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ORNL/TM-2009/233

ROADMAP TO AN ENGINEERING-SCALE NUCLEAR FUEL PERFORMANCE AND SAFETY CODE

September 2009
Revision 0

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Computer Science and Mathematics Division

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ACRONYMS AND ABBREVIATIONS

DOE	U.S. Department of Energy
FMM	Fundamental Models and Methods
FY	fiscal year
IPSC	Integrated Performance and Safety Code
LWR	light water reactor
NEAMS	Nuclear Energy Advanced Modeling and Simulation
OTS	off the shelf
TFC	Transmutation Fuels Campaign
TRL	technology readiness level

1. INTRODUCTION

Developing new fuels and qualifying them for large-scale deployment in power reactors is a lengthy and expensive process, typically spanning a period of two decades from concept to licensing. Nuclear fuel designers serve an indispensable role in the process, at the initial exploratory phase as well as in analysis of the testing results. In recent years fuel performance capabilities based on first principles have been playing more of a role in what has traditionally been an empirically dominated process. Nonetheless, nuclear fuel behavior is based on the interaction of multiple complex phenomena, and recent evolutionary approaches are being applied more on a phenomenon-by-phenomenon basis, targeting localized problems, as opposed to a systematic approach based on a fundamental understanding of all interacting parameters.

Advanced nuclear fuels are generally more complex, and less understood, than the traditional fuels used in existing reactors (ceramic UO_2 with burnable poisons and other minor additives). The added challenges are primarily caused by a less complete empirical database and, in the case of recycled fuel, the inherent variability in fuel compositions. It is clear that using the traditional approach to develop and qualify fuels over the entire range of variables pertinent to the U.S. Department of Energy (DOE) Office of Nuclear Energy on a *timely* basis with available funds would be very challenging, if not impossible.

As a result the DOE Office of Nuclear Energy has launched the Nuclear Energy Advanced Modeling and Simulation (NEAMS) approach to revolutionize fuel development. This new approach is predicated upon transferring the recent advances in computational sciences and computer technologies into the fuel development program. The effort will couple computational science with recent advances in the fundamental understanding of physical phenomena through ab initio modeling and targeted phenomenological testing to leapfrog many fuel-development activities. Realizing the full benefits of this approach will likely take some time. However, it is important that the developmental activities for modeling and simulation be tightly coupled with the experimental activities to maximize feedback effects and accelerate both the experimental and analytical elements of the program toward a common objective. The close integration of modeling and simulation and experimental activities is key to developing a useful fuel performance simulation capability, providing a validated design and analysis tool, and understanding the uncertainties within the models and design process.

The efforts of this project are integrally connected to the Transmutation Fuels Campaign (TFC), which maintains as a primary objective to formulate, fabricate, and qualify a transuranic-based fuel with added minor actinides for use in future fast reactors. Additional details of the TFC scope can be found in the *Transmutation Fuels Campaign Execution Plan*.[1] This project is an integral component of the TFC modeling and simulation effort, and this multiyear plan borrowed liberally from the *Transmutation Fuels Campaign Modeling and Simulation Roadmap*.[2]

This document provides the multiyear staged development plan to develop a continuum-level Integrated Performance and Safety Code (IPSC) to predict the behavior of the fuel and cladding during normal reactor operations and anticipated transients up to the point of clad breach.

2. INTERFACES WITH ASSOCIATED EFFORTS

Additional work in advanced modeling and simulation for nuclear fuels is being performed in associated efforts: at the lower-length scales in both the Fuels IPSC and Fundamental Models and Methods (FMM) efforts and at the reactor scale in the Reactor IPSC. Details of these efforts are not discussed in this document, but the interface between the continuum-level Fuel IPSC activities and both the Reactor IPSC and lower-length scale efforts related to fuels are important.

The continuum-level Fuel IPSC activities will focus on detailed modeling of the fuel pin and the neighboring structures that are integral to the detailed modeling of the fuel pin. The reactor simulation effort will provide the initial and boundary conditions (neutron flux and spectrum, thermal-hydraulic parameters, mechanical constraints) for nominal and transient scenarios. For cases in which the fuel

behavior affects the reactor performance (such as in a sodium-cooled fast reactor), this effort will provide a simplified model to the Reactor IPSC for direct integration into its software.

The process of the integration from the lower-length scale to the continuum scale is illustrated in Fig. 1. This approach is designed to provide a simulation capability not only to understand the results, but also to provide physical insight into fuel behavior in processes in which conditions are too harsh for direct observation. More importantly, the application of the capabilities to model the fuel behavior under normal and accident conditions will be required for fuel licensing.

