STP-NU-057

ASME CODE DEVELOPMENT ROADMAP FOR HDPE PIPE IN NUCLEAR SERVICE

ASME STANDARDS TECHNOLOGY, LLC

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FOREWORD

The ASME HDPE Roadmap has been developed as a guide toward deploying Code rules for the safe use and advancement of HDPE piping in nuclear services. The principle focus of the ASME HDPE Roadmap is to promote the development of rules that will govern the technical aspects of the design, installation, operation and inspection of HDPE piping systems.

Historically nuclear plants have used metallic pipes for service water and other raw water systems. These pipes have been afflicted by both internal and external microbiologically induced corrosion (MIC), soil attack and other factors. As a result, many of the operating nuclear plants have had to perform significant repair and/or replacement of these piping systems well in advance of realizing their original 40 year design life. Duke Energy began using HDPE piping in the conventional service water system at its Catawba Nuclear Station in 1998 after experiencing a variety of corrosion issues in the original carbon steel system piping; only 13 years after commercial operation. To date, the HDPE piping at Catawba Nuclear Station has performed well and has proven to be a cost effective way to address the corrosion issues in the station's service water piping. HDPE piping is durable, requires very low maintenance and has lower overall cost than metallic piping.

As a result of the success at Catawba Nuclear Station, Duke Energy and other utilities have sought to use HDPE piping in buried ASME Section III, Class 3 service water system applications. In 2008, the Nuclear Regulatory Commission (NRC) approved a Relief Request for the AmerenUE Callaway Nuclear Plant for the use of HDPE in buried sections of its essential service water system. The HDPE piping in the Callaway essential service water system has been in operation since late 2008. In 2009, the NRC approved a Relief Request for Catawba Nuclear Station for use of HDPE in buried sections of its nuclear service water system. Sections of the HDPE piping in the Catawba nuclear service water system have been in operation since late 2010.

It is the desire of ASME, Utilities, Regulators, the HDPE industry, Architect-Engineer (AE) firms and Constructors to develop a technology roadmap, which will support technology strategy and planning goals to achieve safety, reliability, economic and research and development.

Achieving a broad acceptance of HDPE pipe for use in water systems at nuclear plants will require collaboration and sponsorship from industry, regulators, government entities, research organizations, domestic and international associations and individuals.

Established in 1880, the American Society of Mechanical Engineers (ASME) is a professional not-for-profit organization with more than 127,000 members promoting the art, science and practice of mechanical and multidisciplinary engineering and allied sciences. ASME develops codes and standards that enhance public safety, and provides lifelong learning and technical exchange opportunities benefiting the engineering and technology community. Visit www.asme.org for more information.

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EXECUTIVE SUMMARY

Existing metallic piping systems in safety related and non-safety related service water in nuclear power plants are prone to tuberculation, corrosion and leaks, and require replacement, in some instances in less than ten years of service. Non-safety related HDPE piping systems currently installed in nuclear power plants have proved to be reliable since 1996. Several utility owners have successfully installed HDPE piping. The owners would then seek approval by the Nuclear Regulatory Commission (NRC) through a Relief Request process.

The NRC Relief Request process normally requires one year to complete. Development of and NRC approval of ASME Boiler and Pressure Vessel Code rules for use of HDPE would be very beneficial to all parties in the nuclear power industry. Much research and testing has been undertaken and is continuing in support of HDPE use for nuclear power piping.

The ASME HDPE Roadmap proposes strategies which will be used to develop appropriate rules to impart science and structure to the HDPE piping application in nuclear service. The Roadmap identifies critical technologies and infrastructure gaps, barriers and opportunities, and recognizes and prioritizes research and development programs and new technology needs [1].

Among the issues identified for resolution are: piping system design requirements and engineering properties; pipe fusion procedures; fusion integrity analyses and testing procedures development; pipe performance requirements; volumetric examination methods and determination of acceptable material flaws applicable to U.S. and international standards and procedures.

The execution of these strategies requires technical and financial commitment by the nuclear industry operators and suppliers as well as academia and regulators. Immediate financial and technical commitments are needed to execute several of these strategies.

HDPE pipe replacement saves money and enhances safety. It is easy to install, it is corrosion free, durable and not subject to fouling. The ASME HDPE Roadmap is the first step toward establishing a disciplined structure toward creating Code rules to address pressing industry's needs. The next step will focus on follow-up activities dealing with executing current needs, and simultaneously developing future endeavors.

STAKEHOLDERS

The ASME HDPE Roadmap stakeholders are members of Section III Stakeholders Group. The members are:

- Richard Barnes – BVP Standards Committee III Chairman
- Gary Park – BPV Standards Committee XI Chairman
- Steve Lefler* – Duke Energy
- Stephen Boros - Plastic Pipe Institute
- Craig Scott* - AREVA
- Bo Clark – EPRI
- Tim Lupold – NRC
- Frank Schaaf – BPV Standards Committee XI

Members with an asterisk (*) next to their name were called on to become members of the Reviewers Team, whose mission was to advise the Roadmap Author and review and edit the Roadmap content.

