to re-scale axes.

The “View Distribution” button allows the user to inspect the input continuous statistical distribution from which the aleatory variate was sampled.

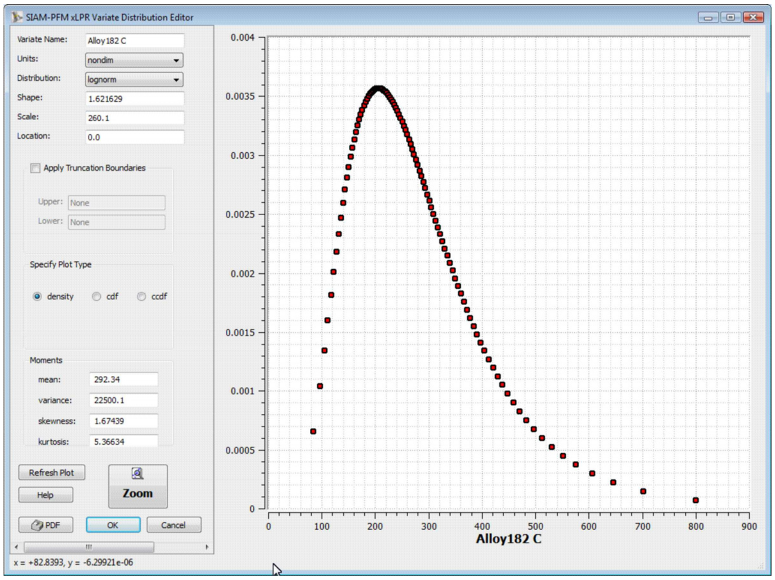


Fig. 42 “View Distribution” button brings up window showing the input distribution from which the variate is being sampled.

3.5.2 Epistemic Inputs

The second dialog window presents the same functionality for epistemic input variates.

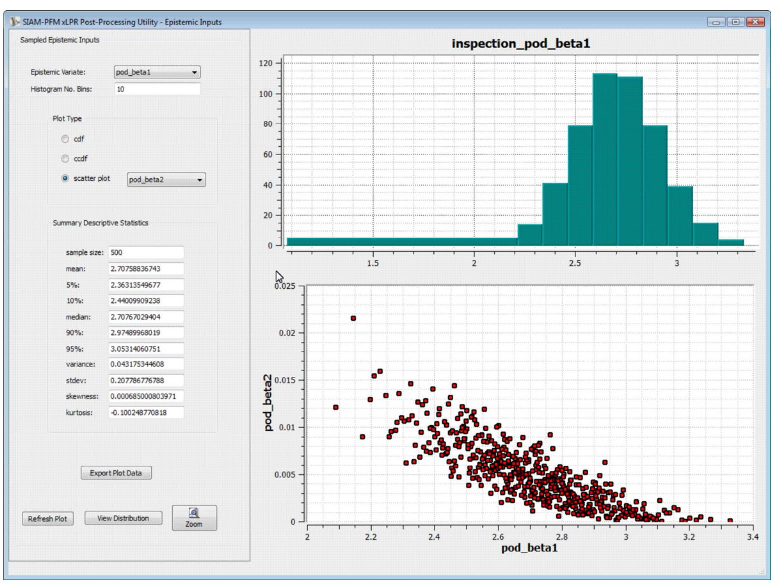


Fig. 43 Epistemic inputs window to check sampling of epistemic variates.

3.5.3 Visualization of Outputs

The third window provides the user with ability to visualize selected output parameters that have been calculated by the post-processor module. The post-processor must first be executed before these plots become available.

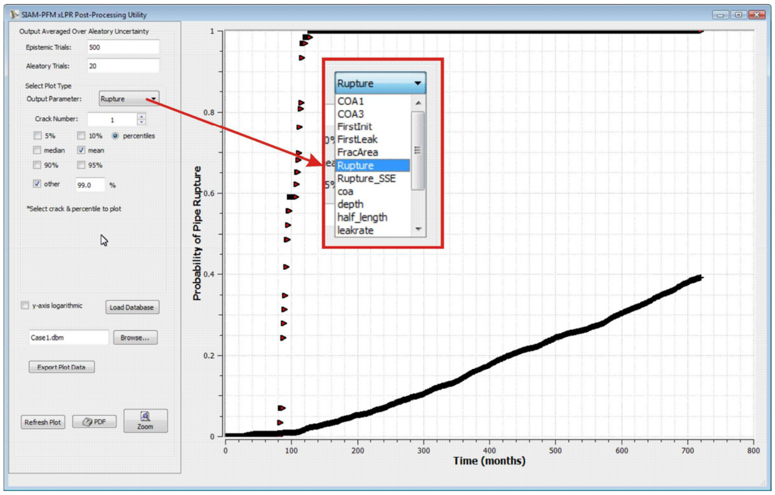


Fig. 44 Selected outputs can be visualized as an x vs y plot of the mean and user-selected percentiles.

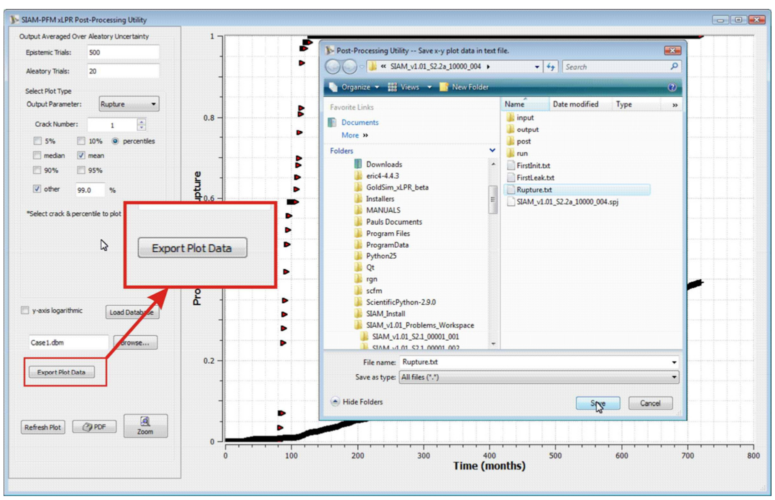
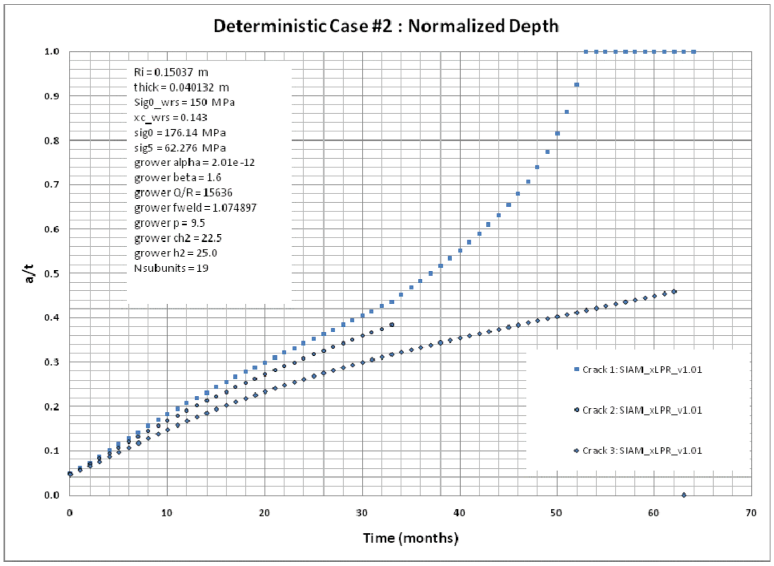


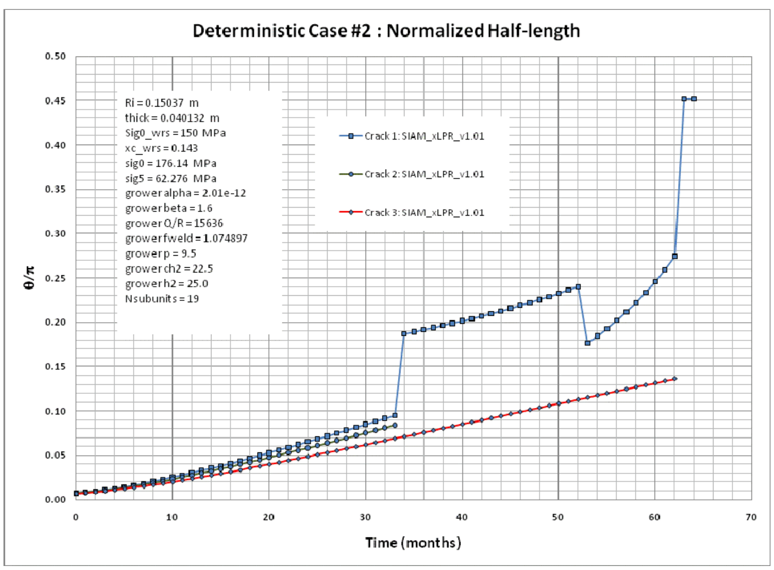
Fig. 45 The plotted data can be saved to a text file by clicking the Export Plot Data button.

3.6 Analysis of deterministic sample problem

In this section, we present the results of a deterministic problem proposed by the collaborative xLPR Computational Group as a means of verification and benchmarking some of the individual modules in the xLPR pilot project [10]. This problem was devised specifically for the purpose of verification and the results have no technical significance for the final probabilistic results that will be developed by the project. Fig. 46 shows the evolution over time of the growth of three inner surface cracks that all initiate at time 0. Crack 1 coalesces with crack 2 at 33 months into the analysis, when combined crack 1/2 now becomes a combined and larger surface crack with a new location. The combined crack 1/2 then transitions to through-wall crack at 53 months and then coalesces with crack 3 at 62 months into the analysis. At 64 months combined cracks 1/2/3 fail the weld.



(a)



(b)

Fig. 46 Deterministic verification problem: evolution over time of (a) normalized crack depth and (b) normalized crack half-length for three surface crack initiating at time 0.

3.7 Analysis of summary results from probabilistic problem

Fig. **47** shows some selected summary results from the baseline specification of the xLPR problem. For each of 50,000 trials, the test weld was analyzed over a 60 year plant time horizon, and any leakages or pipe ruptures were recorded. The results were then post-processed using the Transformers/Expectation post-processing module to produce probabilities of occurrence for first initiation, first leakage, and finally pipe rupture.

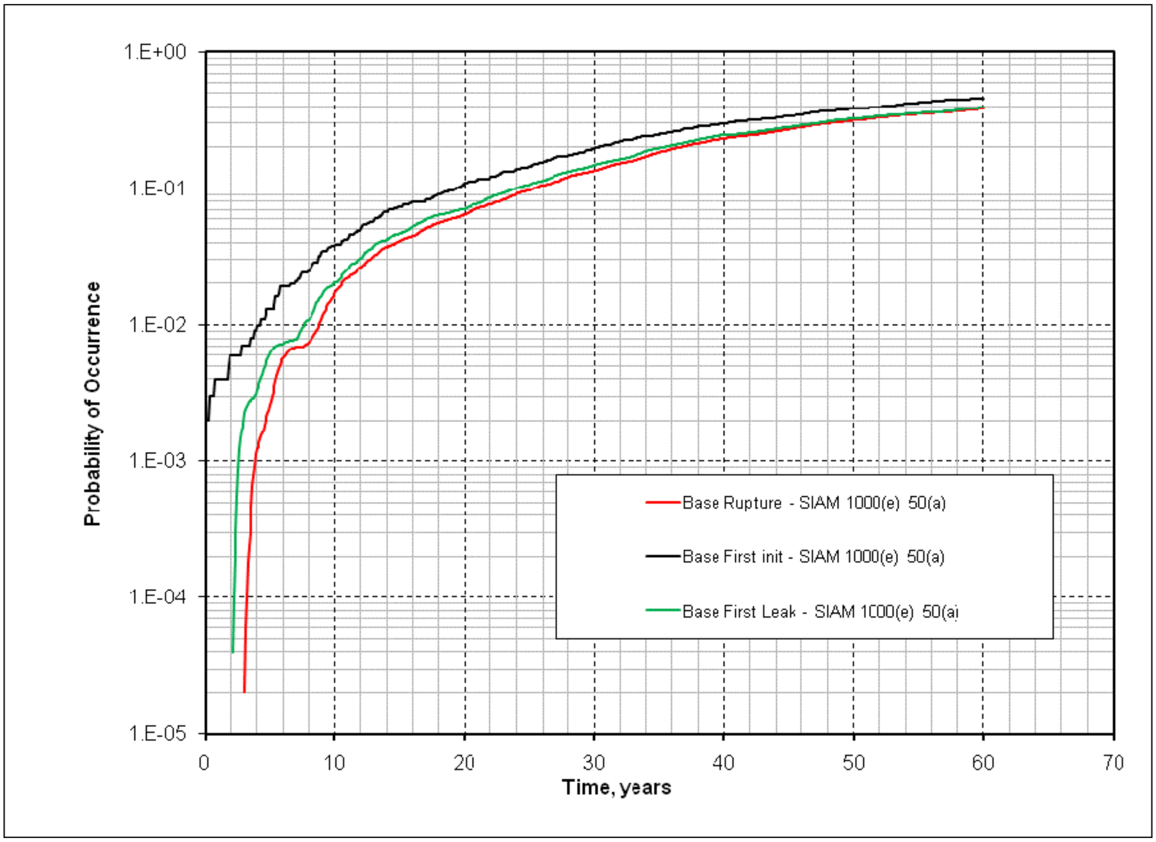


Fig. 47 **Probabilistic results of the of SIAM-xLPR pilot study: (a) cumulative probability of first initiation, first leakage, and pipe weld rupture.**

4 Integrating and Testing New xLPR Modules

Note: The following section assumes that the user has some working knowledge of integrating Python and Fortran codes integration. The online help file "Help on f2py" provides detailed information.

Because the modules that implement the models composing the xLPR core (see Fig. 2 and Fig. 3) can change over time, SIAM-xLPR comes equipped with a utility to integrate upgrades in the Fortran modules. This utility incorporates a new module into the SIAM-xLPR framework and creates the required software wrapper code files that together will work as a communicating "bridge" between the Fortran module and the rest of the SIAM-xLPR framework.

The SIAM-xLPR framework has been developed primarily using the Python v.2.6 programming language. To use the Python/Wrapper f2py Utility (see Fig. 48), the user selects "Fortran to Python Utility" under the Tools menu and follow the instructions given below. As the first step, we advise clearing the temporary folder used to create a temporary copy of the files, by clicking the 'Clear Temp' button in the Source Files Build List. To check the availability of the Fortran 95 and C compilers click on the 'Check' buttons on the right side of the Compilers section.

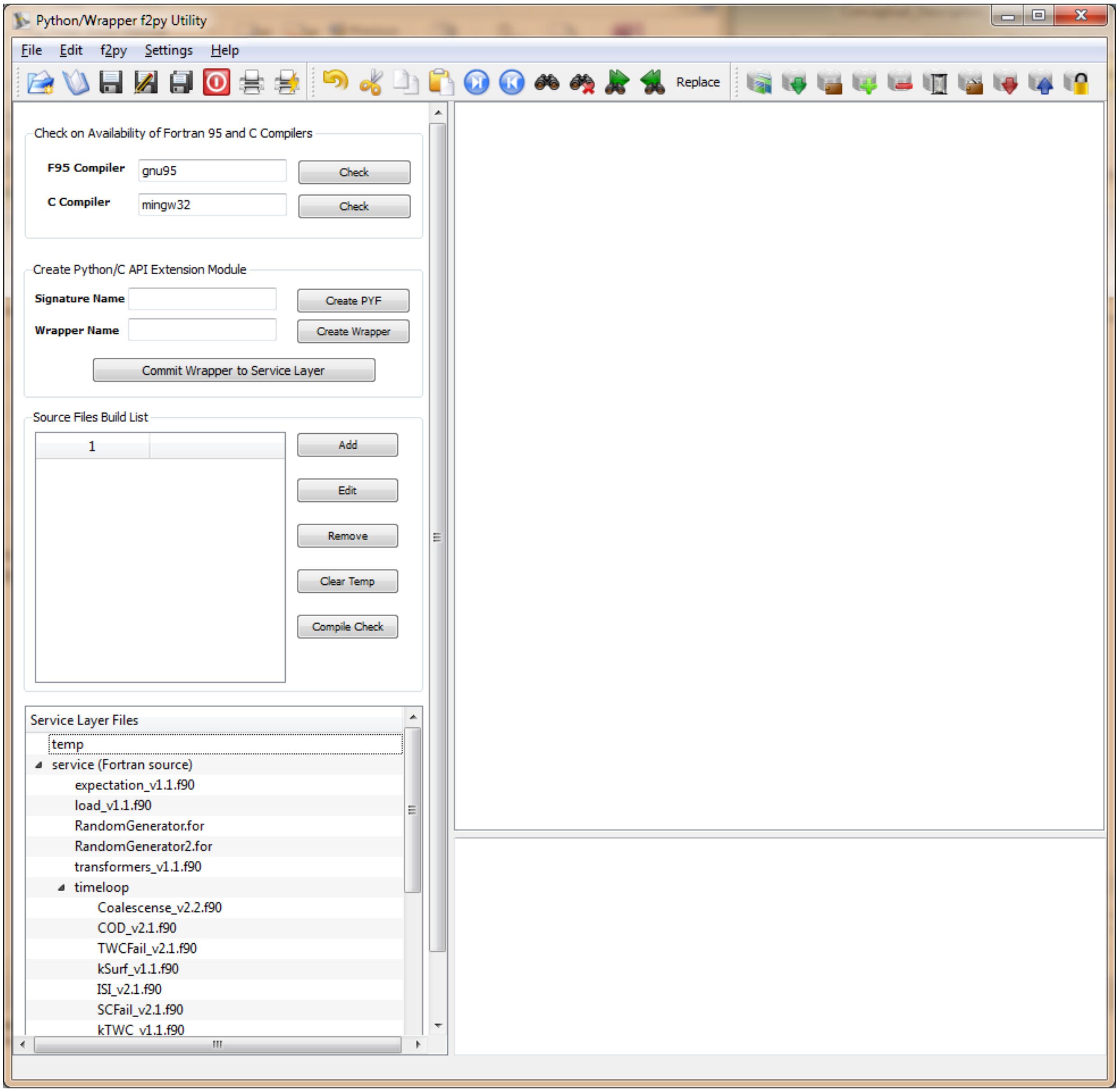


Fig. 48 Python Wrapper f2py Utility Window.