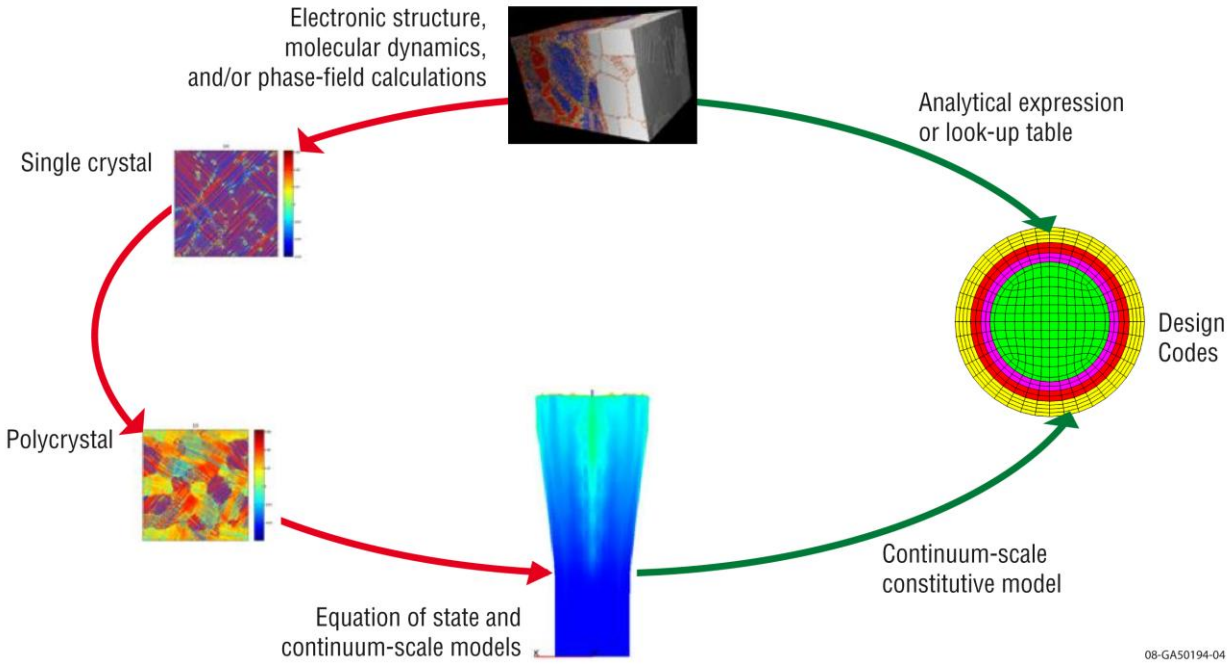

Fig. 1. Interactions between lower-length-scale models and engineering-scale codes.

From the continuum-scale perspective, existing analytic expressions and lookup tables with a strong empirical pedigree exist for material properties, such as thermal conductivity and other physics-based model parameters, as functions of composition, temperature, and density. This capability must be maintained (especially for industrial collaborators), but the proposed approach to predict the properties at the continuum level beyond the existing empirical database, through both the Fuels IPSC and FMM efforts, will eventually replace these empirically derived functions/tables. In most cases the lower-length-scale models will be used to create new expressions and/or lookup tables; therefore, the effort described in this project is associated with the green arrows in Fig. 1. If the mesoscale (polycrystal) models are computationally efficient or a loss of accuracy occurs by representing the material behavior as a simplified function/table, then the lower-length-scale models may be embedded directly within the continuum-level engineering code; this will be determined on a case-by-case basis based on feasibility and sensitivity/uncertainty analysis.

3. TEST-PROBLEM TARGETS

A suite of test problems will be defined to guide the development of the software and evaluate the progress of the development process. These test problems will be selected to represent categories that are each representative of existing and novel fuels in various reactor types. Each test problem will be

developed to (1) answer a specific question that will provide an understanding of the physics to guide the definition of the physics-based requirements, (2) assess the ability of the software to model a specific physical process, or (3) validate the software with respect to a empirical dataset.

For example, the classes of test problems developed in fiscal year (FY) 2009 included

- metal-fueled, sodium-cooled fast reactor fuel pin;
- oxide-fueled, sodium-cooled fast reactor fuel pin; and
- UO_2-fueled boiling water reactor fuel assembly.

4. MODELING AND SIMULATION IMPLEMENTATION STRATEGY

The long-term vision for the Fuels IPSC is to deliver an assessed (verified and validated) computing-based capability for fuel performance in 2022.[3] However, there is a strong need in the fuel performance community to have a new tool to more effectively understand the development process and capability timeline. Therefore, a new integrated fuel performance code, and training course, will be provided in September 2010. A complete guide to the timeline for software releases and anticipated capabilities of the integrated code is shown in Sect. 7.

4.1 2022: THE VISION

It is imperative that there be a consistent focus on the vision for the final product, which is

> a toolset that can be applied by an engineer or analyst with limited computational expertise, but appropriate domain knowledge, to predict the behavior of the fuel and cladding during normal reactor operations and anticipated transients up to the point of clad breach and that will include the detailed modeling of a single fuel pin (particle) up to a single assembly (aka subassembly, bundle, pebble, block).