1 INTRODUCTION AND ORGANIZATION

The objective of the ASME HDPE Roadmap is to develop a strategy for advancing the rules that will govern the technical aspects of the design, installation, operation and inspection of HDPE piping systems in nuclear power plants. Scientifically and statistically based rules will instill safety and confidence, and these rules are in the best interest of the nuclear industry, regulators, the HDPE industry and the general public. The ASME HDPE Roadmap strategy aims to identify gaps, remove roadblocks, facilitate necessary research and resolve concerns.

The Roadmap is intended to lead to the development of Code rules, which can subsequently be endorsed by the regulator (NRC) for generic use and application to facilitate licensing without the need for an application specific Relief Request.

The strategies and plans of the ASME HDPE Roadmap (this document) attempt to identify and characterize the industry and regulators' concerns, establish relevant justifications for desired research, and challenge researchers and providers to deliver solutions [2].

The Roadmap identifies codes and standards related to HDPE piping and may require modification to address HDPE piping applications in nuclear service.

This document does not address the process, or Roadmapping. The technology Roadmapping represents a powerful technique to support technological management and planning, especially to explore and communicate dynamic interactions between resources, organizational goals and environment changes [3].

The Technology Roadmapping process provides a way to develop, organize and present information about critical requirements and desirable performance of objectives that must be achieved at the planned time [2].

This report is structured as follows:

- It describes the research and networking leading to the development of the roadmap strategies and plans.
- It identifies major issues of concerns, gaps and roadblocks.
- It clarifies issues by describing their background and lays out options for technical solutions.
- The roadmap summarizes and prioritizes research projects deemed important to receive technical solutions. It displays projects schedule and milestones in a Gantt style chart and tabulated form.

2 THE HDPE PIPE TECHNOLOGY ROADMAP

The objective of the ASME HDPE Roadmap is to lead the industry toward achieving its principal goal, which is to advance and increase the use of HDPE piping in nuclear power plants. This can be achieved through the development of Code rules following proposed plans and strategies which will result in a structured and safe application. Proposed plans and strategies will serve as instruments to identify gaps and obstacles, resolve technical issues and forecast and identify research needed to establish an acceptable basis to support the use of HDPE piping in nuclear plant applications.

Several projects to replace worn-out metal pipes and or install new piping systems are underway. The use of HDPE piping in nuclear power plants will promote safety, durability and cost saving in construction and operation. The current practice to license an HDPE piping system in nuclear power plants is through an application to the Nuclear Regulatory Commission (NRC) for a Relief Request. This process is complex and time consuming. Instead, ASME has developed this Roadmap which eventually will lead to:

- Researching and finding solutions to current technical issues.
- Developing a comprehensive Code that is specific and succinct, and which precludes the need for extensive licensing activities required for NRC acceptance.

A questionnaire was developed and e-mailed to survey participants to collect information about real and perceived gaps and obstacles associated with current and future use of HDPE piping in nuclear water service applications. The composition of the survey participants were mainly members of ASME Section III Working Group on HDPE Research and Development and other contributors to ASME Sections II, IX and XI. Additionally, input was requested from several members of the international community. Ensuing participant response, the questionnaire was followed by a telephone interview to discuss responders' input.

The total number of responders was 21, or 70%, of those invited to participate. The questionnaire or survey identified gaps, roadblocks, technical issues and proposed solutions. The responders provided a wealth of information relating to actual and perceived issues facing the continued success of HDPE piping in nuclear service. Participant input covered a wide range of subjects concerning applied engineering, product performance, regulatory, financing, etc. The table below summarizes the participant input.

Table 1 - Summary of Survey Responses

General Category	Category	Issues and/or Needs
Regulatory, Standardization	NRC	1- Develop a clear path to gain acceptance (EPRI TR or Topical Report) 2- Acceptance criteria (Tell us what is acceptable and what is not) 3- Remove real or perceived difficulties and/or risks obtaining NRC approval 4- Clear timetable to develop and resolve NRC's concerns 5- Obtain NRC's concurrence with code requirements for use of HDPE piping material so as to avoid the need for a Relief Request 6- Absence of overriding strategy , especially with NRC
	Code Case	1- An approved Code Case that precludes the need for extensive licensing activities…. 2- Place fusing requirements specific to Section III or Section II 3- Place general fusing requirements in Section IX
	Standards	1- Develop standards for tees, reducers, etc…. 2- Identify existing ASTM and ISO standards which need to consider nuclear applications 3- Develop a standard for carbon black pigment or concentrate 4- Standardization of JIS, Code of practice and specification
Testing, Evaluation	All Tests	1- Appropriate test method and service life models based on fundamental knowledge of failure mechanics of PE 4710 resin (piping integrity) 2- Models to evaluate the effect of fusion variables on thermo-rheological characteristics of PE 4710 during the fusion process 3- Reliable, repeatable and capable volumetric inspection technology including identified inspection limits and uncertainties (Allowables) 4- Evaluate joints of pipes, valves, fittings.... under adverse conditions and transient behavior such as stress, chemicals/chlorine, cold fusion, vibration/earthquake, oxidation, fire/heat excursions 5- Assurance that brittle failure will not occur before piping system life-performance design 6- Develop and establish reliable data on design allowables 7- Develop a design process methodology for all designers to follow 8- Damage accumulation - Employ experimental and theoretical techniques to evaluate 9- Use statistical analysis to project confidence in experimental data which predict performance 10- Develop a master curve for SCG under essential parameters 11- Develop a standard method to test fusion for long-term test and correlate to short-term test 12- Develop side-bend test procedure and define acceptance criteria 13- Correlate all long-term performance tests with equivalent short-term instrumented tests where applicable 14- Lifetime prediction of Large Size pipes for circulating hot water 15- Inspection technology of defects in Large Size HDPE pipes and Joints 16- Determine suitable fusion conditions of Large Size HDPE pipes 17- Establish anticipated design conditions, static or dynamic, during normal and upset conditions. These to include time, temperature and pressure