4.1 How to integrate or test a change in one of the timeloop modules

Because the timeloop module is integrated as a unit, compilation of all modules components is required for each change to any of the modules or to the timeloop module itself. This process in outlined in the steps below.

1. Select the module to create:

1.1 Add Signature Name:

1.1.1. In the 'Service Layer Files' panel, navigate to the service (signature)>timeloop and select TimeLoopSignature.pyf

1.1.2. Right click on TimeLoopSignature.pyf and select 'Add file to list'. This will add the TimeLoopSignature.pyf file name in the 'Signature Name' input field on the 'Create Python/C API Extension Module' panel.

1.2 Add Wrapper Name:

1.2.1. In the 'Service Layer Files' panel, navigate to the service (wrapper binaries)>Windows> and select TimeLoopWrapper.pyd

1.2.2. Right click on TimeLoopWrapper.pyd and select 'Add file to list'. This will add the TimeLoopWrapper file name in the 'WrapperName' input field on the 'Create Python/C API Extension Module panel'.

2. Add the 'Source Files Build List':

2.1. In the 'Service Layer Files' panel, navigate to the service (Fortran source)>timeloop> and per each Fortran file:

2.1.1 Right click on it and select 'Add file to list'

Note: To ensure that a files compiles, select a file in the ‘Source Files Build List' and click on 'Compile Check' button.

3. Create PYF. At the 'Create Python/C API Extension Module' panel, click on 'Create PYF'.

4. Create Wrapper. At the 'Create Python/C API Extension Module' panel, click on 'Create Wrapper'.

The creation of the wrapper will take a few minutes and the output of the process will be presented on the right side panel of the screen. If the process completes successfully, the exit code will be zero (0). Otherwise, check the output, fix the issues and repeat the process above.

5. Commit changes. So far, all changes have taken place in a 'Temporal' directory. To commit the changes to the SIAM-xLPR framework, click the 'Commit' button.

4.2 How to integrate or test changes to modules not in the timeloop

To integrate changes to other modules such as the Load module or the Random Generator module, the process is simpler, as the number of required files is smaller. This process in outlined in the steps below.

1. Select the module to create:

1.1 Add Signature Name:

1.1.1. In the 'Service Layer Files' panel, navigate to the <name>Signature.pyf file.

1.1.2. Right click on <name>Signature.pyf and select 'Add file to list'. This will add the file name in the 'Signature Name' input field on the 'Create Python/C API Extension Module' panel.

1.2 Add Wrapper Name:

1.2.1. In the 'Service Layer Files' panel, navigate to the service (wrapper binaries)>Windows> and select <name>Wrapper.pyd

1.2.2. Right click on <name>Wrapper.pyd and select 'Add file to list'. This will add the file name in the 'WrapperName' input field on the 'Create Python/C API Extension Module panel'.

2. Add the 'Source Files Build List':

2.1. In the 'Service Layer Files' panel, navigate to the Fortran source file:

2.1.1 Right click on it and select 'Add file to list'

Note: To ensure that a files compiles, select a file in the ‘Source Files Build List' and click on 'Compile Check' button.

3. Create PYF. At the 'Create Python/C API Extension Module' panel, click on 'Create PYF'.

4. Create Wrapper. At the 'Create Python/C API Extension Module' panel, click on 'Create Wrapper'.

The creation of the wrapper will take a few minutes and the output of the process will be presented on the right side panel of the screen. If the process completes successfully, the exit code will be zero (0). Otherwise, check the output, fix the issues and repeat the process above.

5. Commit changes. So far, all changes have taken place in a ‘Temporal’ directory. To commit the changes to the SIAM-xLPR framework, click the 'Commit' button.

5. References

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6 Installation of SIAM-PFM on Windows OS Computers

6.1 PREPARING FOR INSTALLATION

Administrative privileges are required for installing SIAM_xLPR. If you are not logged in with full-time administrative privileges then you will need to obtain temporary administrative privileges before proceeding with the installation. The following instructions assume that you are working with temporary administrative privileges.

6.2 INSTALLATION

SIAM_xLPR is installed by executing the following three binary installers in the order specified:

1. SIAM_xLPR_<version>.exe
2. SIAM_Dependencies1.exe
3. SIAM_Dependencies2.exe

On computers running the Microsoft XP operating system, right click on the executable file name in Windows Explorer and select “Run As…”. Next select “The following user:”, enter the administrative user name and password, and click “OK”. These instructions also work for Windows 7 and Vista. However, the executable can be run on Windows 7 and Vista simply by double clicking on the executable file name. The user will be prompted for an administrative user name and password when needed. On Windows XP computers double clicking the executable file name will result in a partial install culminating in the display of an error message. When the executable is re-run with administrative

Step 1. Locate (on desktop or in a file folder) and run the three SIAM binary installers in order as shown below:

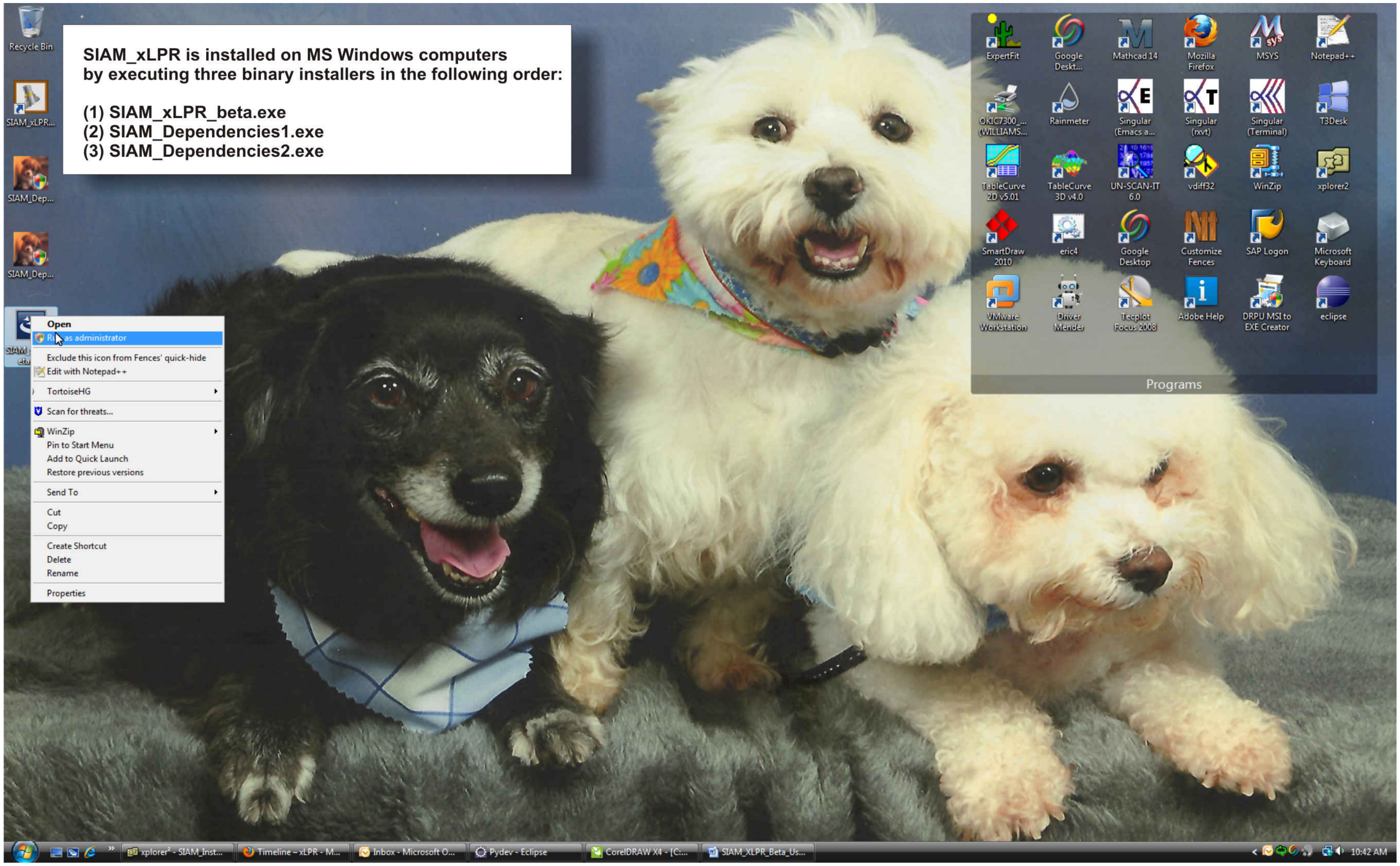


Fig. 49 Locate and run the SIAM_xLPR installer.

Step 2: Click “Next” on the SIAM_xLPR executable welcome screen, see figure 50 below:

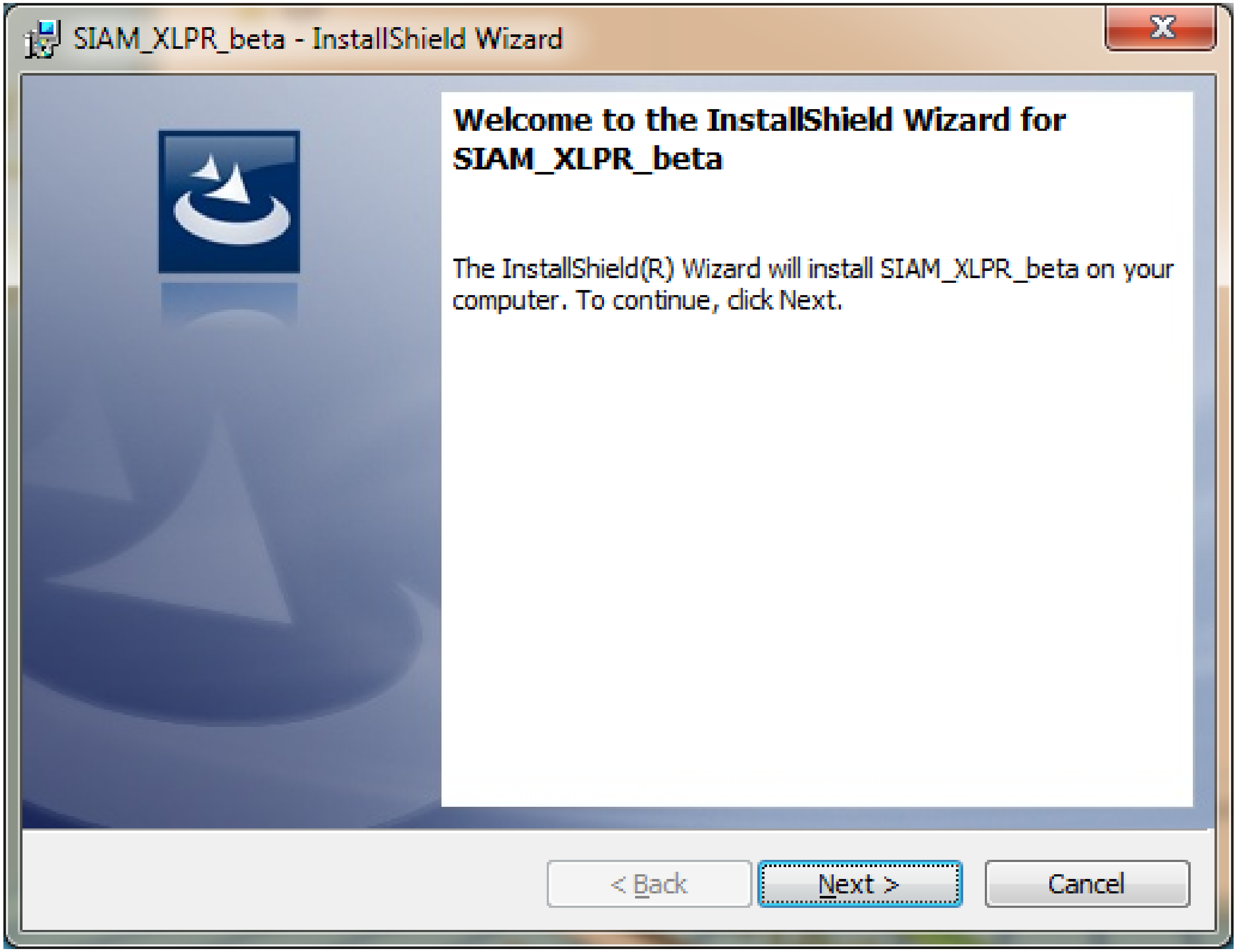


Fig. 50 SIAM_xLPR Installation Wizard.

If the user is not logged into the system with full administrative privileges, Windows 7 and Vista will automatically prompt for a temporary administrator user name and password in a dialog similar to Fig51. An example of the Windows XP administrative privileges dialog is shown in Fig. 54.

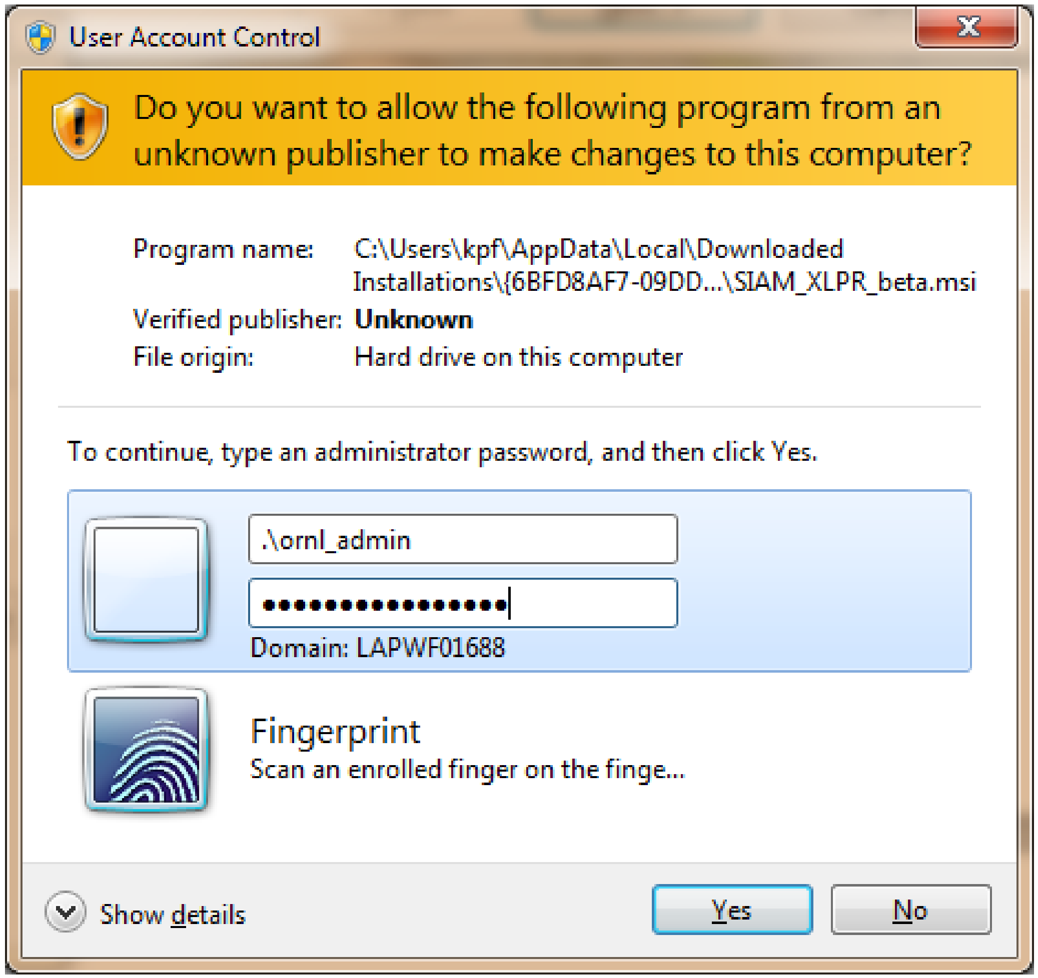


Fig. 51 Administrative privileges dialog for Windows 7 and Vista.

Step 3: A status dialog informs the user of progress as installation files are copied to the installation directory.