It will be capable of modeling all fuel/reactor types presently, historically, or potentially of interest to the DOE Office of Nuclear Energy for transmutation of actinides as well as any fuel/reactor type that might prove useful for validation and/or qualification of the simulation tools, such as UO_2 in light water reactors (LWRs). It will provide a quantified uncertainty in, and evaluated sensitivity of, the performance of the fuel due to data uncertainty, modeling approximations, and computational error to guide and prioritize requirements in associated activities including meso- and atomistic-scale modeling activities, targeted test problems to reduce data uncertainties, and the enhancement of models and algorithms for increased solution fidelity. The three primary purposes of the tool are for the

1. qualification of transmutation fuel (to demonstrate that the fuel will perform predictably and acceptably under normal operations and transient conditions),
2. design of new fuel (sufficiently predictive to evaluate the potential of novel fuel design options that are beyond the empirical database used to qualify the software), and
3. development of a simple engineering model to be integrated with the reactor simulation toolset (to provide a computationally efficient approximation of the fuel response to full-core and transient physics).

The long-term vision is achievable but a tremendous challenge due to (1) the breadth of the fuel/reactor types that must be considered, (2) the need for a quantified estimate of the uncertainty of the solution to all aspects of the simulation, and (3) the need for an interface for a user with limited computational expertise. Therefore, a staged delivery plan has been adopted to provide a more concise toolset that will provide a relevant capability by 2015.

4.2 2015: A DEMONSTRATED CAPABILITY

An integrated fuel performance simulation capability that demonstrates a significant advance in analysis capability beyond the empirical database without undermining the accuracy of existing (empirically tuned) fuel performance codes will be developed by 2015. This intermediate-term capability will focus on multidimensional modeling of cylindrical fuel by expert users that is built upon a solid foundation of modern software engineering practices to ensure the toolset is "born-verified and born-assessed."

This intermediate capability will provide a toolset that can be applied by an engineer or analyst with sufficient computational expertise and domain knowledge to assess the behavior of the fuel and cladding during normal reactor operations and anticipated transients up to the point of clad breach and that will include the detailed modeling of a single fuel pin (cylindrical in nature). It will be capable of modeling metal and ceramic fuels with a variety of structural and coolant options for transmutation of actinides, as well as UO_2 in LWRs for validation and/or qualification of the simulation tools. It will demonstrate the ability to provide a quantified estimate of the uncertainty in the performance of the fuel due to several sources. The three primary purposes of the tool are for the

- qualification of transmutation fuel with a sufficiently complete empirical database,
- design of new cylindrical fuel for which material property estimates exist,
- guidance and prioritization of requirements in associated activities (including meso- and atomistic-scale modeling activities, targeted test problems to reduce data uncertainties, and the enhancement of models and algorithms for increased solution fidelity), and
- development of a simple engineering model to be integrated with the reactor simulation toolset.

This intermediate capability will be thoroughly planned and designed to meet these driving requirements and delivered in four annual releases (2012 through 2015) with progressively enhanced capability. However, a much nearer-term capability is required because the fuel performance community needs a new tool that can model three-dimensional fuel dynamics, and the architects of the 2015 code require a tool to clarify various software requirements that remain unresolved.

4.3 2010: AMP – AN INITIAL FUEL PERFORMANCE CODE

To meet the immediate need of the fuel performance community and provide a tool for clarifying the requirements of the 2015 code, the AMP software will be delivered in August 2010 with a user-focused training session to follow in September. AMP will be a new code developed through a close collaboration of the Oak Ridge, Idaho, and Los Alamos national laboratories and major leveraging of existing off-the-shelf (OTS) codes to provide an interim capability to (1) deliver a useful, new capability to the user community; (2) enhance our understanding of the software and user requirements; (3) demonstrate an understanding of the coupled physics simulation process with best-of-class software; and (4) gain experience developing software as a multi-institutional team with a single set of coding conventions, standards, and tools.

This effort will solidify the joint understanding of the physics that must be modeled, how they interrelate, and how the developers can streamline the process toward a true collaborative, multi-institutional software development environment. Much of the required capability exists in OTS codes that were enhanced and modularized in FY09, but the multidimensional core of the fuel performance code (thermomechanical chemistry) will be developed from scratch in FY10 by leveraging the experience gained in FY09. This new code will tightly couple these core physics and leverage zero- and low-dimensional approximations for much of the associated physics. The AMP project will provide

- a tightly-coupled, three-dimensional thermochemical-mechanical solver that accounts for contact;
- approximate models for the material properties, depletion, heat generation, plenum pressure, and convective heat transfer, which are similar to those found in FRAPCON[4] and SCALE;[5,6]
- a simple user interface to set up, simulate, and understand the performance of LWR oxides; and
- a compiled version that executes in parallel on a cluster at Oak Ridge National Laboratory.

With a final release in August 2010, AMP will be developed in five 2-month iterations (Fig. 2) that will each include an opportunity for a few expert users and associated NEAMS efforts (Enabling Computational Technologies, Capability Transfer, and Verification, Validation and Uncertainty Quantification) to review what has been accomplished and provide feedback.

AMP will be rapidly designed and developed without a focus on extensibility or software quality engineering (especially within the OTS components). Because of the fundamental limitations that are present when working with a collection of OTS codes that were not designed with a consistent approach toward quality, modularity, or coupling, the initial release of the 2015 code in August 2012 will replace AMP with software designed and built to simplify maintenance, enhance inherent quality, add additional physics, and incorporate lower-length-scale models. Therefore, there will be no additional releases of AMP after August 2010.