General Category	Category	Issues and/or Needs
Quality, Performance	Design & Acceptance Criteria, Essential parameters	1- Volumetric examination of fused joints 2- Encoded UT System 3- Slow Crack Growth 4- Flaw/Scratch depth 5- Modulus as a function of stress 6- Fusion (essential variables) under different stresses, temperatures and environments 7- Piping integrity 8- How to design for HDPE/Understand the difference between designing for HDPE (visco-elastic) and metal and know the considerations 9- Know tensile properties, creep, deformation 10- Pressure boundaries (In-service inspection) 11- Piping System design requirements, including worst case scenario 12- Explore the use of Miner's rule for estimating pipe lifetime as means to reducing the severity of service life requirements 13- Establish an experimental program (protocol) and data (statistical) analysis which will verify that HDPE pipe meets current design requirements 14- Use short term (analytical/instrumented) test protocol to establish verification program that HDPE resin meets requirements
	Allowables	1- Scratches … minimum acceptable depth 2- Cold fusion 3- Fusion essential variables 4- Minimum acceptable fusion per area or volume (account for voids)
	Detection, Limits, Definitions	1- Voids 2- Critical vs. non-critical flaw size or geometry 3- Scratch 4- Chemicals which potentially will come in contact with HDPE piping….. Cooling tower water treatment, chemicals to kill mussels, others…… 5- Long-term performance, years? (same performance after 50 years as day one? or will it be prorated?) 6- Short-term performance 7- Deformation 8- Good vs. bad fusion by NDE or other test methods (Pass/Fail) 9- Flaw: When is or is not a defect and non-injurious
Complementary Projects, Research		1- Fracture Mechanics based standards 2- Develop Specimens with known relevant flaws and examination 3- Optimize UT technique 4- Electrofusion coupling 5- Qualification of additional fittings such as tees, reducers 6- Develop a holistic approach to piping system integrity that includes state-of-the-art science-based service life estimation 7- Volumetric inspection technology 8- Reliable fusion joint integrity test which correlates with hydrostatic test 9- Alternative to high speed tensile test (HSTT) - Research at EWI has shown that HSTT may not be the most reliable method 10- Investigate annealing the fused joint to achieve microstructure uniformity between joint and parent pipe 11- Develop a technology which can continuously monitor changes (leaks, temperature ....) in piping system - FIBER OPTICS? 12- How to monitor cold fusion? 13- Notch-bar test to determine SCG and resolve the question of thermal stresses 14- In-service Inspection (ISI) 15- Improved technology for characterizing SCG performance of HDPE resins: Research to understand and characterize the slip-stick crack growth phenomenon in HDPE resin and subsequent modeling of this behavior to provide estimate of pipe lifetimes 16- Evaluate resistance of large size pipe to rapid crack propagation
Other		1- Engage carbon black manufacturers and suppliers in the specification process of their product - As of now they are absent 2- Address concerns of resin manufacturers about liability and potential legal action.... Deep pocket scenario!

3 IDENTIFIED R&D PROGRAMS

The survey was successful in identifying solutions to many of the issues. Many solutions are currently in place or under development, such as the ongoing research by the Electric Power Research Institute (EPRI). Others are awaiting implementation, and are in need of research funds, such as the program outlined in a white paper jointly written by the Gas Technology Institute (GTI) and the National Institute of Standards and Technology (NIST), entitled "Improving the Performance of Service Water Piping in Nuclear Power Plants." Other research firms, individual researchers affiliated with testing laboratories or universities and resin manufacturers proposed solutions through testing or developing tests through experiments. These will be discussed in the Action Plan later in this Roadmap.

3.1 Work In Progress

The roadmap survey revealed several issues of importance to the piping applications. They are related to codes and standards, quality and performance and testing and evaluation. A few of these are:

- CC N-755-1: Split the needs and requirements of ASME Section III and Section XI so each Section will have its own Code Case.
- U.S. and International Standards: Identify U.S. and international standards and modify where needed to reflect the requirements of HDPE in nuclear application. (Aaron Forster, Leader).
- Define and specify design and acceptance criteria, and allowable essential parameters.
- Develop new, and optimize existing, test methods and procedures which deal with piping lifetime performance and prediction, based on models and/or experiments.

The aforementioned issues will be further discussed later in this document.

3.2 Schedule and Key Milestones [4]

- The Roadmap strategies are to be executed in a timely manner.
- An events schedule with key milestones will be displayed by a Gantt chart.
- A justification of the events schedule with key milestones will be represented in tabulated form.
- The Roadmap will be a living document and must have a flexible approach to adapt to future considerations.
- Events schedule will include frequent peer reviews by all stakeholders to ensure acceptance of the final results.
- A process for resolving conflicts that arise during peer review will be provided.