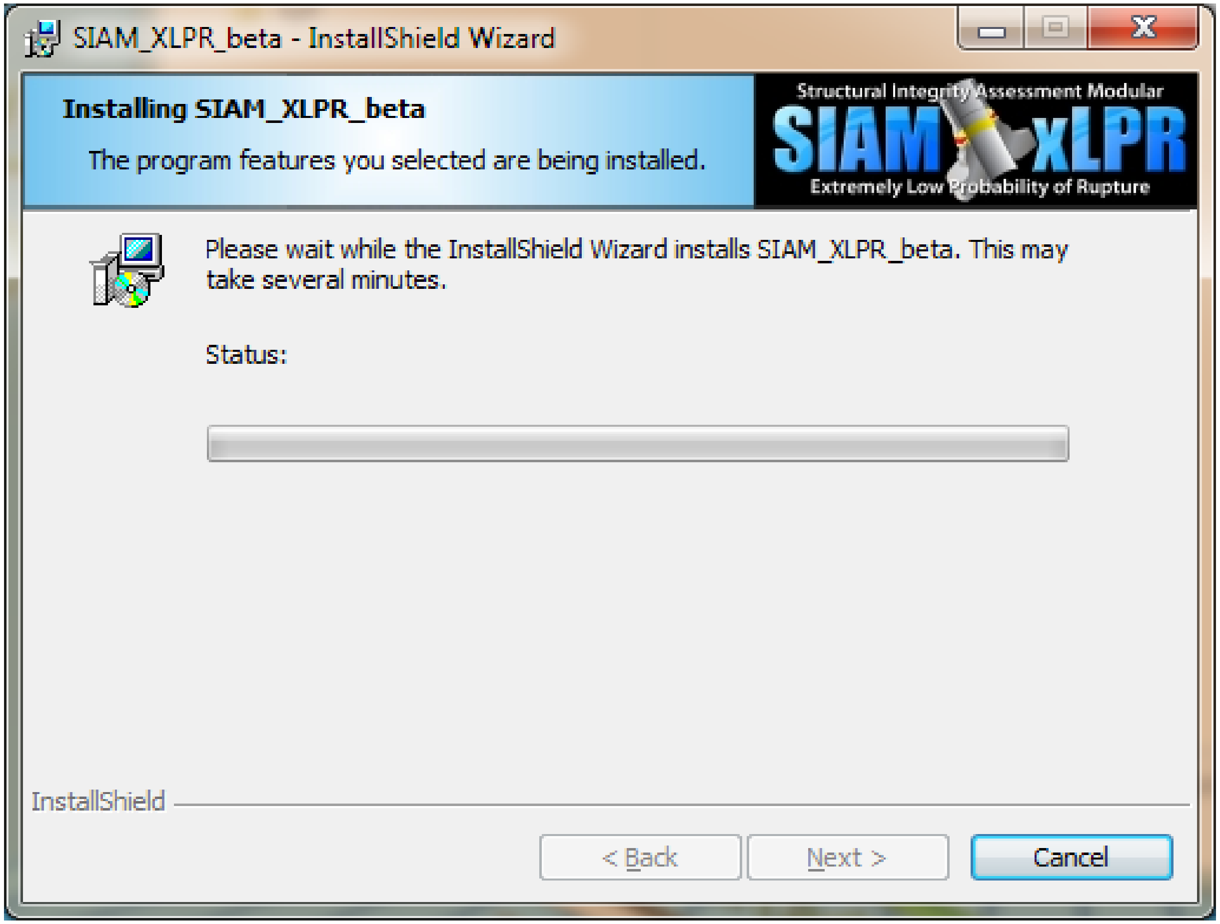


Fig. 52 SIAM_xLPR installation status dialog.

Step 4: Another dialog is displayed when installation is completed successfully:

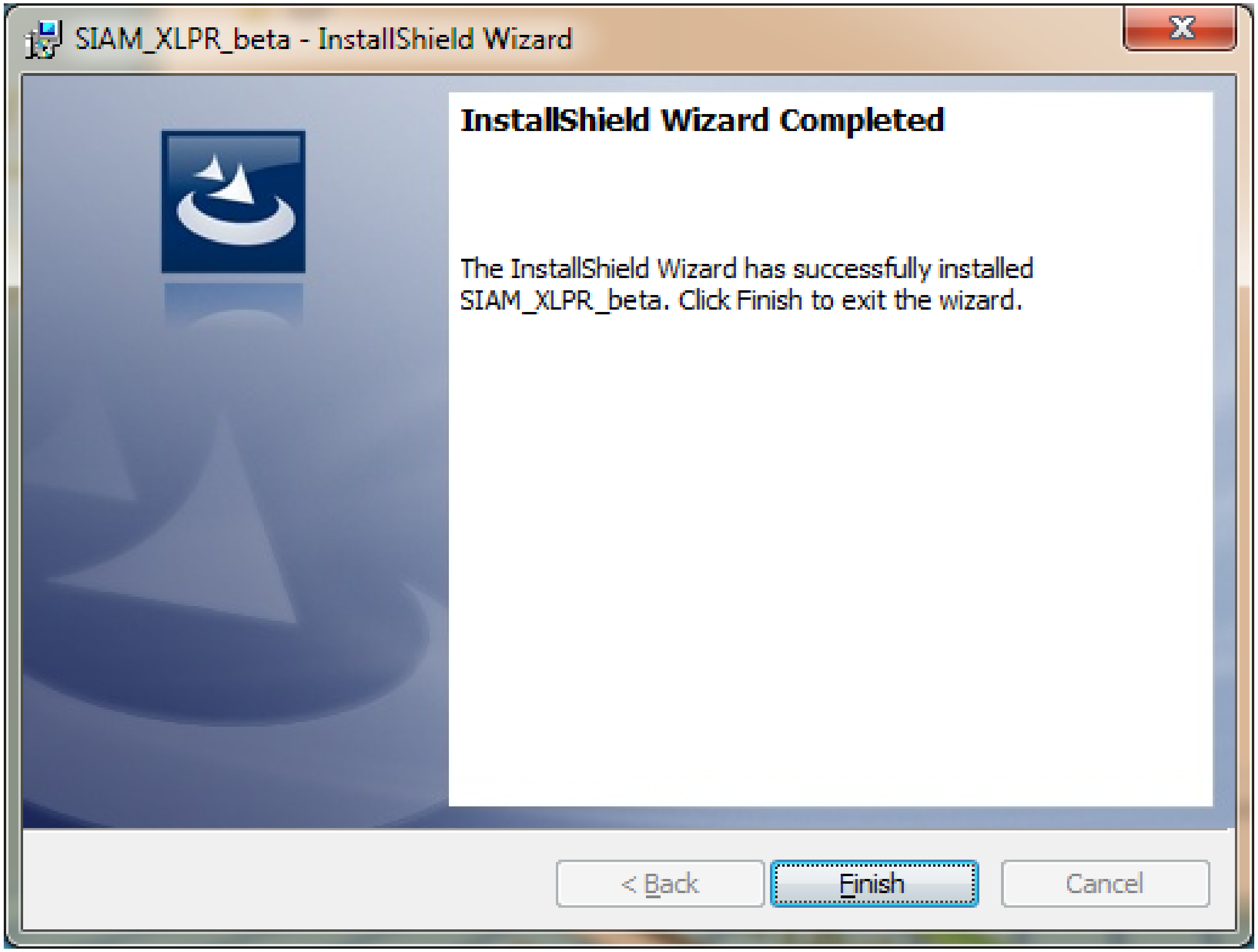
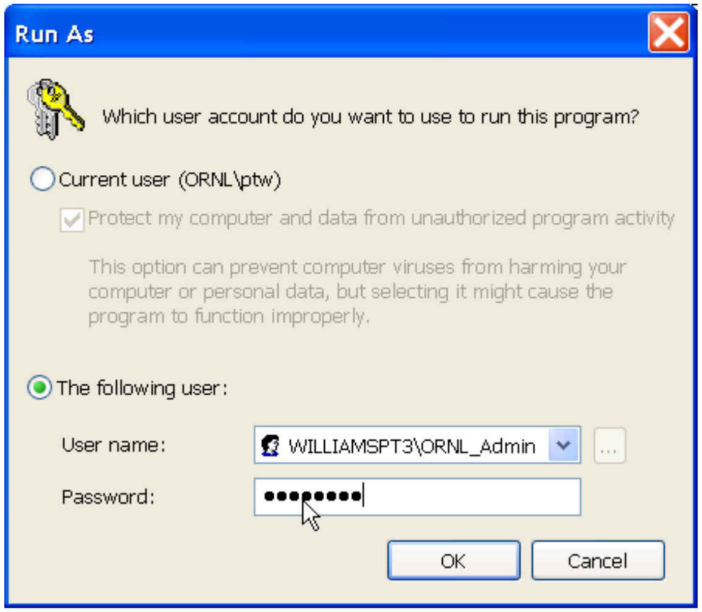


Fig. 53 SIAM_xLPR installation completed dialog.

Step 5: Run SIAM_Dependencies and enter administrative privileges user name and password when prompted.



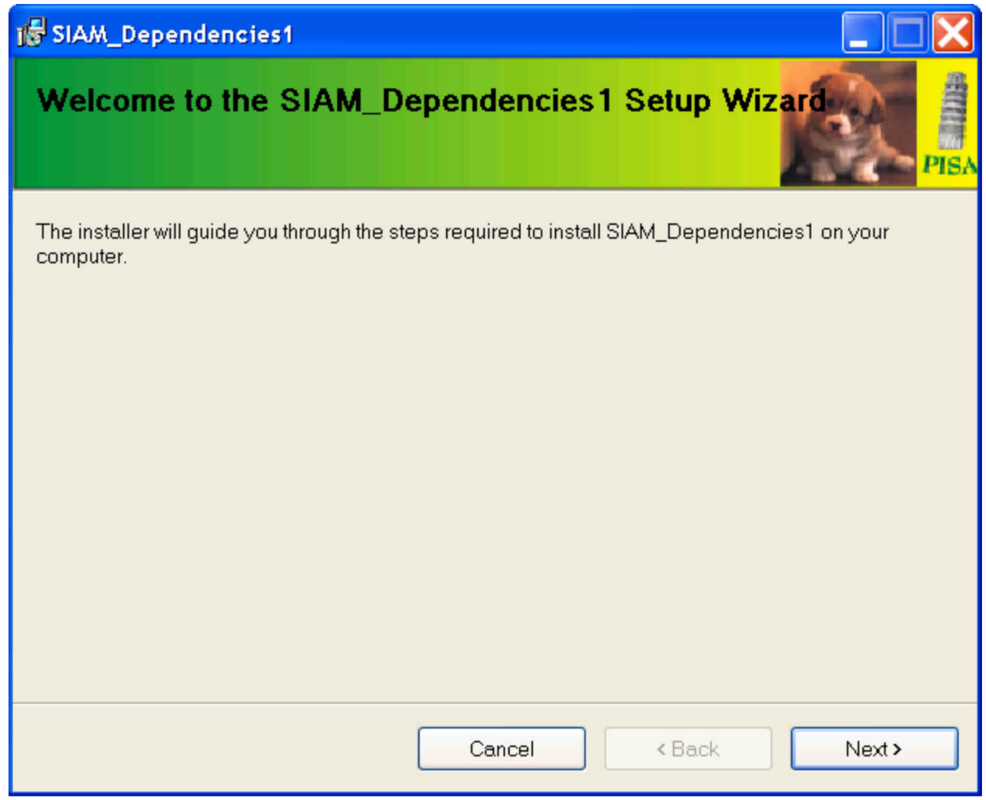
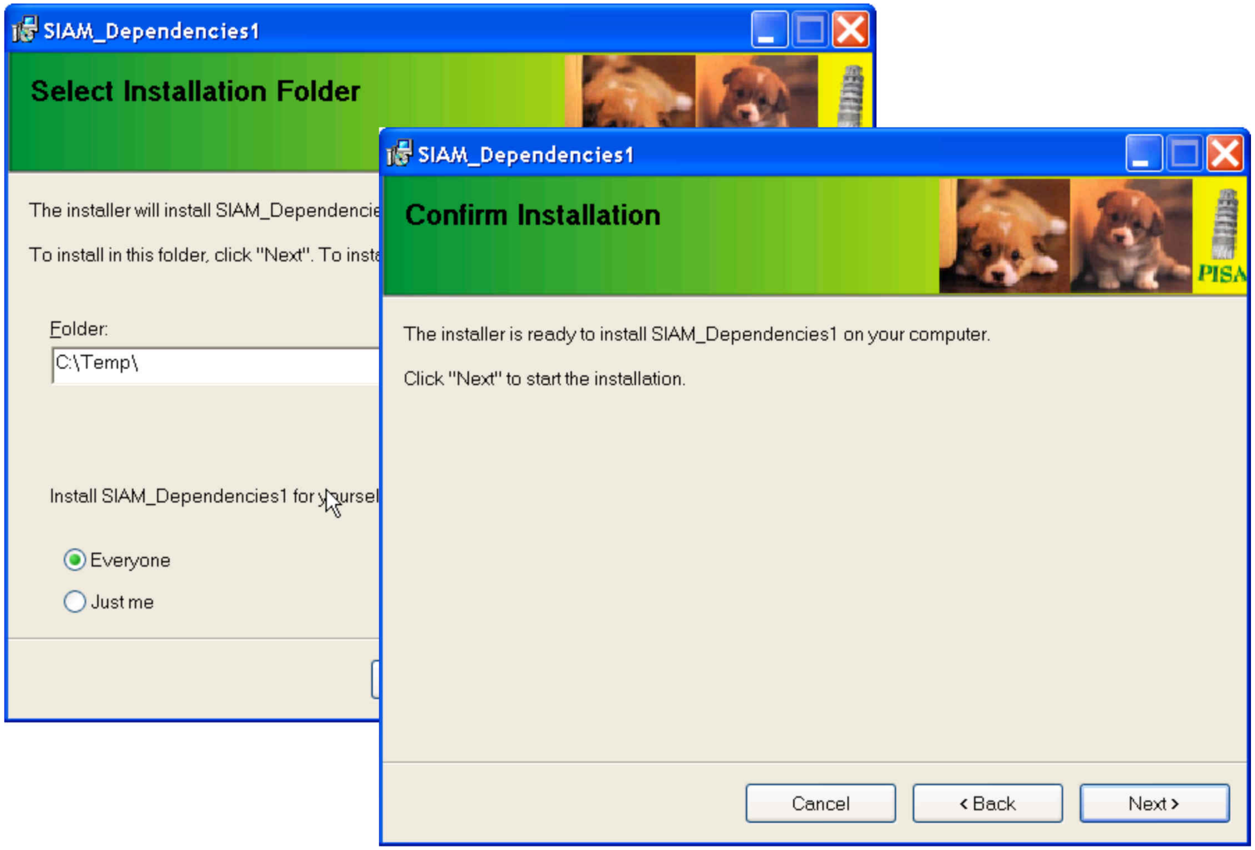


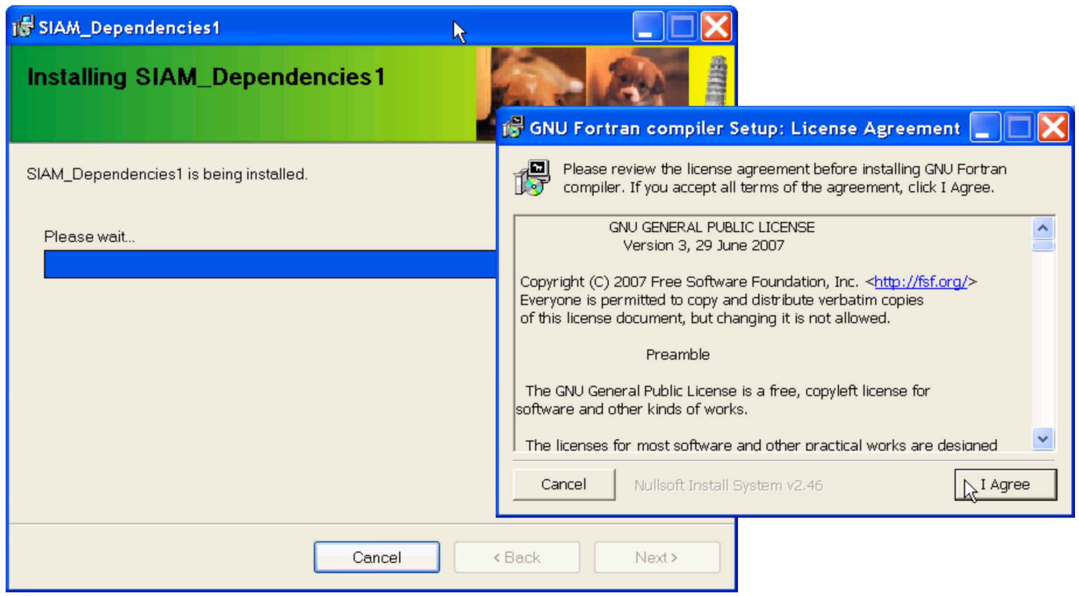
Fig. 54 Windows XP administrative privileges dialog and SIAM_Dependencies1 installation welcome dialog.

Select install for “Everyone” on the Select Installation Folder dialog. The folder selected in this dialog is used for temporary file space and is not the location where the permanent files will be located.



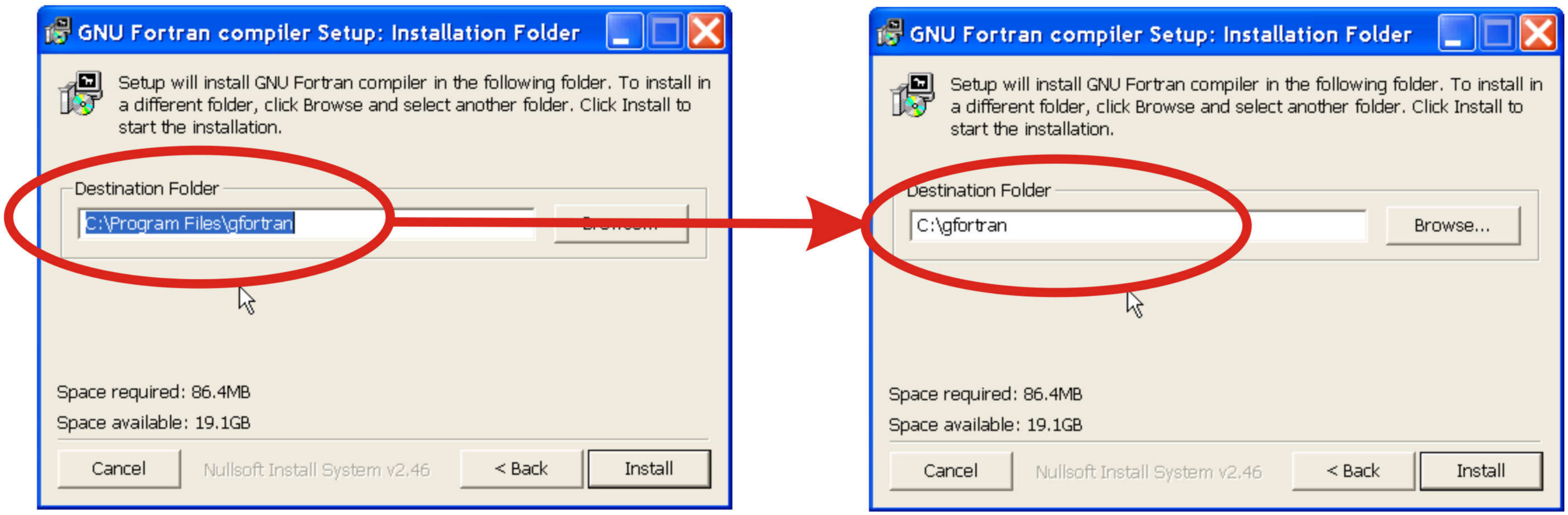
The SIAM_Dependencies1 executable first installs the GNU Fortran 95 compiler. On some small-screen laptops, you may need to move the "Installing SIAM_XLPR" window to the side in order to see this "GNU Fortran compiler Setup" window.