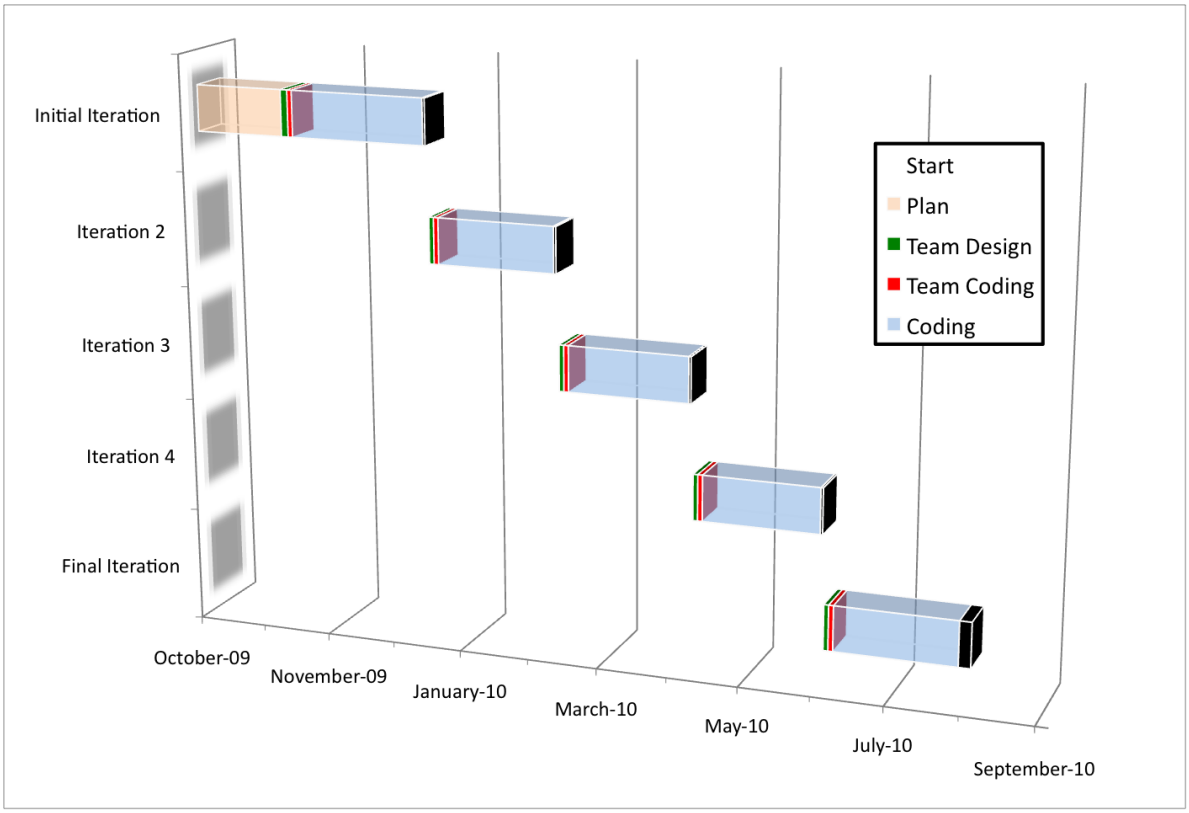

Fig. 2. AMP iterative development plan.

5. STAGED DELIVERY FOR THE 2015 CODE

The software described in Sect. 4.2 will use a staged delivery process that will include an extensive software planning phase followed by three software development cycles. Each software development cycle will include (overlapping) planning, design, construction, testing, review, and use phases (Fig. 2).

5.1 DEFINING THE REQUIREMENTS

Nuclear fuel performance software is used for predicting the behavior of the fuel and cladding during normal reactor operations and anticipated transients, which leads to several high-level requirements that the software product must provide throughout the time domain simulated. The software product shall predict

- temperature distribution throughout the fuel element;
- stress-strain state, dimensions of the fuel and cladding, and fuel-cladding mechanical interaction;
- irradiation effects in fuel, including as change in actinide and fission product inventory, fission gas release, constituent redistribution, oxygen redistribution, restructuring, solid and gaseous fission product swelling, cracking, densification, and creep;
- irradiation effects in cladding, including as material degradation, irradiation-induced creep and thermal creep, swelling, hardening, and embrittlement;
- cladding wastage due to fuel-cladding chemical interaction and coolant-cladding chemical interaction;
- heat transport from the clad into the coolant across the span of steady-state operation and design-base accident environments; and
- safety margin, or margin between the thermomechanical state and the criteria that would lead to a breach of the cladding.

In addition to these physics-based requirements, modern software engineering and project management practices require that the software product shall

- be verified in its functionality, including the impact of implementation assumptions;
- be modular in design to facilitate maintenance, testing, and extensibility;
- be maintained under configuration control, along with software, documentation, data, and inputs;
- be developed in a process that supports peer review; and
- be validated with a suite of experimental data for a variety of fuel types but
- not be qualified to a standard that would allow for full-scale testing of a given fuel type.