3.3 Technology Development and Deployment

3.3.1 Short-term Deployment

- Has a timeframe of 0-5 years.
- Concerned with existing gaps and technology and immediate needs, these are:
    - Develop and support acceptance criteria for volumetric flaws.

- Provide Code requirements for volumetric inspection of joints.
- Slow crack growth (SCG) resistance of butt fused joint relative to parent pipe.
- Develop data to support the use of 10% scratch criteria.
- Provide a methodology for UT testing requirements for inspection personnel.
- Identify or develop a method to detect cold fusion of joints.

3.3.2 Long-term Deployment

- Has a timeframe of 5-10 years.
- Concerned with emerging issues which are not well defined or understood:
  - Develop a constitutive model to show how a polymer system works.
  - Develop a holistic approach to piping system integrity that includes state-of-the-art science based service life estimation.
  - Investigate lifetime prediction of large size diameter HDPE pipe in circulating hot water.

4 DESIGNING WITH HDPE

A major concern with HDPE polymer is its long-term creep deformation. This property is inherent to viscoelastic materials, which are defined as those which exhibit both viscous and elastic characteristics when undergoing deformation. Viscoelastic materials, such as HDPE, are stress, time and temperature dependent. HDPE displays rapid creep rate early on, and then tapers off with time, revealing that most of the creep deformation occurs during the early stage of its life [5]. The creep of HDPE is generally recoverable at strain levels not exceeding the yield point. Creep modulus of HDPE decreases with increased temperature, leading to the conclusion that not only time and stress, but also temperature affects creep behavior.

Based on the above the following issues must be addressed and resolved:

- Determine flaw acceptance standards.
- Determine tensile, creep and deformation limits of HDPE polymer and pipe at pre-determined temperature intervals acceptable to ASME Section II.
- Construct isochronous stress-strain curves up to failure at different sets of stresses and temperatures. Cover wide enough range of test parameters to ensure inclusion of all potential failure mechanisms, including transitions.
- Use data as basis for proper design for construction and safe operation.
- Determine the modulus as a function of load duration, stress and temperature. Identify if stress has significant impact on modulus.
- Define ductile-brittle transition.
- Collaborate with resin manufacturers and ASME Section II to develop methods for establishing allowable stresses.
- Develop minimum data quality requirements for material properties.
- Investigate the feasibility of expediting regulatory approval by limiting maximum allowable temperature in the code case (e.g. 105°F).

5 FUSED JOINTS INTEGRITY

Pipe fusion consists of prepping the interface of pipe-ends by resurfacing and cleaning them; bringing them against a hot plate for a predetermine hold-time at specific pressure and temperature. Once the hot plate is removed, the two pipe-ends are pushed against each other and held in place for a predetermined time to create intimate fusion. To safeguard the integrity of fused joints, the following concerns must be addressed and resolved:

- Develop procedures to qualify fusion equipment and operators (covered in ASME BVPC Section IX).
- Determine which fusion parameters must be monitored and recorded (covered in ASME BVPC Section IX).
- Consult the Plastics Pipe Institute's (PPI) Technical Report [6] on pipe fusion to derive usefulness and gaps in the report.

Other issues which require the industry's dedication are the certitude of the integrity of short-term and long-term performance of the fused joints, including fittings and flanges under adverse conditions. These conditions include:

- Exposure to chemicals
- Radiation
- Excursion in temperature/heat and pressure
- Vibration/earthquake
- Oxidation
- Any combination of two or more of the above.

Fused large diameter (>36" OD) and thick wall pipes (>3.5") have not received as much attention in research and performance evaluation as smaller pipes. Fusion procedure, inspection and long-term performance requirements must demonstrate the integrity and repeatability of the process to satisfy regulators and power plant owners.

Strong emphasis has been devoted to cold fusion and voids. These flaws may or may not be a detriment to the fusion integrity if they exist in a small percentage of the total fused area. Voids may or may not be avoidable or detectable; therefore, research must be conducted to determine and define allowable flaws and ironically their potential benefits. Small voids are theorized to arrest the propagation of a crack should they happen to be in its path.

Based on the responses to the survey, the following issues must be addressed and resolved to instill confidence in the fusion process and integrity:

- Evaluate the short-term and long-term performance of joints of pipes, valves, fittings and flanges under adverse conditions and transient behavior such as stress, chemicals/chlorine, cold fusion, vibration/earthquake, oxidation, fire/heat excursions.
- Develop short-term fusion integrity test methods which correlate with long-term standard method.
- Develop a model to evaluate the effect of fusion variables on thermo-rheological characteristics of PE 4710 during the fusion process.

- Develop an appropriate test method and service life models based on fundamental knowledge of failure mechanics of PE 4710 resin. Service life prediction models are needed for fusion joints with and without flaws.
- Determine suitable fusion conditions of Large Size HDPE pipes.
- Develop an inspection technology for defects in Large Size HDPE pipes and Joints.
- Determine lifetime prediction of Large Size pipes for circulating hot water.
- Investigate and quantify the injurious and non-injurious potential of voids and cold fusion within the bounds of an acceptable fused joint.
- Develop a reliable, repeatable and capable volumetric examination technology including acceptance criteria.
- Correlate examination results with destructive testing of fused joints.
- Determine morphology and extent of failure for a joint with a flaw.
- Develop a test method to monitor cold fusion.