Next install the GNU Fortran 95 compiler: "gfortran"

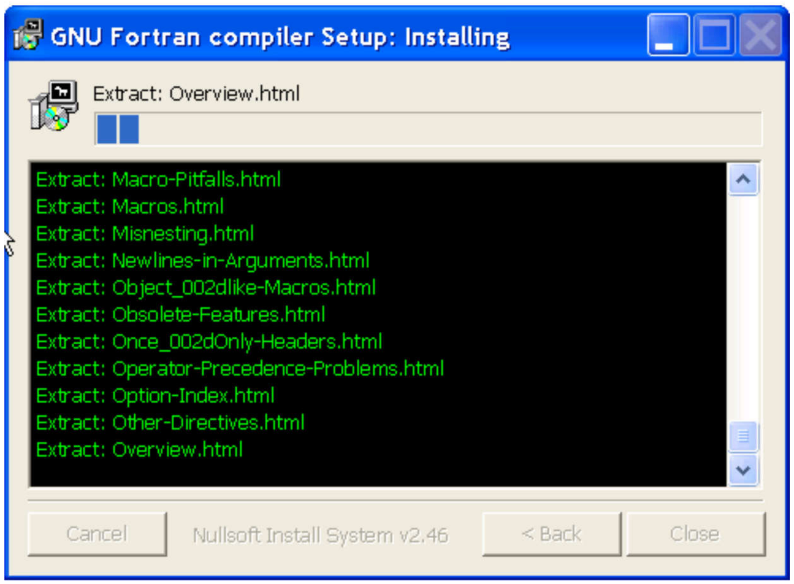


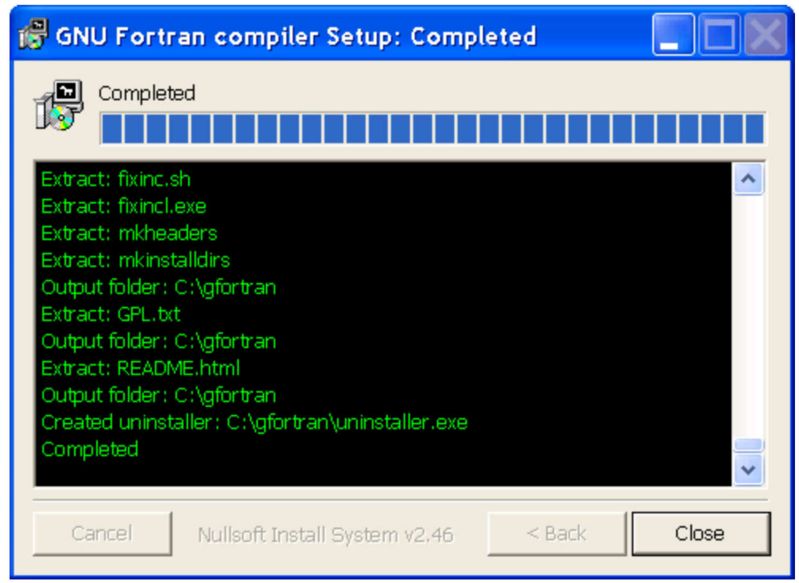
The install folder for the Fortran compiler MUST be changed from “C:\Program Files\gfortran” to “C:\gfortran”. Installation in the Program Files directory may cause problems in the execution of SIAM due to the space in the file name.

Be sure to change the installation directory from “C:\Program Files\gfortran” to “C:\gfortran”

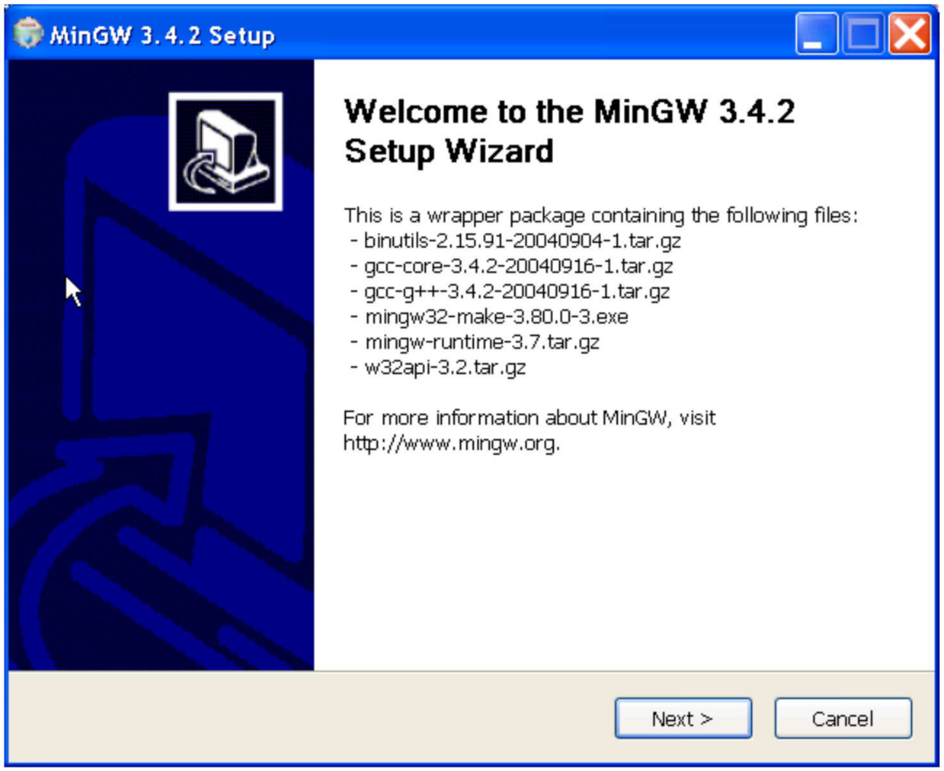


Complete the installation of "gfortran"

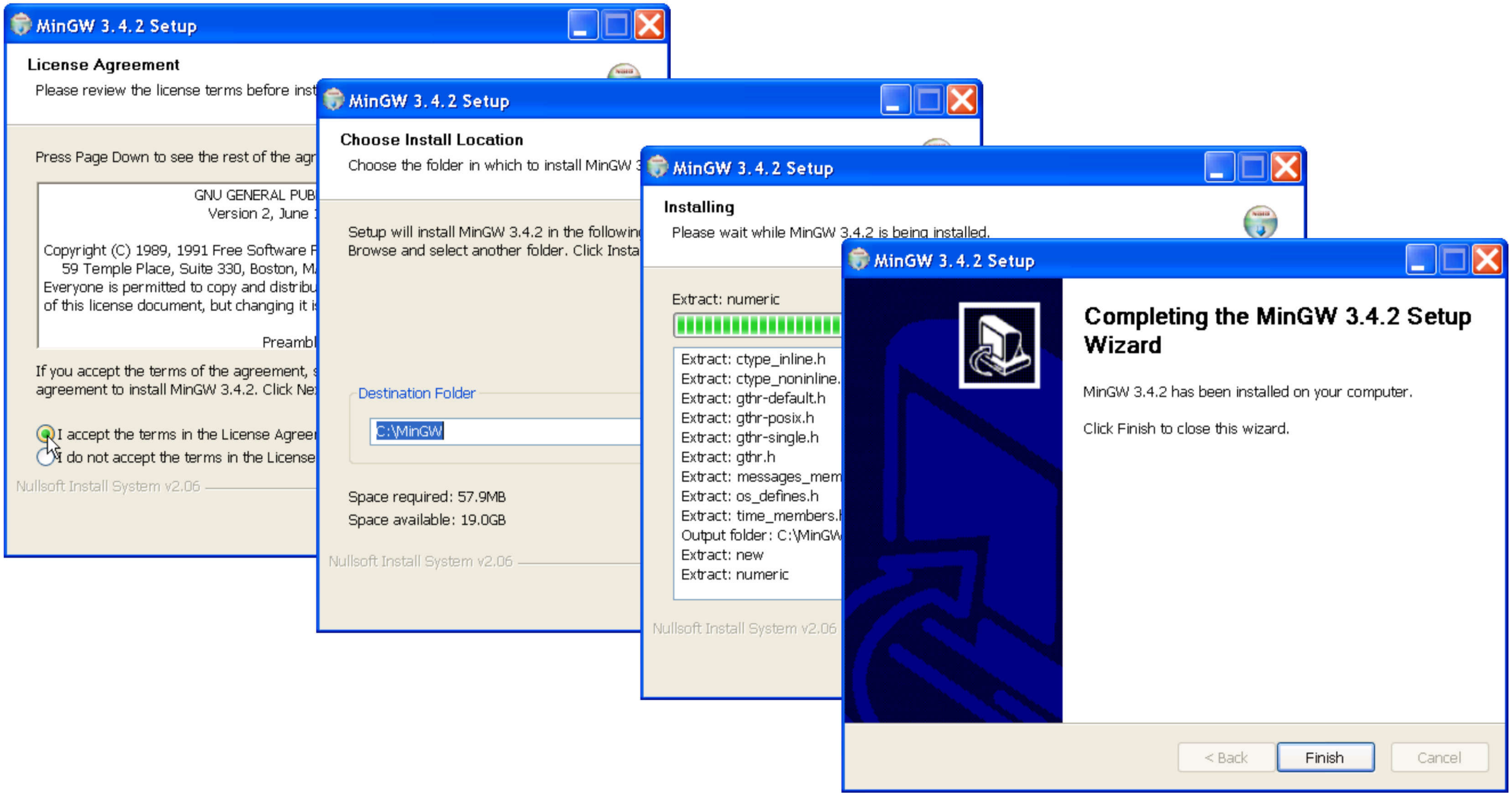




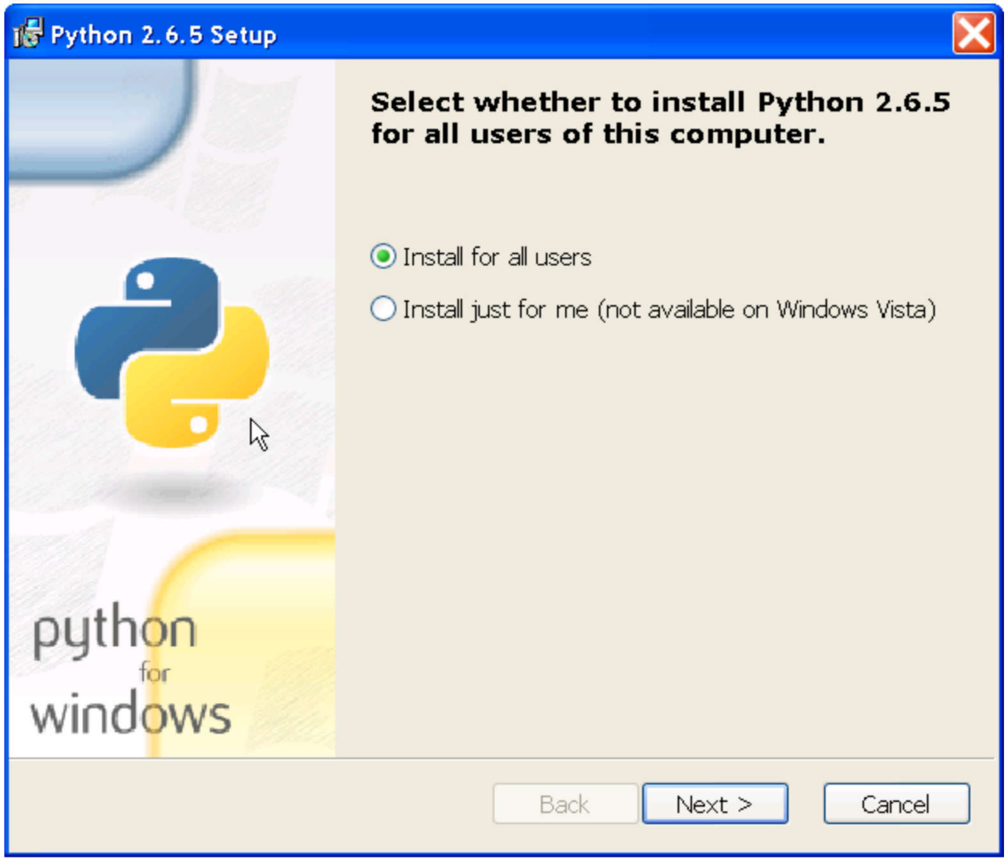
Next install the "Minimalist GNU for Windows" MinGW port of the GNU Compiler Collection (GCC) and GNU Binutils which includes C and C++ compilers.



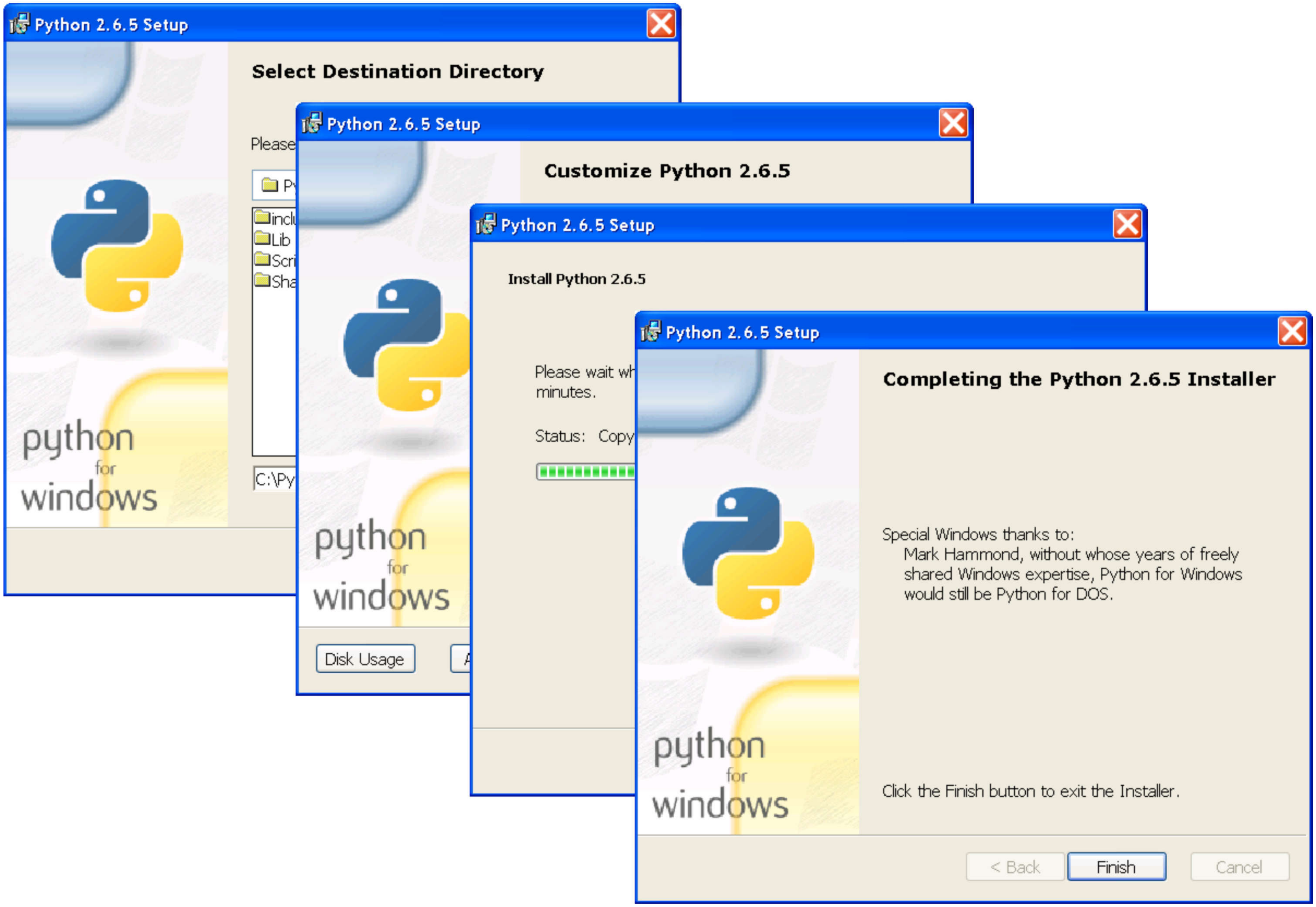
Accept the GNU License agreement and install in the default folder.