The qualification of a fuel type will require close collaboration with the other aspects of the TFC and Fuels IPSC and is considered beyond the scope of this software development effort. However, it is anticipated that this software product would serve a primary role in the qualification of a new fuel through a combined effort between several programs.

A review of existing open-source, multidimensional thermomechanical OTS codes has revealed the tremendous challenge associated with the proper verification of their functionality. Therefore, the intermediate capability will develop an entirely new code suite that is born-verified through the use of modern software engineering practices. This effort began (FY09 through FY10) with a software planning process to ensure that the software is designed and developed to meet the requirements of the expert users, software developers, and key stakeholders. A more thorough discussion of this software development effort is provided in Sect. 5.3.

During the initial requirements development phase, it became apparent that there are significant unresolved issues related to the specific requirements of the individual and coupled physics that must be understood before the process of designing the software can begin. Therefore, a third phase will be devoted to attaining a better understanding of the physics-based requirements.

5.2 UNDERSTANDING THE REQUIREMENTS

Because a tightly coupled, three-dimensional nuclear fuel performance code with all physics modeled to a high fidelity has never been developed, defining the scope and requirements is challenged by conflicting assumptions of coupling, uncertainty, and computational burden. Therefore, the primary effort in FY11 will be devoted to evaluating and understanding specific questions to guide the requirements, design, and architecture of the 2015 code. An enhanced understanding of the physics-based requirements will be attained through specific targeted test problems and unreleased enhancements to AMP.

Specific unresolved questions to be addressed include those with the potential to limit or expand the scope and fidelity of the physics that must be modeled. Test problems will be defined to evaluate the fidelity required, if at all, for explicit modeling of these continuum-level physics in the integrated code because neglecting or minimizing them would greatly reduce the software development and computational burden of the integrated code:

- Neutronics
  - Can we use coarse power distributions from the reactor code, or does the within-pin power distribution significantly affect the thermomechanical state?
- Flow
  - Can we use simple one-dimensional flow, or does the subchannel three-dimensional flow distribution affect the heat removal and power distribution significantly affect the thermomechanical state?
  - Can the fluid–structure interaction that leads to wear on the cladding be modeled separately and incorporated as a "functional property," or must it be modeled in a fully integrated way?
- Continuum Fracture
  - Can macroscopic fractures in oxide fuel be neglected or predefined (with upscaled or empirically defined functions), or does the mechanism of fracture need to be modeled for accuracy?

It is assumed that for most problems of interest, the thermal, mechanical, and chemical (species diffusion) physics are tightly coupled and will be solved self-consistently on a unified mesh. However, there are open questions related to the computational error that is introduced by various numerical simplifications, which can reduce the computational burden of solving the multiphysics problem when one has "weakly" coupled physics, such as depletion-species formation, neutronics, and flow. The prototype code and test problems will be developed to provide an answer to several specific questions:

- Multimesh
  - Does the zero-dimensional isotopic (elemental, species) concentration need to be computed on the fine grid, or can a coarse grid be used without introducing significant error, as tracking 20 to 2000 isotopes (elements, species) per spatial element would be memory restrictive?
  - Is significant computational error introduced in the thermal solver from mapping the heat transfer across non-conformal surface meshes on the cladding-coolant interface?
  - Can the power density be mapped across nonconformal volumetric meshes within the fuel pin so the neutronics solver can use a coarse mesh?
- Multiphysics time integration
  - Because flow and power vary slowly during nominal operation, can they be loosely coupled without a significant loss of accuracy?
  - Because the terms in the depletion matrix depend upon slowly varying parameters (power, density), can they be loosely coupled without a significant loss of accuracy?
- Contact
  - There will be thousands of contact situations, including fuel–clad and fuel–fuel. (Fuel is a full pellet or a fractured pellet in the case of an oxide.) What algorithm will be used to model this,

how complete must it be, and how will it be solved—mortar methods, implicitly posed, including friction?

As noted in Sect. 2, if the mesoscale (polycrystal) models are computationally efficient and a loss of accuracy occurs in representing the model as a simplified function/table, then the lower-length-scale models may be embedded directly within the continuum-level engineering code. Though a general "upscaling" infrastructure can be designed into the software, specific lower-length-scale models must be defined in the planning process and embedded in the requirements such that the upscaling will be demonstrated in the 2015 code for a few of the most significant physical processes that occur at a microstructural level.

Identifying which lower-length-scale processes are (1) significant to the thermomechanical-chemical state, (2) not suited to a functional fit, and (3) computationally efficient enough to be embedded in the engineering code is critical to evaluating the requirements for the 2015 code. This identification process will initially include discussions with the relevant personnel and experts and may include fission gas release, microfracture and grain restructuring, fuel–clad chemical interaction, and conductivity. Then the test problem will be developed to evaluate potential upscaling algorithms to examine and demonstrate their feasibility.