6 SLOW CRACK GROWTH AND FLAW ALLOWANCE

Slow crack growth propagation ultimately will lead to a life-ending brittle failure of a HDPE pipe. Scientifically and accurately predicting the lifetime performance of an HDPE pipe is significant, for it satisfies the Nuclear Regulatory Commission's (NRC) need to thoroughly and fairly evaluate and rule on new licenses, and design engineers' need to conform to design criteria.

Slow crack growth (SCG) is an event that is initiated when an applied external or internal stress, such as an impingement or a cut, a gel or impurity, causes a microscopic craze to develop. The craze develops as a void with an acute tip as the leading edge and trailing fibrils. When fibrils reach their ultimate strain, they break and usher the crack initiation process. This process is intermittent and the void expands until it is manifested as a full-grown crack. This process can take decades to complete; however, the duration of this process depends on the characteristics of the HDPE resin. Regardless of the nature of the crack initiator, be it oxidation, stress concentration or other, the true resistance to slow crack growth lies within the molecular structure of the resin.

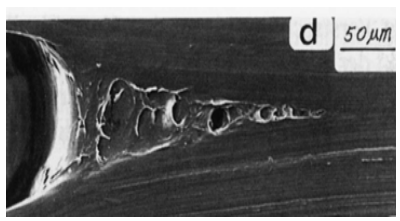

Figure 1 - Craze with Fibrils during SCG

(Courtesy of LyondellBasell)

There are several varieties of PE 4710 HDPE pipe grades:

- Ones made with Ziegler-Natta catalyst in dual reactors are known as bimodal. They are manufactured with ethylene long chain backbone and either butene or hexene short chain side branches.
- Ones made with a chromium catalyst in a single reactor are called "mono-modal" HDPE grades. They are made by melt blending two or more "mono-modal" resins in a post reactor process.

All grades are stabilized with anti-oxidant additives, which allow the resin to resist heat and shear during manufacturing and pipe processing, and to a certain degree help retard molecular degradation when oxidizing chemicals, such as chlorine, attack the pipe surface.

Any one of these grades can be legitimately labeled as PE 4710 if it meets minimum performance requirements per industry standards [7]. Not all PE 4710 HDPE pipe grades, however, display equal performance. Some are better than others and some far exceed minimum performance requirements. Therefore, each individual commercial grade must be evaluated based on its merits.

There are several methods to test for SCG resistance available today.

- Pennsylvania Notch Test (PENT) per ASTM F 1473 Standard is an instrumented static creep test conducted on a notched rectangular test specimen at 80°C and 2.4 MPa, in a laboratory environment. Such tests can last for >10,000 hours before failure. PENT is used to screen and rank HDPE resin's resistance to SCG.

- Notch pipe test (NPT) per ISO 13279 Standard is a test conducted under hydrostatic stress in a water environment at 80°C. It serves to determine the time-to-failure of the pipe due to slow crack growth. This test can last for >3000 hours until failure. Most laboratories have the capability of testing 4” OD pipe. Laboratories for testing larger diameter pipes, 36” OD or greater, are difficult to find and the test can be cost prohibitive.
- Full Notch Creep Test (FNCT) per ISO 16770 is a constant load tensile test which makes use of a tensile bar with square cross-section notched on all sides. The test is conducted in the presence of a surfactant, which acts as an accelerator toward reaching time-to-failure.
- Cracked round bar (CRB) test is a round circumferentially notch test bar [8]. The test relies on fatigue as the driving force. It is designed to provide a quick screening and ranking of HDPE pipe material.
- Accelerated SCG Cyclic Pressure Fatigue (CPF) Tests [9] serve to develop an accelerated SCG test method for HDPE Pipe and correlate it with hydrostatic stress rupture test method ASTM D 1598.
- Strain hardening modulus as a measure of environmental stress crack resistance of high density polyethylene, typically measured at 80°C [10].

The ability to determine the time-to-failure via SCG test of an individual HDPE resin, and to accurately predict its lifetime performance, is an essential step toward the successful design and use of HDPE piping in nuclear power plants. Any predictive model should be validated by performing a pipe test.

PE 4710 pipe test specimens have been observed not to display a D-B transition, during long term hydrostatic stress (LTHS) at 73°F environment and high stress, in >50,000 hours testing. The NRC will not accept an indefinite lifetime performance and requires well documented scientific substantiation of actual performance envelope. The NRC also requires an end-point test result.

There is often a disagreement among HDPE scientists as to the relationship of SCG and D-B transition. It is imperative that this disagreement be addressed and resolved and a measurable response to a ductile-to-brittle transition point in-time be defined for LTHS pipe performance at 73°F, and SCG time-to-failure be researched for medium and large pipe sizes.

Scratches, dents, nicks and cuts are unavoidable on HDPE pipe surfaces during pipe transportation and installation. Efforts by the researchers must be made to evaluate the effect of these flaws on the pipe SCG performance and define and recommend allowable flaws.