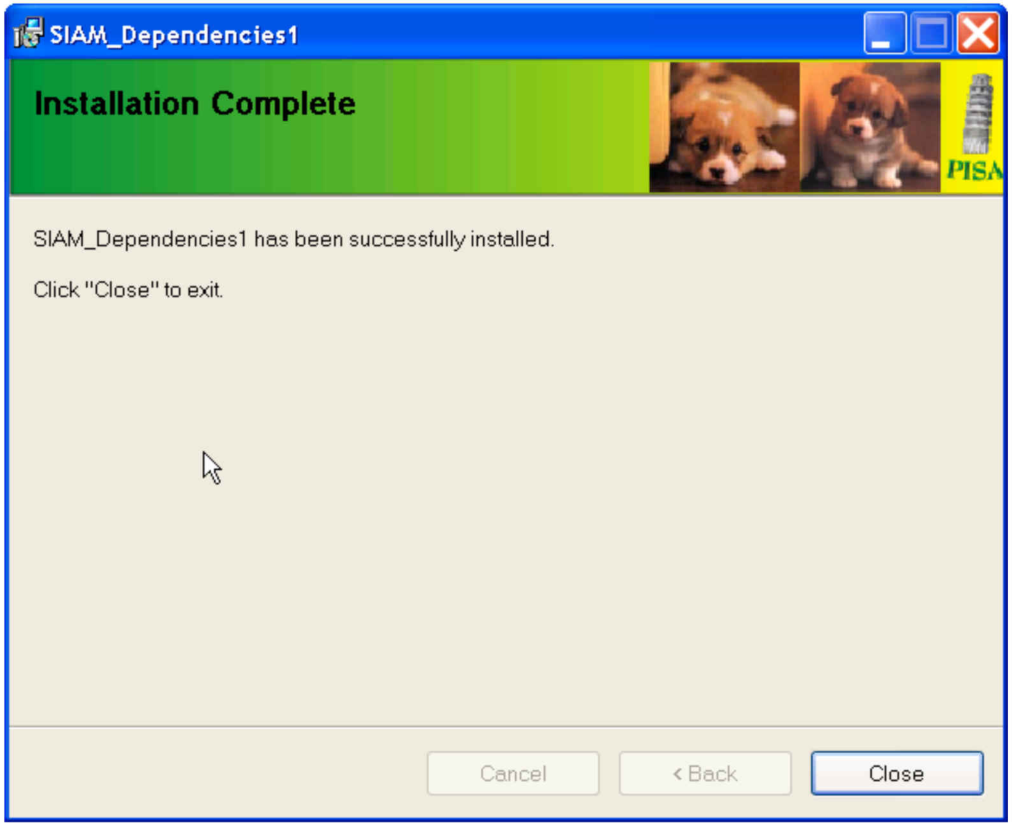
Install Python 2.6 for all users.



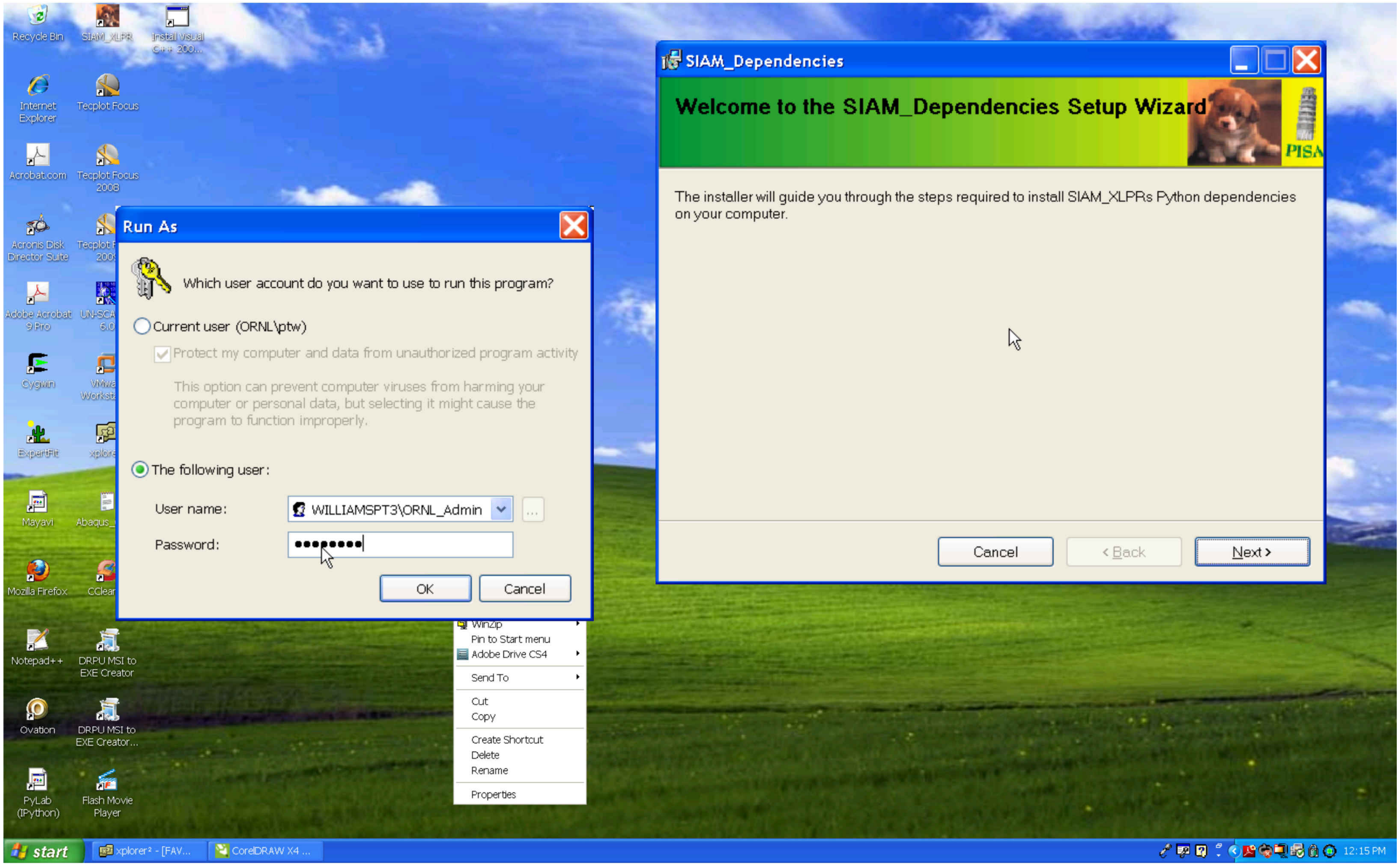
Accept all defaults and proceed with the installation.



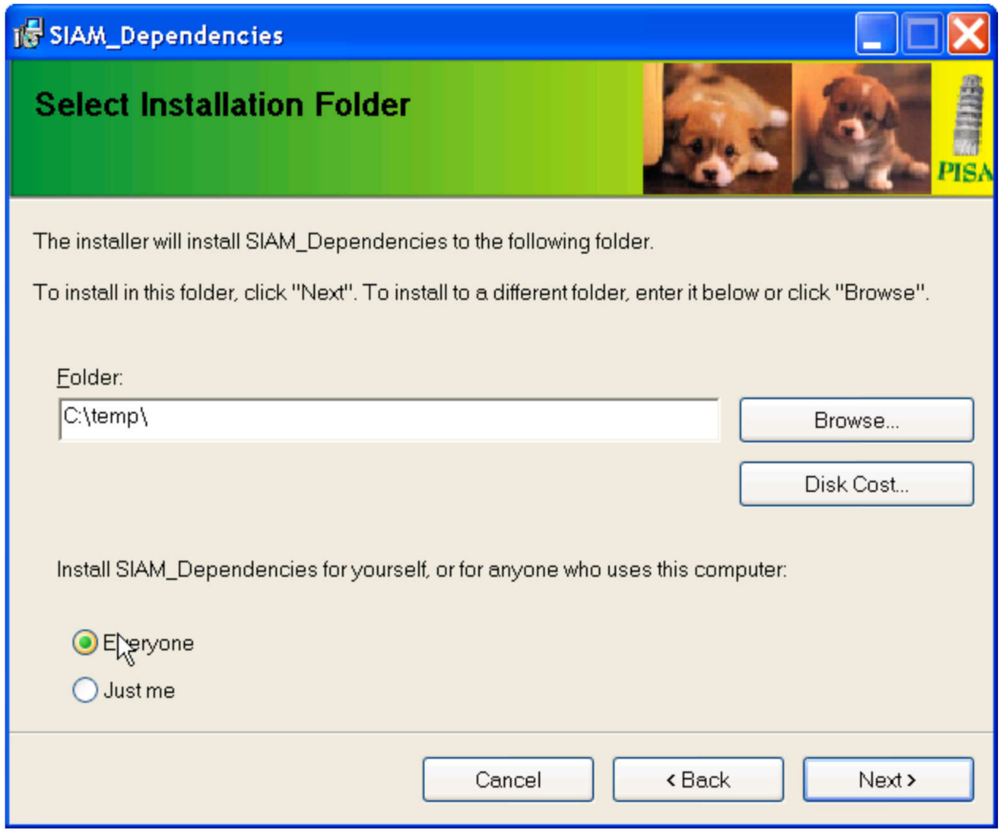
The next step is to install the SIAM_XLPR Python dependencies by running the SIAM_Dependencies2.exe installer.



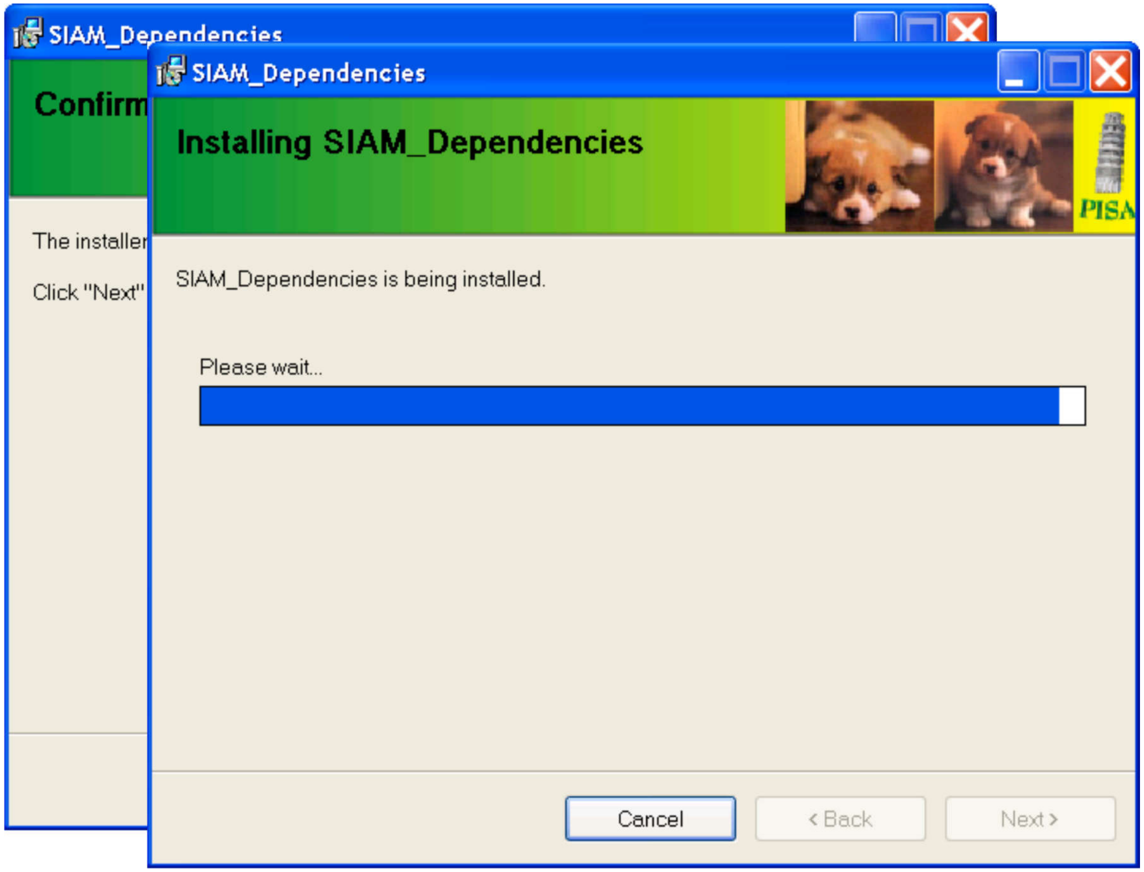
Run SIAM_Dependencies2.exe (required Administrator Privileges)



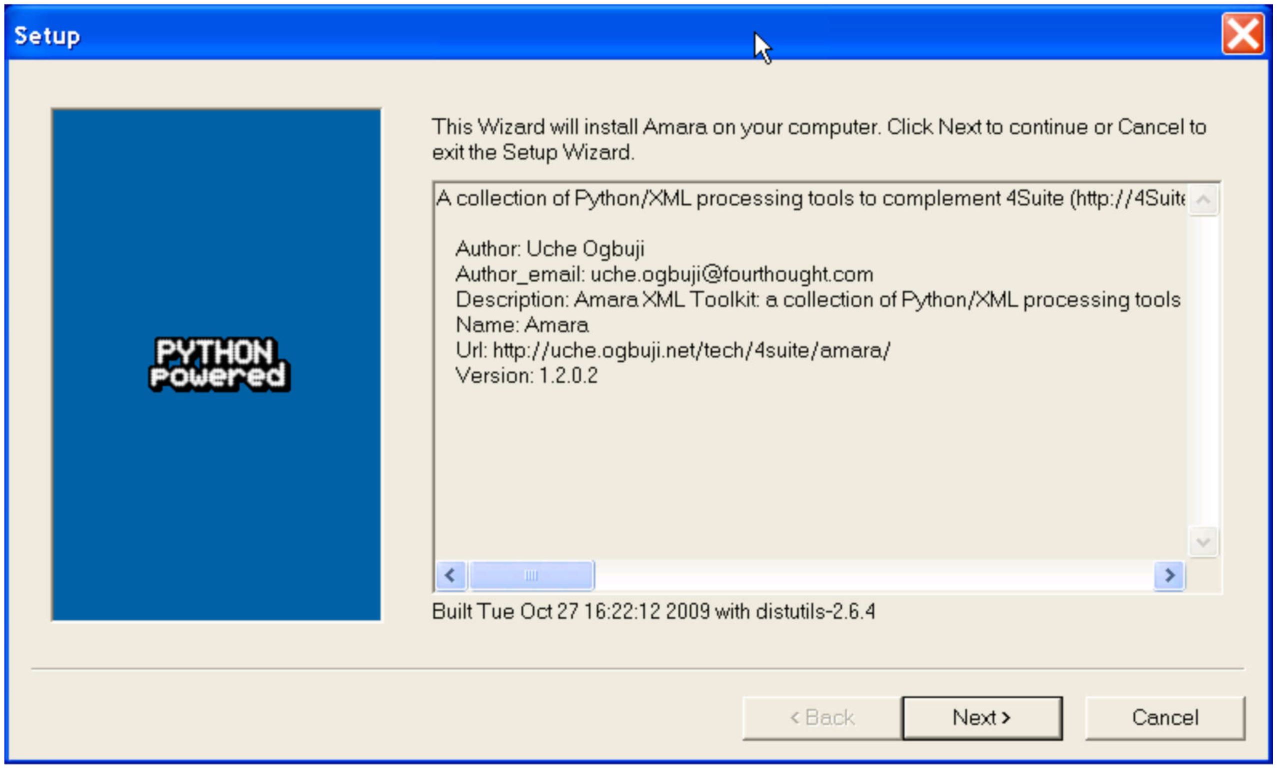
Be sure to install for Everyone.



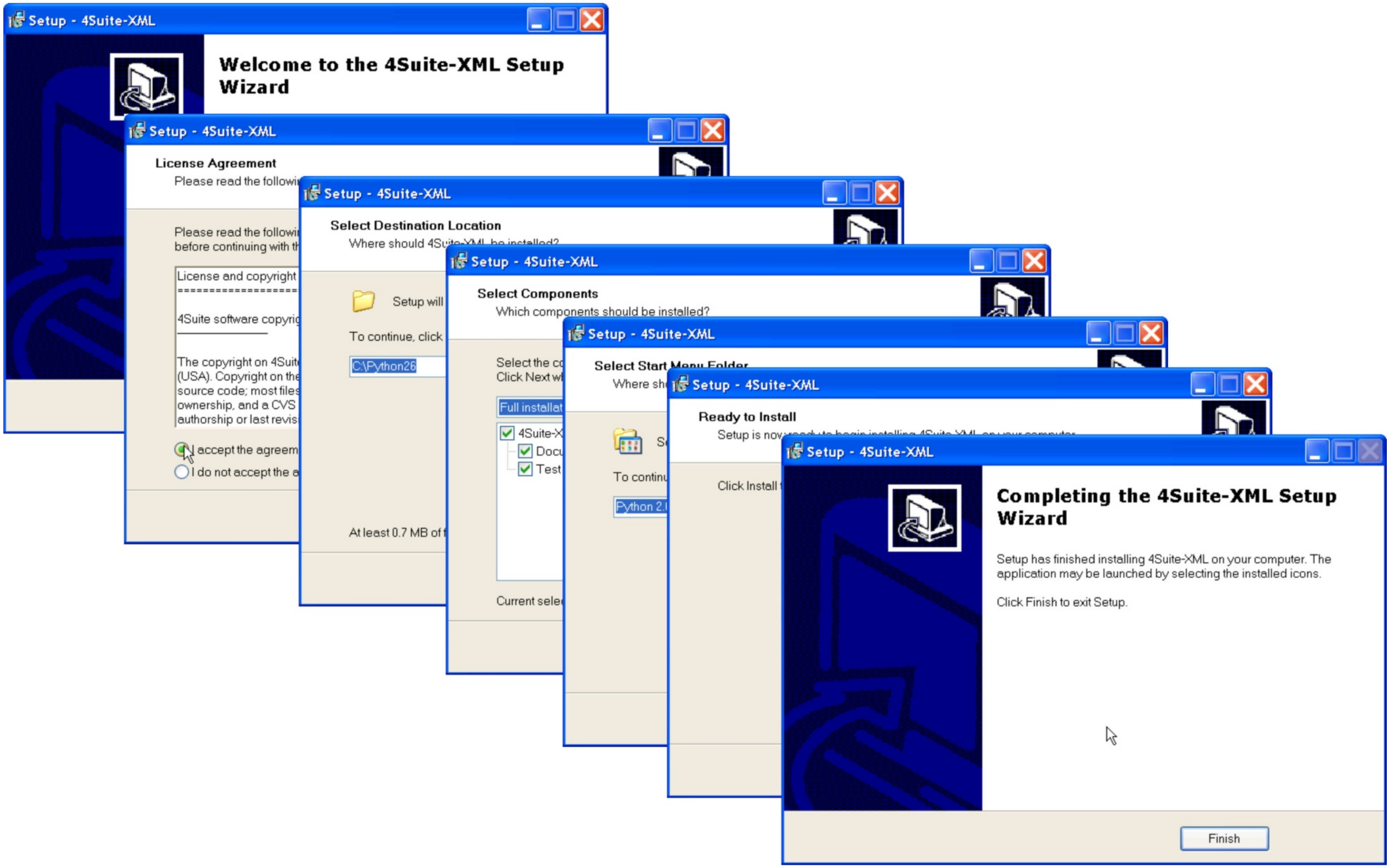
After the installation is complete, you can delete the installer files in the “C:\temp” folder.