5.3 SOFTWARE PLANNING

The software planning process is shown in Fig. 3. A plan for the coding standards, conventions, and software quality[7] will be developed through development/review cycles and approved by the software development team before any coding begins. An Expert User Advisory Board will be defined, and funded, to serve as a continual resource for understanding the physics-based and user-interface requirements for the software. This collection of knowledge will be defined in an extensive user-defined requirements document that will be reviewed and approved by the Expert User Advisory Board. A prototype user interface will be developed to provide a tangible simulation environment to ensure the developers understand the needs of the user from an input/output point of view. Three-dimensional, unstructured mesh generation, CAD geometry definitions, and backward compatibility result in potentially conflicting requirements, and several iterations of a prototype user interface will serve to clarify the user needs to the developers.

Because of the unresolved questions related to physics-based requirements (discussed in Sect. 4.2), a suite of test problems (discussed in Sect. 3) will be developed to evaluate the significance of various approaches to modeling aspects of the physics of the fuel. These will be targeted simulations designed to provide an understanding of the significance of effects and how they can be incorporated into the software. For example, test problem 3 relates to the significance of an embedded radiation transport solver for the fuel performance code. The radiation transport solution, if highly multidimensional, could lead to a multidimensional power distribution, which could in turn drive a multidimensional thermomechanical response. However, because a radiation transport solver can overwhelm the computational resources in a coupled physics simulation, it would be highly desirable to demonstrate that the thermomechanics solution is weakly dependent upon the multidimensional power distribution.

There will be annual reviews by a body of expert users, the TFC leadership, the Fuels and Reactor IPSC leadership, the software development leadership, and DOE Office of Nuclear Energy sponsors of the progress and planning to assess the viability of developing the integrated code with the given plan and the resources available.

5.4 STAGED DELIVERY

The staged delivery timeline, shown in Fig. 4, includes AMP (described in Sect. 4.3). This timeline assumes that the independent exploratory enhancements to AMP in FY11 (to clarify requirements for the 2015 code) will not be integrated, tested, and reviewed as an official release. Therefore, there will be only one official release of AMP, as it will be replaced with the initial release (August 2012) of the new

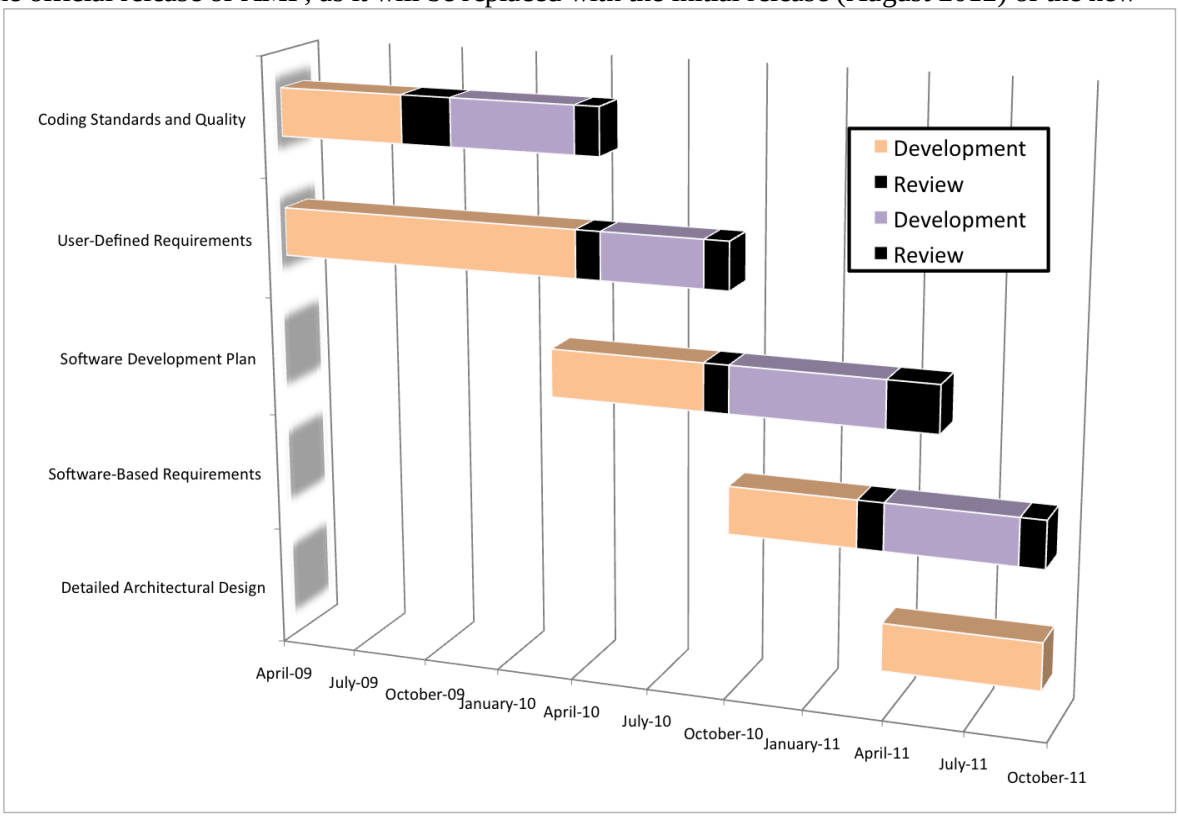

Fig. 3. Software planning timeline.