Time-to-failure experiments must be conducted under worst case conditions, to safely determine a pipe lifetime performance.

Test methods must ultimately demonstrate that brittle failure will not occur during the service life of the pipe.

7 REGULATORY ISSUES

The many functions of the NRC include formulating policies and regulations governing nuclear reactor and materials safety, issuing orders to licensees and adjudicating legal matters brought before it. Additionally, the NRC reviews Codes for acceptability for use in nuclear plant construction. The acceptability of Code Cases of ASME Section III-Division 1 and Section XI-Division 1 is identified in Regulatory Guides 1.84 and 1.147, respectively. The U.S. nuclear utilities (i.e. licensees) cannot utilize ASME Code or Code Cases for systems falling under the jurisdiction of the NRC without at least a conditional acceptance from the NRC.

The ASME Boiler and Pressure Vessel (BPV) Code Committee has issued rules for the construction of buried Section III, Division 1, Class 3 HDPE piping systems in Code Case N-755, Revision1. To date, the NRC has not formally reviewed Code Case N-755. Therefore, neither acceptance nor conditional acceptance has been provided for Code Case N-755 in Regulatory Guide 1.84 or 1.147. To date, NRC approval for the use of HDPE in buried Section III, Division 1, Class 3 applications has only been provided by means of licensee specific 10 CFR 50.55a Relief Requests without reference to Code Case N-755. By definition, a Relief Request is only valid for the remainder of current 10 year In-service Inspection (ISI) interval and must be renewed each subsequent ISI interval. Furthermore, the initial approval process can take anywhere from 6 months to a year from the initial issuance of the Relief Request to the NRC.

While the NRC has not formally reviewed Code Case N-755, the NRC staff has provided a list of HPDE related concerns and unmet needs to the Working Group on HDPE Research and Development, which is shown in Table 2. The NRC's role is not to specify resolutions to these concerns but rather to review resolutions proposed by the Code Committee and licensees for acceptability. In some cases, additional research may be needed to address the NRC concerns that have been identified. The NRC's role is not to perform this additional research to resolve the concerns, but rather to perform only confirmatory research to help the NRC staff make informed regulatory decisions. Therefore, it is up to the Code Committee, the HDPE industry and the end users of the Code Case (i.e. utilities, AE's, constructors, etc.) to provide resolutions to these concerns. Providing a satisfactory response or solution to the NRC concerns will eventually lead to a formal NRC review of Code Case N-755. Several of these concerns are currently being researched and addressed, while others require funding to be evaluated and resolved.

The current path for obtaining regulatory approval (i.e. a Relief Request) is viewed by many licensees as requiring additional schedule time and NRC review costs for approval. As a case in point, one licensee recently opted not to use HDPE in a major buried piping replacement project, in large part due to the risk and schedule uncertainty associated with the current HDPE licensing path. If a Code Case existed that had been at least conditionally accepted by the NRC, a licensee specific Relief Request would not be required and the licensing risk and uncertainty would be eliminated. As a result, many responders to the survey view the current licensing process as a significant roadblock to the use of HDPE and are calling on the NRC to be more pro-active in working with the Code Committee to revise Code Case N-755 as required such that it can be at least conditionally accepted.

Regardless of the Code Committee's position on the NRC's list of concerns, projects utilizing HDPE in systems falling under the jurisdiction of the NRC cannot proceed without NRC approval.

Table 2 - NRC's Concerns

Issue/Concerns	Status
Resistance of butt joints to slow crack growth (SCG) relative to parent pipe material needs to be established.	SCG testing is planned by EPRI.
Flaw sizes of 10% t in the pipe wall may be unacceptable for thick wall PE pipes as the removal of this amount may affect the integrity of the PE piping. Equally, sharp cracks, may not be acceptable from a slow crack growth. Limitations should be specified to show acceptable flaw depth based on pipe dimension ratio (DR), pressure and temperature.	EPRI conducting SCG testing to evaluate SCG resistance. Analysis needed to establish the allowable flaw size. Limitation on flaw size is currently being addresses as well.
Through-wall thermal gradient stresses.	ASME addressed hoop stresses. Axial stresses are being analyzed.
Use of Miner's Rule approach to determining allowable service life stresses.	Initially, the WG HDPE Design (formerly TG Design) determined the current allowable stresses are more conservative than using a Miner's Rule approach. Recently, the use of Miner's rule is being reconsidered by the WG HDPE Design. Will need to be reconsidered for above-ground piping where effect of cumulative time and temperature effect on modulus is critical.
There is a need for creep data (strain vs. time) and modulus for PE 4710 materials at stresses and temperatures of interest as the PE materials exhibit creep at much lower temperatures compared to metallic materials. Long term creep data that accounts for the viscoelastic nature of PE is required to establish the safe allowable stress.	EPRI has included creep testing into their next phase of testing.
Models used for service life prediction based on the use of accelerated testing data (account for SCG).	Certain design considerations help mitigate the effect of the stress on modulus, but data is needed to accurately determine modulus as a function of stress, temperature and time.
Essential Variables for Fusion Procedure: The Code Case does not have a complete list of essential variables. Subjective variables should be replaced with measured variables.	TG Fusion and Section IX TG on PE Fusion working to resolve this issue. NRC is reviewing recent fusion experiments conducted to address this concern.
The NRC believes that performance demonstrations are necessary to validate capability, and repetitions are necessary to statistically establish reliability. Performance demonstration qualifications apply to joining pipe-to-pipe, pipe-to-fitting and fitting-to-fitting.	Visual and volumetric testing must be performed. Visual examination alone is insufficient. NRC will not accept less rigorous assurance of fusion joint integrity than that which was accepted to develop the basis of the approval of the Catawba and Callaway relief requests.
Modulus as a function of stress.	WG HDPE Design (formerly TG Design) is addressing this issue.
For a known range of resin properties (density, melt index, etc.), determine the effect of the essential variable ranges on the fusion process.	New Concern