SIAM_Dependencies
Confirm
The installer
Click "Next"
SIAM_Dependencies
Installing SIAM_Dependencies
PISA
SIAM_Dependencies is being installed.
Please wait...
Cancel
< Back
Next >

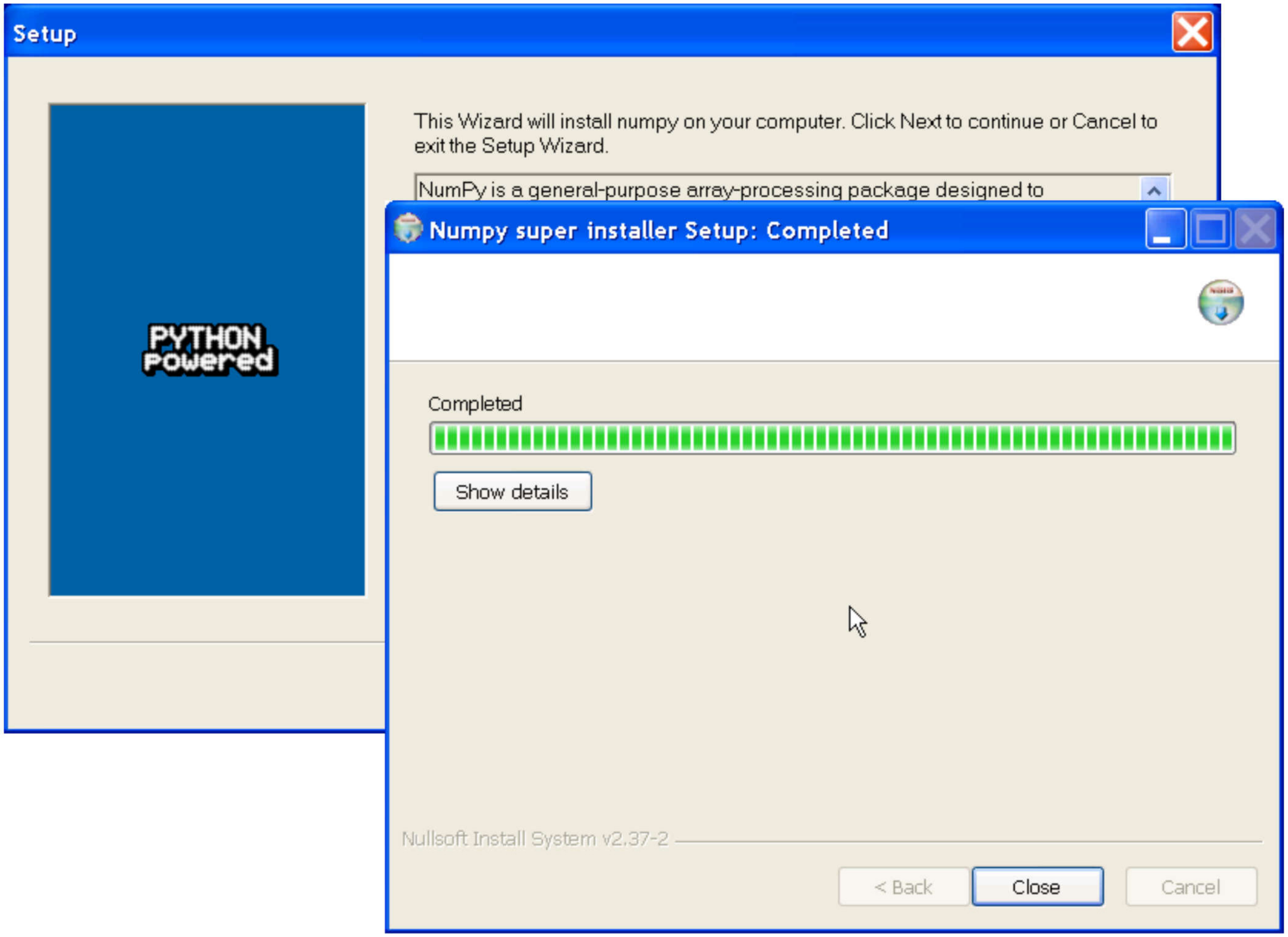
Install Amara and accept the defaults. Be sure to install in the Python 2.6 site-packages folder when prompted.



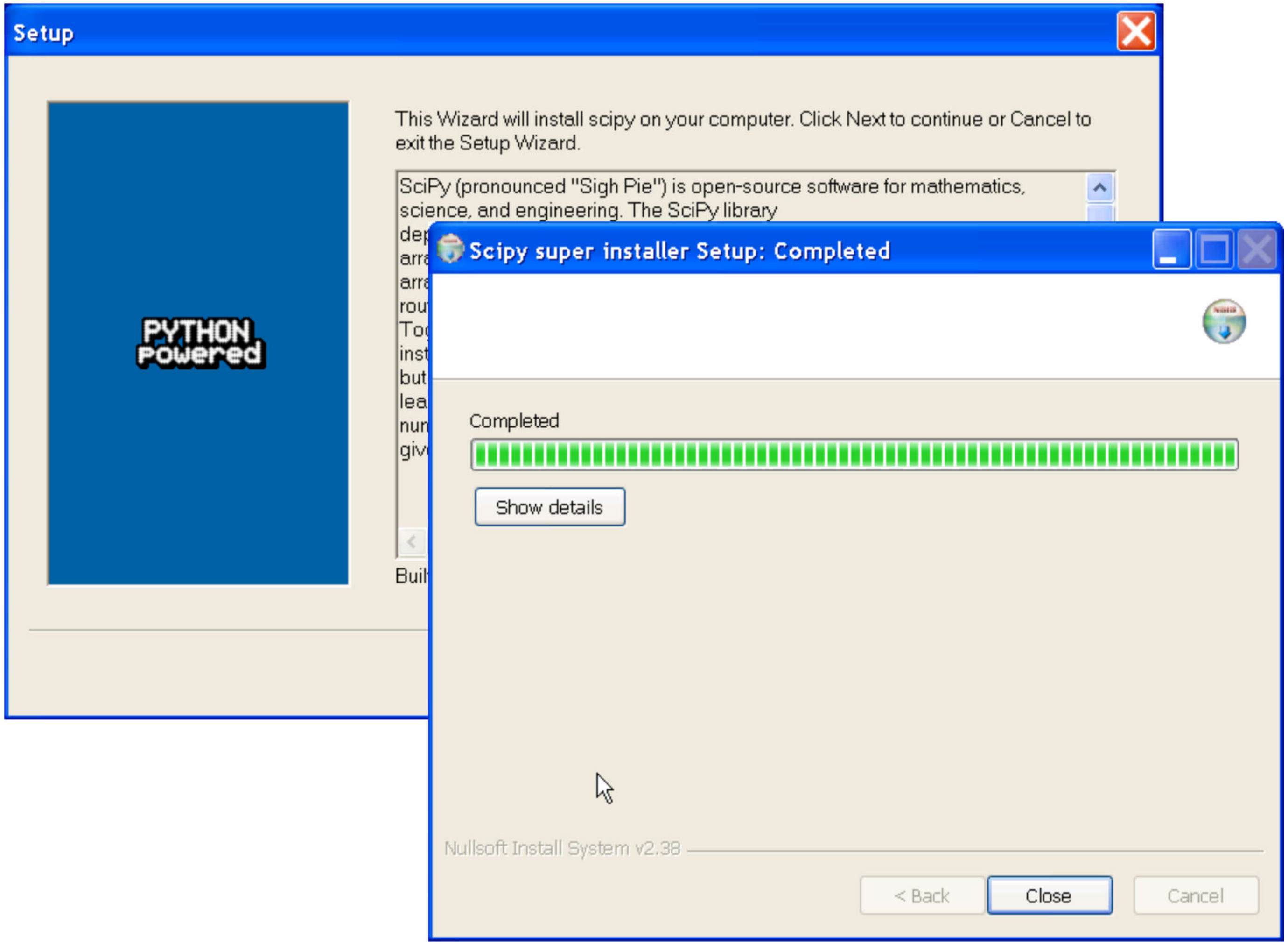
Install 4Suite-XML and accept all defaults.



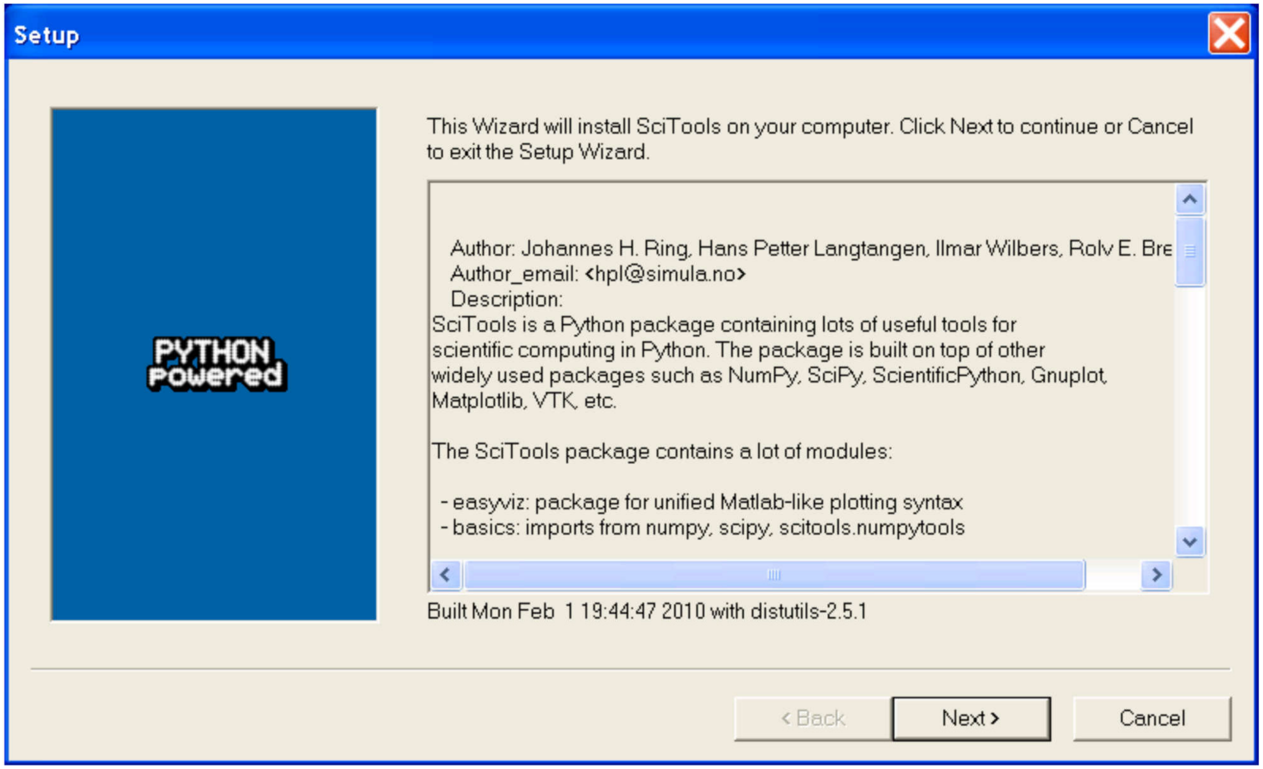
Install Numpy to the Python 2.6 site-packages folder.



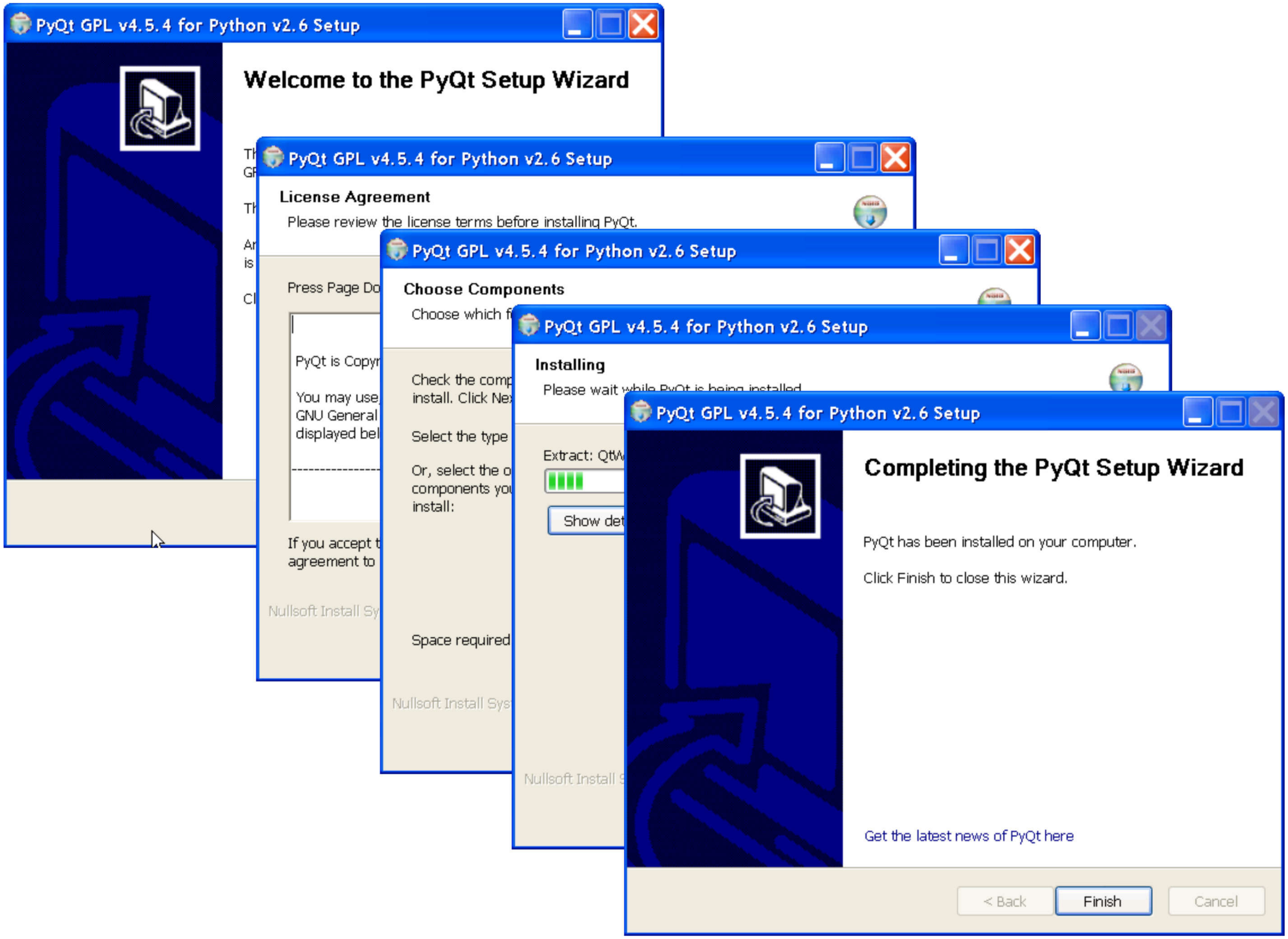
Install Scipy to the Python 2.6 site-packages folder.