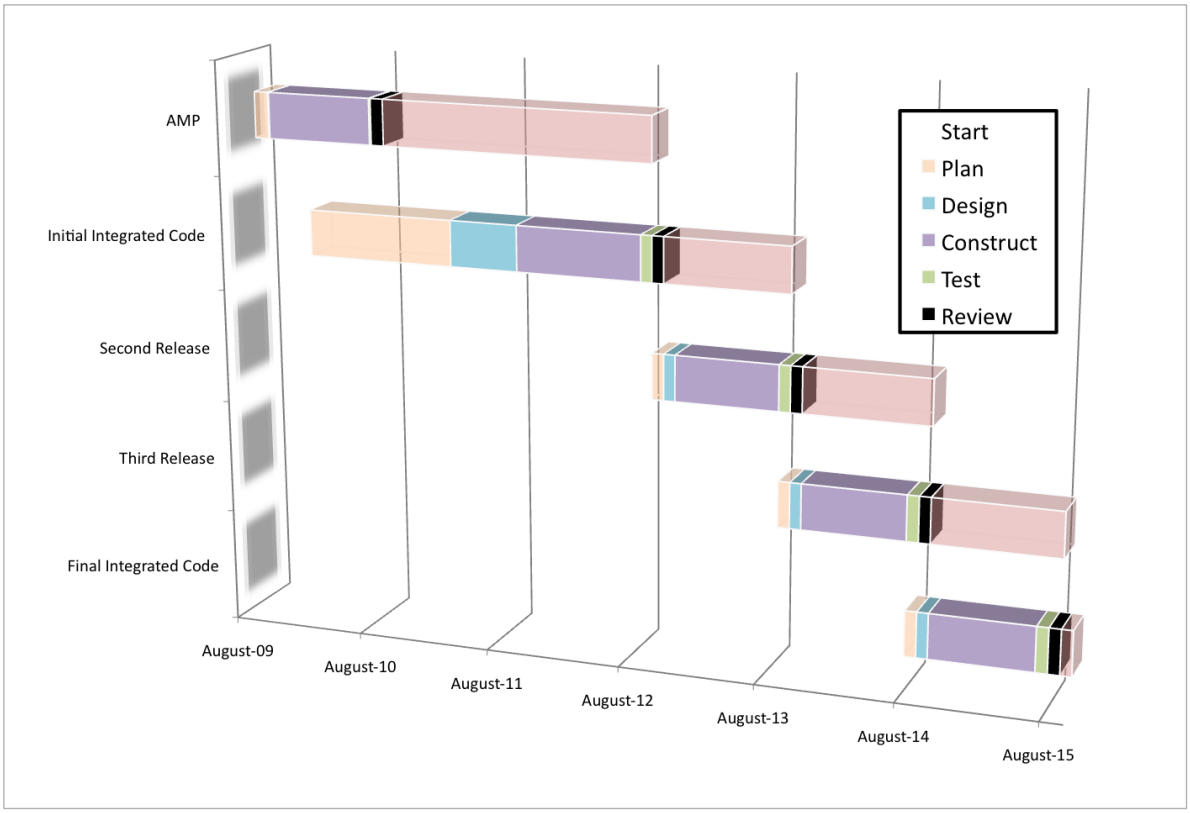

Fig. 4. Staged delivery timeline.

integrated code. This will include a 12-month software development cycle with intermediate releases in August of 2013 and 2014 and a final release in August 2015. Each 12-month release cycle will include a planning, design, construction, and testing phase. After each release there will be a 1-month review phase, which will coincide with the planning phase of the following release, and a final "use" phase until the release of the subsequent version.

6. COST AND QUALITY

The scope and schedule described herein are assumed to be fixed, which implies a direct relationship between the budget and quality of the product. Before the planning phase is completed, budget requirements will have a high uncertainty; at this early stage we assume a +100% and –50% uncertainty in the cost for a given level of quality. Table 1 provides a summary of the estimated FY funding requirements for each technology readiness level (TRL).

Table 1. Fiscal-year funding requirements (in $M) for various levels of software quality

	2010	2011	2012–2015	Total
TRL 3	2	3	4	21
TRL 4	2.5	5.5	6	32
TRL 5	3	6	8	41
TRL 6	3.5	7.5	10	51
TRL 7	4	8	12	60

Though quality, often hidden within scope, is a difficult metric to quantify in a software development project, it is a very real consideration in that it has a strong bearing on future cost. Low quality will lead to additional indirect future costs associated with maintenance, bug fixes, and modifications of the scope. The project manager will maintain, under revision control, a continuously updated budget requirement with associated levels of quality. Therefore, the level of quality will be defined with the TRL of the Fuel Cycle R&D Campaign.[8] A TRL of 7–9 is considered a proof of performance, which must be evaluated for a specific fuel type in a specific reactor and requires a sufficient empirical database. A TRL of 4–6 is considered a proof of principle and requires sufficient physics models, verification of the software, and validation with an empirical database to have demonstrated that advanced modeling and simulation tools can be used to simulate the relevant physics within a fuel pin. A TRL of less than 4 simply demonstrates some capability useful for nuclear fuel simulation, with very little validation or verification and possibly resulting in software that may not be extensible enough to incorporate the requisite physics models or software quality engineering to become a qualified tool.