8 DEVELOPING NEW GENERATION RESEARCH AND TESTING

The Long-term and short-term projects lists below represent current and future issues and concerns expressed by the NRC, the industry operators and engineers, scientists and other survey participants. They are prioritized and ranked by members of the HDPE Research & Development Working Group.

Table 3 - Long-term Issues and Solutions

1	Alternative to high speed tensile test (HSTT) – *Research at EWI has shown that HSTT may not be the most reliable method*
2	Investigate annealing fused joint to achieve microstructure uniformity between joint and parent pipe.
3	In-service Inspection (ISI) - Develop a technology which can continuously monitor changes (leaks, temperature ....) in piping system. *I.e. FIBER OPTICS? Acoustical, Sniffer, Smart Balls.*
4	Improved technology for characterizing SCG performance of HDPE resins.
5	Evaluate resistance of large size pipe to rapid crack propagation.
6	Explore the use of Miner's rule for estimating pipe lifetime as means to reducing the severity of service life requirements. *In progress.*
7	Develop training on HDPE manufacturing and pipe installation *A design guide.*
8	Develop Sidebend test procedure. *In progress.*
9	Investigate the use of ultrasonic testing for In Service Inspection.
10	Investigate lifetime prediction of large size diameter HDPE pipe in circulating hot water.

Table 4 - Short-term Issues and Solutions

1	Develop and support acceptance criteria for volumetric flaws *Define Flaw* *Develop the basis and analytical method to how to determine and define a flaw* *NDE Methods which detect and characterize flaws* *Optimize UT technique* *Develop inspection technology of defects in large size pipes & joints*
2	Provide Code requirements for volumetric inspection of joints
3	SCG resistance of butt fused joint relative to parent pipe *Determine requirement with the understanding that neither pipe nor joint should fail before the piping system designed service life.* *Reliable fusion joint integrity test which correlates with hydrostatic test*
4	Data needed to support use of 10% scratch criteria. Need for criteria to be function of thickness *Characterize through different flaw sizes*
5	Provide a methodology for UT testing requirements for inspection personnel
6	Identify or develop a method to detect cold fusion of joints *Coordinate with Section V.*
7	Code performance demonstration requirements; procedures, equipment and personnel (Fusion) *Coordinate with Section IX*
8	Establish all essential variables needed for fusion process (*Use GTI's model to determine good or bad weld*) *Coordinate w/ <u>Section IX</u> and ask what are the expectations? (do we have existing data or do we need experimental data?)*
9	Provide performance based qualification requirements at extremes of essential variables (based on TR33 Testing)
10	Cumulative effect of different duration loads. *Have the Design Group input if this project is needed.*
11	Develop Creep Data for PE 4710 *Tensile properties, isochronous curves, etc…*
12	Dimensional standards needed for fittings (Elbows, Tees Reducers)
13	Modulus as function of Stress and Temperature *EPRI is working on this*
14	Define surface conditions for examinations (What parameters would allow a good physical examination?) *It follows flaws definition (Gouges, scratches, dirt, grease…..)*
15	Need to include thru-wall thermal gradients in design analysis *In progress. Status by August 2012*
16	Fracture Mechanics Based Standards -*TBD*
17	Electrofusion coupling *Application requirements of EF-C in a piping system (rules and performance requirements)* *Procedures* *Inspections* *Operator Qualification*

9 STANDARDS AND CODES

A few of existing ASME, ASTM and ISO codes and standards do address HDPE piping for nuclear power plants, while the majority do not. A common practice is to review and convert ASTM Standards to ASME Standards when applying them to BPV Codes (i.e. ASTM A 106 was converted to SA-106). The following table identifies Standards that apply to HDPE piping which would require to be modified to satisfy nuclear service needs.