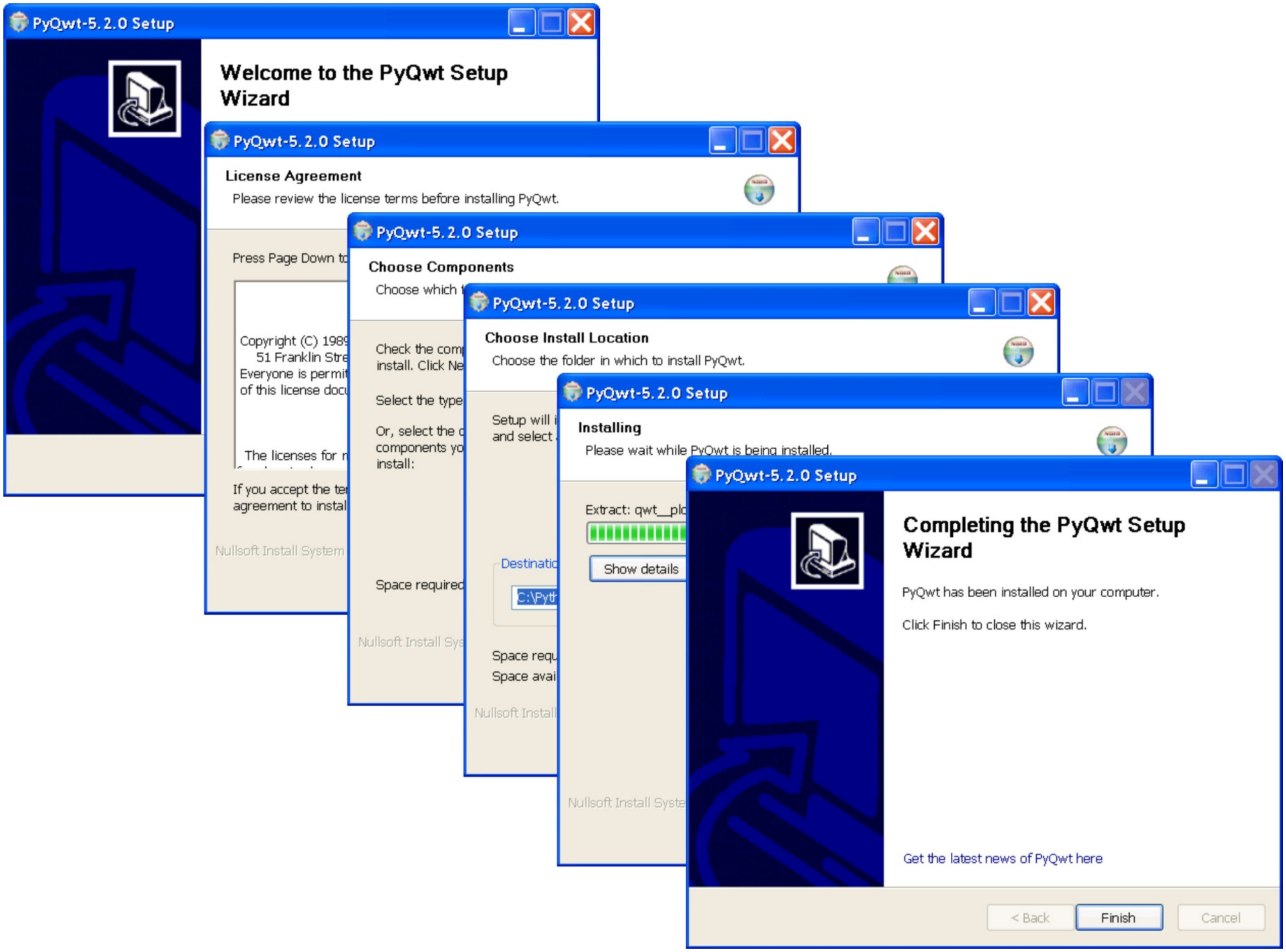
Install SciTools to the Python 2.6 site-packages folder.



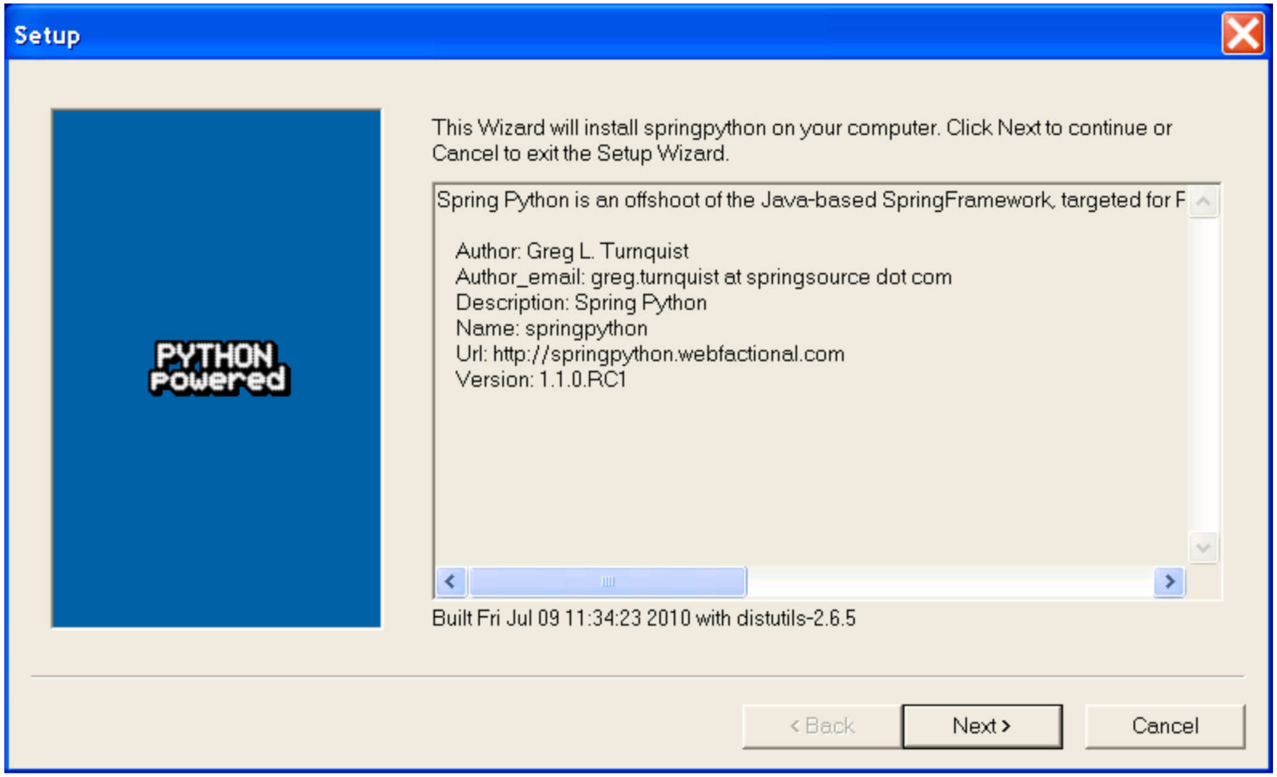
Install PyQt GPL v4.5.4 and accept all defaults.



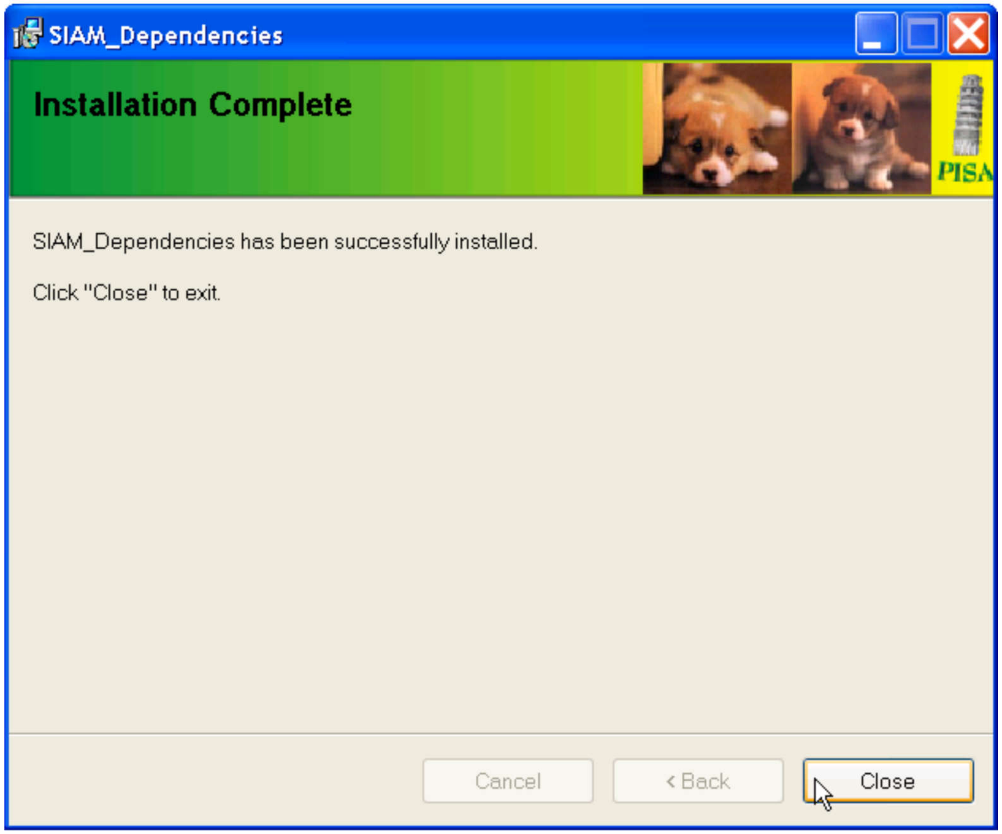
Install PyQwt and accept all defaults.



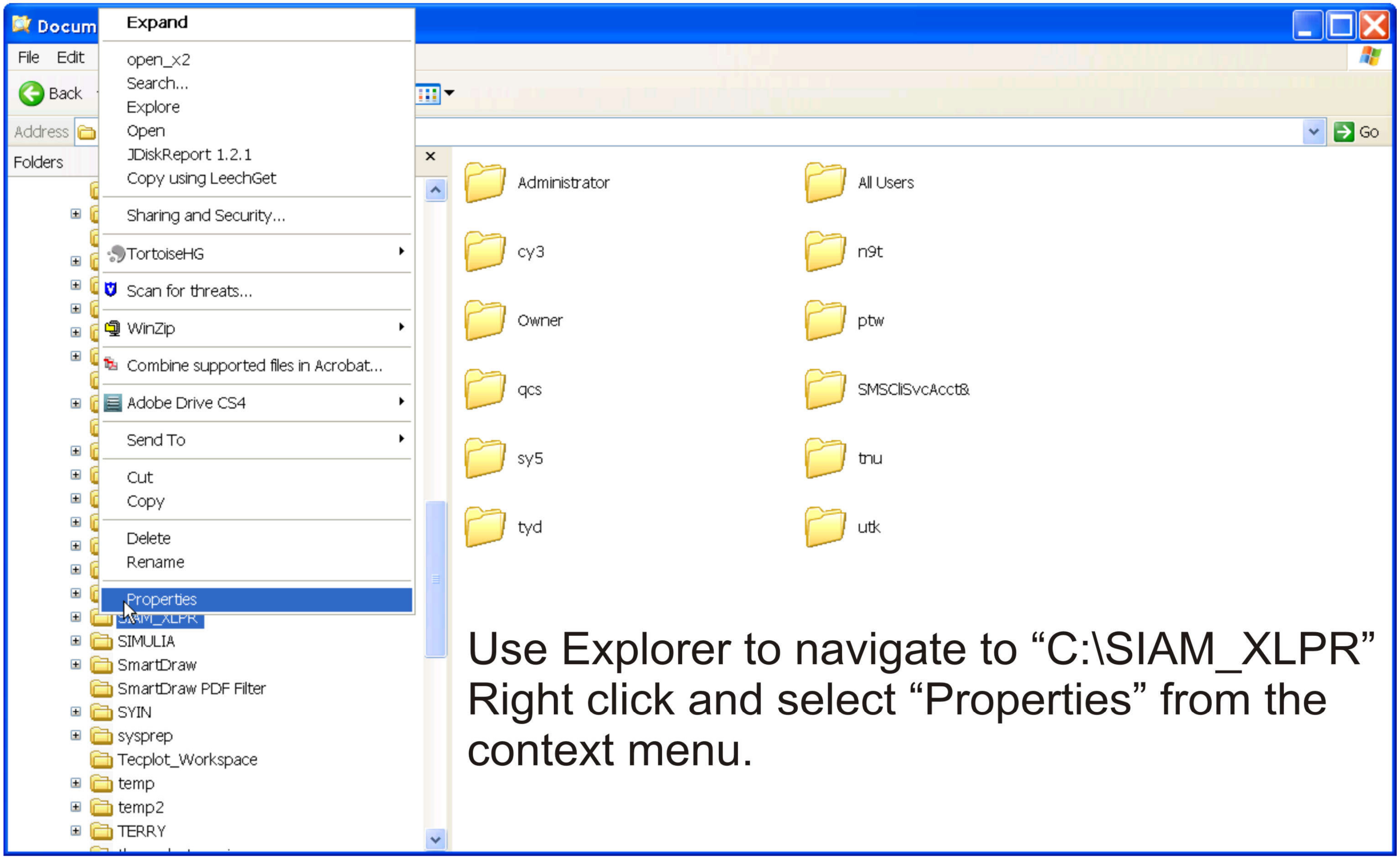
Finally, install SpringPython



This completes the installation.

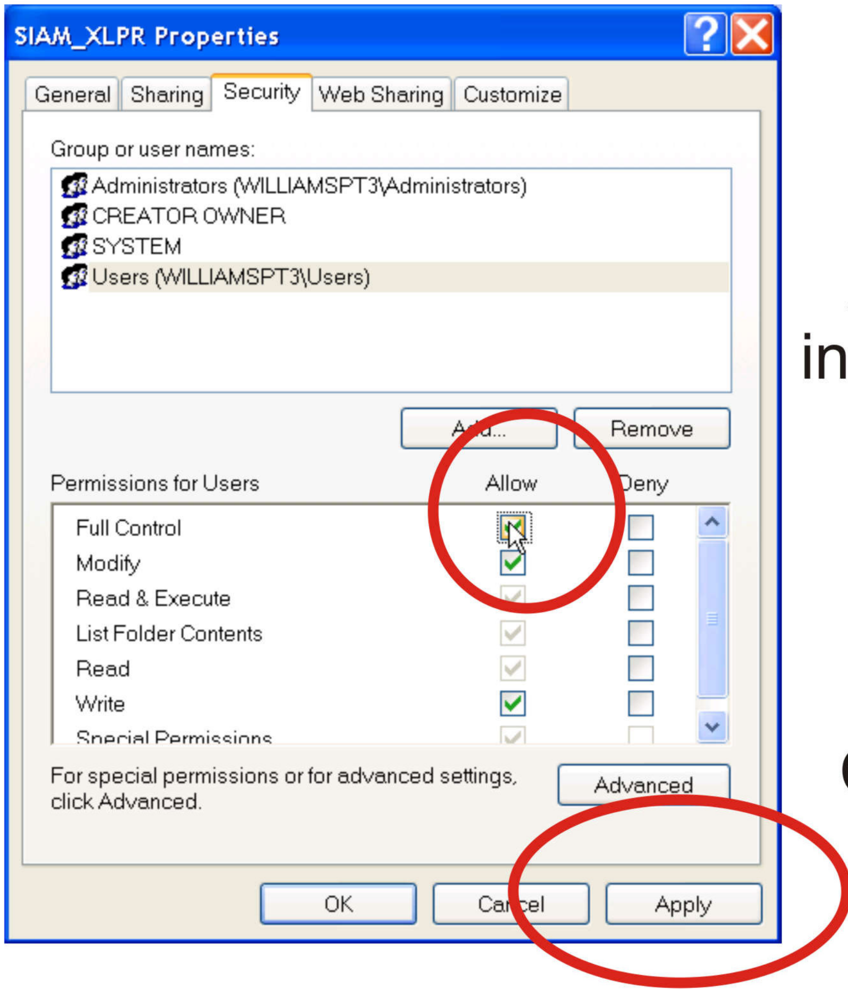


On some installations on Windows XP, VISTA, and 7, it has been necessary to grant the User “Full Control” for the SIAM_XLPR installation folder.



Use Explorer to navigate to “C:\SIAM_XLPR” Right click and select “Properties” from the context menu.

On the SIAM_XLPR Properties dialog, select the "User" from the "Group or user names" panel on the "Security Tab".



Allow "Full Control" in the "Permissions for Users" panel.