With regard to the 2015 code, a software TRL of 9 for a given fuel type is defined as having been qualified to be used for licensing purposes, but requiring extensive integral testing data, such as in-core testing with lead-test assemblies, which is beyond the scope of this project. A software TRL of 8 is considered, within this project, to have gone through an initial phase of qualification for an advanced fuel. A minimum proof-of-performance level (TRL of 7) could be achieved for a fuel type that has developed an extensive empirical database. This would require a fully verified code with extensive user experience and validation with the empirical database for nominal and transient tests. A high proof-of-principle level of software quality (TRL of 6) is defined as fully verified software that is validated with a general empirical database, but without a use-case pedigree that would provide any level of qualification for a specific fuel type. A moderate proof-of-principle level (TRL of 5) would incorporate legacy software that is not born-verified and include substantially less verification. The transient capability would include legacy effects and far less verification. It would not be immediately ready for qualification. A minimal proof of principle (TRL of 4) would include extensive use of legacy tools, especially material properties, as little focus would be placed on incorporation of lower-length-scale models into the engineering code. Little software would be born-verified, and extensive work would be required to extend it beyond the specific target fuel types for which it was designed. However, it would provide a three-dimensional simulation capability that could be used by engineers. Finally, a proof of concept (TRL of 3) could be achieved with minimal funding levels. This would include little new software, none of which is born-verified. It would likely extend the capabilities in the existing codes that are integrated in the prototype code. It would include very little multi-institutional collaboration, and there would be major questions regarding the quality of the solution due to missing physics and algorithms that are not consistently robust.

7. SUMMARY OF SCHEDULE AND SCOPE

As noted in Sect. 6, there is potential variability in the quality of the software delivered based on the funding provided, but the schedule and general scope of the software will remain fixed, assuming the minimum level of funding is provided and the scope remains fixed. A summary of the capability provided by software release, through 2015, is shown in Table 2.

Table 2. Software releases and capability included

Release	Date	Scope
AMP	8/2010	Advanced three-dimensional thermal-mechanical-chemical solver for nominal operation of a light water reactor pin with cylindrical oxide pellets in clad with zero- and one-dimensional physics
Initial	8/2012	Specifics to be determined, but likely an advanced three-dimensional thermal-mechanical-chemical solver for nominal operation of a CAD-defined geometry of metal or oxide fuel in clad with fracture and plenum flow and associated zero- and one-dimensional physics
2	8/2013	An extension of the initial release with the addition of upscaled physical properties, such as alloy segregation (chemical diffusion and segregation) and fission gas release
3	8/2014	An extension of the second release with the addition of a transient capability (and associated multidimensional physics) and additional upscaled physical properties
Final	8/2015	An extension of the third release with extensive testing on many platforms and a greatly simplified interface for users to efficiently run on large computational platforms; additional upscaling as required for transient simulations

8. REFERENCES

1. K. O. Pasamehmetoglu, *Transmutation Fuels Campaign Execution Plan*, GNEP-FUEL-PMO-PM-PL-2007-000326, Rev. 0, Idaho National Laboratory, 2007.
2. C. Unal and K. O. Pasamehmetoglu, *Transmutation Fuels Campaign Modeling and Simulation Roadmap*, INL/EXT-08-14221, Rev. 0, Idaho National Laboratory, Idaho Falls, Idaho, 2008.
3. J. A. Turner and K. T. Clarno, *Vision and Scope for an Engineering-Scale Nuclear Fuel Performance and Safety Code*, ORNL-TM/2009/241, Rev. 0, Oak Ridge National, Laboratory, Oak Ridge, Tenn., 2009
4. Pacific Northwest National Laboratory, "FRAPCON-3," 2005, http://www.pnl.gov/frapcon3/.
5. *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation*, ORNL/TM-2005/39, Version 5.1, Vols. I–III, November 2006. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-732.
6. Oak Ridge National Laboratory, "SCALE: Standardized Computer Analyses for Licensing Evaluation," 2009, http://www.ornl.gov/sci/scale/.
7. T. M. Evans and K. T. Clarno, *C^{++} Coding Standards for the AMP Project*, ORNL-TM/2009/240, Rev. 0, Oak Ridge National, Laboratory, Oak Ridge, Tenn., 2009.
8. J. Carmack and K. O. Pasamehmetoglu, *Definition of Technology Readiness Levels for Transmutation Fuels Development*, INL/EXT-08-13780, Idaho National Laboratory, Idaho Falls, Idaho, 2008.