Click "Apply"

7 Appendix B SIAM-xLPR input parameters

7.1 Problem Setup Tab

7.1.1 Source of Flaws:

Parameter Name	Parameter Description	Reference
PWSCC Initiated		xLPR Program Plan [4]

7.1.2 Problem Specification – Monte Carlo Setup

Parameter Name	Parameter Description	Value	Reference
Number of aleatory realizations	Number of aleatory realizations	20	xLPR Program Plan [4]
Number of epistemic realizations	Number of epistemic realizations	52	xLPR Program Plan [4]
Total Number of realizations	Number of aleatory realizations X Number of epistemic realizations	1040	xLPR Program Plan [4]
Initial Random Number Generator Seeds	Initial Random Number Generator Seeds	Seed1 = 1234567890 Seed2 = 123456789	P. L'Ecuyer and S. Cote, "Implementing a Random Number Package with Splitting Facilities" [11]

7.1.3 Surface Crack Failure Criteria

Parameter Name	Parameter Description	Reference
Net-section plastic collapse		xLPR Program Plan [4]

7.1.4 Through-Wall Crack Failure Criteria

Parameter Name	Parameter Description	Reference
Net-section collapse of LBB.ENG2 EPFM		xLPR Program Plan [4]

7.1.5 Setup Plant Time Horizon, Time Increment for Analysis, and Mitigation Schedule

Parameter Name	Parameter Description	Value	Units	Reference
tfinal	Plant time horizon	720	Months	xLPR Program Plan [4]
time_mts	Number of futures to simulate; 1= no mitigation	1	Non-dimentional	xLPR Program Plan [4]
time_step	Time step interval used for time integration	1	Months	xLPR Program Plan [4]

7.1.6 Pipe/Weld Geometry

Parameter Name	Parameter Description	Value	Units	Reference
pipe_outer_diameter	Pipe/weld outer diameter	0.381	Meters	xLPR Pilot Study Model Problem Statements [10]
pipe_wall_thickness	Pipe/weld wall thickness	0.040132	Meters	xLPR Pilot Study Model Problem Statements [10]

7.1.7 Setup Analysis Methods

Parameter Name	Parameter Description	Value	Reference
method_cod	COD analysis method [integer], unitless = 0, blended GE/EPRI > 0, reserved for future methods	0	COD_v2.0 Conceptual Description [22]
method_initiation	Initiation Probability method. Two approaches are available: 1. Direct: Initiation time given as explicit function of stress and temperature, with randomness in parameters in the function. 2. Weibull: The initiation time is taken to be Weibull distributed with a slope of 3 and a scale parameter that depends on stress and temperature.	2	Crack Initiation v2.0 Conceptual Description [23]
method_scfail	SC analysis method [integer], unitless = 0, constant depth surface crack NSC = 1, semi-elliptical surface crack	1	SC Fail v2.0 Conceptual Description [24]

	NSC > 1, reserved for future methods		

7.2 Material Properties

7.2.1 A516 Gr70

Parameter Name	Parameter Description	Value	Unit	Reference
A516Gr70 elasticModulus	modulus of elasticity	186300	MPa	xLPR Program Plan [4]
A516Gr70 F	F_A516_Gr_70: F factor for Ramberg-Osgood model	911.5219	MPa	xLPR Program Plan [4]
A516Gr70 n	n_A516_Gr_70: n exponent for Ramberg-Osgood model	4.288899	nondim	xLPR Program Plan [4]
A516Gr70 ultimateStrength	sigu_A516_Gr_70: ultimate strength	519.1096	MPa	xLPR Program Plan [4]
A516Gr70 yieldStrength	sigy_A516_Gr_70: yield strength	227.4765	MPa	xLPR Program Plan [4]

7.2.2 TP 304

Parameter Name	Parameter Description	Value	Unit	Reference
TP304 elasticModulus	modulus of elasticity	177100	MPa	xLPR Program Plan [4]
TP304 F	F_TP304: RO_F = F factor for Ramberg-Osgood model	562.1217	MPa	xLPR Program Plan [4]
TP304 n	n_TP304: RO_n = n exponent for Ramberg-Osgood model	4.260565	nondim	xLPR Program Plan [4]
TP304 ultimateStrength	sigu_TP304: ultimate strength	450.6127	MPa	xLPR Program Plan [4]
TP304 yieldStrength	sigy_TP304: yield strength	168.763	MPa	xLPR Program Plan [4]

7.2.3 Alloy 182

Parameter Name	Parameter Description	Value	Unit	Reference

Alloy182 C	C_Alloy_182: Resist_C = ductile-tearing J-R curve parameter C	260.1	Non-dimensional	xLPR Program Plan [4]
Alloy182 E Alloy600	Young's modulus for Alloy 600	207000	MPa	xLPR Program Plan [4]
Alloy182 elasticModulus	modulus of elasticity	203100	MPa	xLPR Program Plan [4]
Alloy182 JIc	JIc_Alloy_182: Resist_JIc = ductile-tearing initiation JIc	482.7	kJ/m**2	xLPR Program Plan [4]
Alloy182 m	m_Alloy_182: Resist_m = ductile-tearing J-R curve parameter m	0.612089	Non-dimensional	xLPR Program Plan [4]
Alloy182 sigUS Alloy600	ultimate strength for Alloy 600	689.5	MPa	xLPR Program Plan [4]
Alloy182 sigYS Alloy600	yield strength for Alloy 600	344.7	MPa	xLPR Program Plan [4]
Alloy182 ultimateStrength	sigu_Alloy_182: ultimate strength	580.1362	MPa	xLPR Program Plan [4]
Alloy182 yieldStrength	sigy_Alloy_182: yield strength	361.5464	MPa	xLPR Program Plan [4]

7.3 Crack Initiation and Growth

Parameter Name	Parameter Description	Value	Unit	Reference
grower_alpha	reference alpha parameter for PWSCC growth model	2.01E-12	Nondim (see note below) Note: The unit is hard coded as: (m/s)/(MPa-m0.5)1.6 System presents as nondim to prevent user from changing it.	Grower_v2.0 Conceptual Description [13]
grower_beta	reference beta parameter for PWSCC growth model	1.6	nondim	Grower_v2.0 Conceptual Description [13]

grower_ch2	c: characteristic width of crack growth rate curve. Growth Rate Curve *(mV)	22.5	mV	Grower_v2.0 Conceptual Description [13]
grower_fweld	f_weld: weld fabrication factor	0.99894	nondim	Grower_v2.0 Conceptual Description [13]
grower_h2	concentration of hydrogen in primary water (cc/kg-STP)	25	cm**3/kg	Grower_v2.0 Conceptual Description [13]
grower_kth	reference k threshold parameter for PWSCC growth model. (MPa(m)^0.5)	0	nondim Note: The units are hard coded as: MPa(m)^0.5 System presents as nondim to prevent user from changing it.	Grower_v2.0 Conceptual Description [13]
grower_p	peak to valley ratio	9.5	nondim	Grower_v2.0 Conceptual Description [13]
grower_qoverr	reference Q/R for PWSCC growth model	15636	K	Grower_v2.0 Conceptual Description [13]
grower_tref	reference temperature Tref for PWSCC growth model	598.15	K	Grower_v2.0 Conceptual Description [13]
grower_zinc	concentration of zinc in primary water	0	cm**3/kg	Grower_v2.0 Conceptual Description [13]
initiation_A	A: Heat to heat - Method 1 median - within heat sampling	3.163	nondim	Crack Initiation v2.0 Conceptual Description [23]
initiation_AWH_Stdev	geometric stdev for within heat Method 1	2.9153795	nondim	Crack Initiation v2.0 Conceptual Description [23]
initiation_AWH0	Method 1 - quantile for median within heat (lognormal)	0.5	nondim	Crack Initiation v2.0 Conceptual Description [23]
initiation_B1	B1: Heat to heat - Method 2 median - within heat sampling	1.20E-09	nondim	Crack Initiation v2.0 Conceptual Description [23]
initiation_B1WH_Stdev	geometric stdev for within heat Method 2	1.741941	nondim	Crack Initiation v2.0 Conceptual Description

				[23]
initiation_B1WH0	Method 2 - quantile for median within heat (lognormal)	0.5	nondim	Crack Initiation v2.0 Conceptual Description [23]
initiation_C1	parameter for Method 3	0.04	nondim	Crack Initiation v2.0 Conceptual Description [23]
initiation_crack_depth_init	initial crack depth	0.0015	m	Crack Initiation v2.0 Conceptual Description [23]
initiation_crack_half_length_init	initial crack half-length	0.003	m	Crack Initiation v2.0 Conceptual Description [23]
initiation_qoverr	reference Q/R for PWSCC initiation module	22000	K	Crack Initiation v2.0 Conceptual Description [23]
initiation_RandU30	RandU3: Method 3 - initiation time sampling	0.5	nondim	Crack Initiation v2.0 Conceptual Description [23]
initiation_RandULoc0	random number sampled for use in crack placement	0.5	nondim	Crack Initiation v2.0 Conceptual Description [23]
initiation_SigTH	SigTH: threshold stress for Method 1	137.9	MPa	Crack Initiation v2.0 Conceptual Description [23]
initiation_subunits	number of circumferential subunits in weld	19	nondim	Crack Initiation v2.0 Conceptual Description [23]
initiation_XN1	parameter for Method 1	4	nondim	Crack Initiation v2.0 Conceptual Description [23]
initiation_XN3	parameter for Method 3	4	nondim	Crack Initiation v2.0 Conceptual Description [23]

7.4 Operating, Loading and Mitigation

7.4.1 Operating Conditions

Parameter Name	Parameter Description	Value	Unit	Reference
ambient_pressure	ambient pressure	0.1013565	MPa	xLPR Program Plan [4]
pressure	Pressure: internal pressure	15.5132	MPa	xLPR Program Plan [4]
temperature	Temperature: metal temperature	344.9	degC	xLPR Program Plan [4]

7.4.2 Loading Conditions

Parameter Name	Parameter Description	Value	Unit	Reference
DW_Fx	Axial force due to dead weight [kN], Fx axial force component	0.31	kN	Load Module v1.0 Conceptual Description [14]
DW_Mx	Moment due to dead weight (Mx) [kN-m], Mx moment component	1.31	m*kN	Load Module v1.0 Conceptual Description [14]
DW_My	Moment due to dead weight (My) [kN-m], My moment component	0.21	m*kN	Load Module v1.0 Conceptual Description [14]
DW_Mz	Moment due to dead weight (Mz) [kN-m], Mz moment component	1.02	m*kN	Load Module v1.0 Conceptual Description [14]
NT_Fx	Axial force due to normal thermal [kN], Fx axial force component	3.87	kN	Load Module v1.0 Conceptual Description [14]
NT_Mx	Moment due to normal thermal (Mx) [kN-m], Mx moment component	65.3	m*kN	Load Module v1.0 Conceptual Description [14]
NT_My	Moment due to normal thermal (My) [kN-m], My moment component	-57.54	m*kN	Load Module v1.0 Conceptual Description [14]

NT_Mz	Moment due to normal thermal (Mz) [kN-m], Mz moment component	52.99	m*kN	Load Module v1.0 Conceptual Description [14]
P_Fx	Axial force due to pressure [MN], Fx axial force component	1.10195056	kN	Load Module v1.0 Conceptual Description [14]
P_Mx	Moment due to pressure (Mx) [kN-m], Mx moment component	0	m*kN	Load Module v1.0 Conceptual Description [14]
P_My	Moment due to pressure (My) [kN-m], My moment component	0	m*kN	Load Module v1.0 Conceptual Description [14]
P_Mz	Moment due to pressure (Mz) [kN-m] , Mz moment component	0	m*kN	Load Module v1.0 Conceptual Description [14]
SSE_Fx	Axial force due to SSE (safe-shutdown earthquake) [kN], Fx axial force component	28.02	kN	Load Module v1.0 Conceptual Description [14]
SSE_Mx	Moment due to SSE(safe-shutdown earthquake) (Mx) [kN-m], Mx moment component	32.39	m*kN	Load Module v1.0 Conceptual Description [14]
SSE_My	Moment due to SSE (safe-shutdown earthquake) (My) [kN-m], My moment component	59.25	m*kN	Load Module v1.0 Conceptual Description [14]
SSE_Mz	Moment due to SSE (safe-shutdown earthquake) (Mz) [kN-m], Mz moment component	94.89	m*kN	Load Module v1.0 Conceptual Description [14]
TS_Fx	Axial force due to normal thermal stratification [kN], Fx axial force component	17.39	kN	Load Module v1.0 Conceptual Description [14]
TS_Mx	Moment due to normal thermal stratification (Mx) [kN-m], Mx moment component	2.51	m*kN	Load Module v1.0 Conceptual Description [14]
TS_My	Moment due to normal	-80.79	m*kN	Load Module v1.0

	thermal stratification (My) [kN-m], My moment component			Conceptual Description [14]
TS_Mz	Moment due to normal thermal stratification (Mz) [kN-m], Mz moment component	87.9	m*kN	Load Module v1.0 Conceptual Description [14]

7.4.3 Normal WRS State

Parameter Name	Parameter Description	Value	Unit	Reference
S0WRS	sig0_wrs: weld residual stress parameter S0WRS	300.3	MPa	xLPR Program Plan [4]
WRSRand	OD_stress_random: random number U(0.5,1) WRSRand	0.5	nondim	xLPR Program Plan [4]
XcWRS	Xc: weld residual stress parameter	0.25	nondim	xLPR Program Plan [4]

7.4.4 Mitigation WRS State

Parameter Name	Parameter Description	Value	Unit	Reference
S0WRS_mitigate	sig0_wrs_mitigated: weld residual stress parameter S0WRS after mitigation	-344.75	MPa	xLPR Program Plan [4]
WRSRand_mitigate	OD_stress_random_mitigated: random number U(0.5,1) req'd after mitigation	0.5	nondim	xLPR Program Plan [4]
XcWRS_mitigate	Xc_mitigated: weld residual stress parameter Xc after mitigation	0.38	nondim	xLPR Program Plan [4]

7.5 In-Service Inspection (ISI)

Parameter Name	Parameter Description	Value	Unit	Reference
inspection_pod_beta1	POD_beta1: probability of detection model beta1	2.7076	nondim	Inspection v2.0 Conceptual Description [15]

	parameter			
inspection_pod_beta2	POD_beta2: probability of detection model beta2 parameter	0.0031	nondim	Inspection v2.0 Conceptual Description [15]
inspection_Urnd	POD_detection: used in SC inspection module	0.5	nondim	Inspection v2.0 Conceptual Description [15]

7.6 Post-Processing Options

7.6.1 Include CCDFs in analysis

Parameter Name	Parameter Description	Value	Reference
Include CCDFs in analysis	CCDF option (yes or no)	Selected = yes	Expectation v1.0 Conceptual Description [17]
Time of interest (yrs)	Time to use for CCDF (optional)	50	Expectation v1.0 Conceptual Description [17]
Number of Points	Number of discretization points	30	Expectation v1.0 Conceptual Description [17]
Specify Discretization basis for parameter of interest (POI)	Specify Discretization basis for parameter of interest (POI): Linear or Logarithmic.	Linear	Expectation v1.0 Conceptual Description [17]

7.6.2 Treatment after Rupture

Parameter Name	Parameter Description	Value	Reference
Maximum over time (create running maximum)	Take max over time or not (1 = max; 0 = no change)	Selected by default.	Transformers v1.0 Conceptual Description [16]
Apply no changes to framework results	If the output of interest needs to be taken as it is calculated by the framework or if it needs to be transformed such that the maximum over time is taken at each time step (**integer = 0 for no change** and 1 if max over timestep is taken).	Not selected by default.	Transformers v1.0 Conceptual Description [16]
Quantiles of Interest	Listing of the quantiles of interest	1) 0.05	Transformers v1.0 Conceptual

		2) 0.25 3) 0.50 4) 0.90 5) 0.95 6) 0.99	Description [16]

7.6.3 Include in-service inspections (ISI)

Parameter Name	Parameter Description	Value	Reference
Include in-service inspection s(ISI)	Include in-service inspection s(ISI) for post-processing.	Not selected by default.	Transformers v1.0 Conceptual Description [16]
Inspection Times (yrs)	Inspection time in years	1) 15.0 2) 30.0 3) 45.0	Transformers v1.0 Conceptual Description [16]
Specify Conditional Dependency Rule	Specify Conditional Dependency Rule: independent or dependent	Independent option selected by default.	Transformers v1.0 Conceptual Description [16]
Specify Treatment of Multiple Cracks	Specify Treatment of Multiple Cracks: use minimum PND or multiple PNDs	Use minimum PND option selected by default.	Transformers v1.0 Conceptual Description [16]

7.6.4 Create Indicator Function

Parameter Name	Parameter Description	Value	Reference
Create Indicator Function	The second set of changes that can then by applied to the data for any variable is to change it into an indicator function (a set of 0 and 1) in case the user would be interested in threshold values.	Not selected by default	Transformers v1.0 Conceptual Description [16]
Limit-type Operator	type of threshold: 0 : "<" 1: "=" 2: ">"	0 : "<" default	Transformers v1.0 Conceptual Description [16]
Time option	When to apply transform time option: at time of event or after event.	At time of event option selected by default	Transformers v1.0 Conceptual Description [16]

Threshold value	Threshold value for the transformed	1.0	Transformers v1.0 Conceptual Description [16]

7.6.5 Include leakage rate threshold correction

Parameter Name	Parameter Description	Value	Reference
Include leakage rate threshold correction	leak rate threshold correction: 1 = threshold, 0=no threshold. Default=0	Not selected by default	Transformers v1.0 Conceptual Description [16]
detection_LOCA_TS_Limit	If correction with respect to leak rate threshold is applied (integer ->0 for no and 1 for yes). The following option is added only if this option is 1 (Leak rate threshold (real)). The leak rate threshold is called the LOCA_TS_Limit in the Program Plan.	1 m**3/s	Transformers v1.0 Conceptual Description [16]; xLPR Program Plan [4]

7.7 Execution

7.7.1 Epistemic Sampling Procedure

Parameter Name	Parameter Description	Value	Reference
Epistemic Sampling Procedure	Epistemic Sampling Procedure either Random Sampling or LHS	LHS selected by default.	xLPR Program Plan [4]

7.7.2 Execution Mode

Parameter Name	Parameter Description	Value	Reference
Execution Mode	The execution mode options are: Monte Carlo with uncertainties, Deterministic Baseline Case # 1 and Deterministic Baseline Case # 2	Monte Carlo with uncertainties selected by default	xLPR Pilot Study Model Problem Statements [10]

7.7.3 Output Options

Parameter Name	Parameter Description	Value	Reference
Debug mode	For the deterministic cases	Not selected.	xLPR Pilot Study Model Problem Statements [10]

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10. SUPPLEMENTARY NOTES

1 1. ABSTRACT *(200 words or less)*

This document provides an overview of the structure/user instructions for the SIAM-xLPR software tool under development at the Oak Ridge National Laboratory, which supports the Nuclear Regulatory Commission initiative for a new piping system assessment methodology. The new methodology will provide a tool for demonstrating compliance with the regulatory requirement that primary system water piping exhibits an extremely low probability of rupture (xLPR). SIAM-xLPR is a modular-based assessment tool that incorporates a prototype xLPR model assembled from new and existing fracture mechanics models and software. xLPR represents one of the four subsystems currently installed in the ORNL-developed SIAM Problem-solving Environment. The prototype SIAM-xLPR models and software modules are linked within a probabilistic framework and a fully open-source architecture as described herein..

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

probabilistic fracture mechanics, piping rupture, primary water stress corrosion cracking

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