Table 5 - Codes & Standards

Organization	STD No.	Title	Subject Matter
ASME	N-755	Use of Polyethylene (PE) Class 3 Plastic Pipe	Pipe & Material
ASTM	D 3350	Standard Specification For Polyethylene Plastics Pipe and Fittings Materials	Material
ASTM	D 2513	Standard Specification for Polyethylene (PE) Gas Pressure Pipe, Tubing, and Fittings	Pipe
ASTM	D 2837	Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Product	Pipe
ASTM	D 1693	Standard Test Method for Environmental Stress-Cracking of Ethylene Plastics	Methodology
ASTM	D 1598	Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure	Methodology
ASTM	D 1599	Standard Test Method for Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing and Fittings	Methodology
ASTM	D 1765	Standard Classification System for Carbon Blacks Used in Rubber Products	Material
ASTM	D 3261	Standard Specification for Butt Heat Fusion Polyethylene (PE) Plastic Fittings for Polyethylene (PE) Plastic Pipe and Tubing	Pipe
ASTM	D 3035	Standard Specification for Polyethylene (PE) Plastic Pipe (DR-PR) Based on Controlled Outside Diameter	Pipe
ASTM	D 2239	Standard Specification for Polyethylene (PE) Plastic Pipe (SIDR-PR) Based on Controlled Inside Diameter	Pipe
ASTM	D 3895	Standard Test Method for Oxidative-Induction Time of Polyolefins by Differential Scanning Calorimetry	Material
ASTM	F 714	Standard Specification for Polyethylene (PE) Plastic Pipe (SDR-PR) Based on Outside Diameter	Pipe
ASTM	F 1473	Standard Test Method for Notched Tensile Test to Measure the Resistance to Slow Crack Growth of Polyethylene Pipes and Resins	Methodology
CSA	B137	Polyethylene (PE) Pipe, Tubing, and Fittings for Industrial and Water Pressure Services using ISO Rating Method	Pipe
ISO	9080	Plastic Piping and Ducting Systems - Determination of the Long-Term Hydrostatic Strength of Thermoplastics Materials In Pipe Form by Extrapolation	Pipe
ISO	1167	Determination Of The Resistance to Internal Pressure (Creep) 4 Parts	Pipe
ISO	13479	Polyolefin Pipes for the Conveyance of Fluids - Determination of Resistance to Crack Propagation - Test Method for Slow Crack Growth on Notched Pipes (Notch Test)	Pipe
ISO	13760	Plastics Pipes for the Conveyance of Fluids under Pressure - Miner's Rule - Calculation Method for Cumulative Damage	Methodology
ISO	12176	Plastics Pipes and Fittings - Equipment for Fusion Jointing Polyethylene Systems (4 Parts)	Pipe

Organization	STD No.	Title	Subject Matter
ISO	21307	Plastics Pipes and Fittings - Butt Fusion Jointing Procedures for Polyethylene (PE) Pipes and Fittings Used in the Construction of Gas and Water Distribution Systems	Pipe
DVS	Code Book	DVS Technical Codes on Plastics Joining Technologies	Pipe & Fittings
PPI	TR 3	Policies and Procedures for Developing Hydrostatic Design Basis (HDB), Hydrostatic Design Stresses (HDS. Pressure Design Basis (PDB), Strength Design Basis (SDB), and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials or Pipe	Pipe LTHS
PPI	TR 19	Chemical Resistance of Thermoplastic Piping Materials	Chemical Resistance
PPI	T3 33	Generic Butt Fusion Joining Procedure for Field Joining of Polyethylene Pipe	Pipe

The National Institute for Standards and Technology (NIST), separately, has formed a Work Group to address the needs to update Standards and Codes to incorporate HDPE piping in nuclear service. This effort is highly commended and the Work Group outcome will have fulfilled the strategic goal of this Roadmap toward addressing gaps in existing standards and codes. The following is the action plan from the NIST Work Group with permission to publish:

- Identify and review all NRC regulatory documents related to polymeric pipes for nuclear power plants;
- Identify and review all ASTM, ASME, AWWA, ISO and PPI standards related to polymeric pipe water applications;
- Identify ancillary standards needed to certify manufacturers and the installation and inspection of piping. Conduct a survey of current ASME, ASTM, AWWA, ISO, PPI and ancillary standards related to polymeric pipe and fittings.
- Comment on the applicability of each piping and fitting standard to current and future applications in the nuclear industry. This includes non-safety and safety related applications.
- Identify existing gaps in piping standards for nuclear applications.
- Identify a reasonable mechanism and time frame to fill identified gaps.
- Develop a 5 to 10 year roadmap for the application of polymeric piping in non-safety and safety related nuclear applications and the anticipated standard's needs.

Work is underway to overhaul Code Case N-755-1 (in N-755-2). The goal of this work is to split the needs and requirements of Section III and Section XI so each Section will have its own Code Case. Tim Adams proposed the following toward achieving the HDPE Implementation Project Plan Outline.

A. HDPE Implementation Project Plan Outline: Split Code Case into Two Code Cases

    1. N-755-2 will become Section III case

    2. New case (N-808) will be written for Section XI

    3. N-755-2 will remove Section XI requirements.

B. Issue N-755-2 to do the following

    1. Remove Section IX requirements from Code Case

    2. Incorporate new accreditation requirements

    3. Incorporate Section III IOU’s
    4. Incorporate Required Technical Changes.

C. Develop a Section XI Code Case N-808

D. Develop a Low Temperature Code Case
    1. Time to meet the next revision of Regulatory Guide 1.84
    2. Determine Temperature Acceptable to USNRC

E. Develop Revision 3 of Code Case N-755 (as needed)

F. Issue updated NCA-3900 and Non Mandatory Appendix D
    1. Editorial changes
    2. Latest Forms, etc.

G. Create new book Section NI for HDPE (Section III Activity)
    1. Outline shown in Attachment A
    2. Convert Code Case N-755 and Low Temperature Code Case to NI Article NIC

H. Section IX (Section IX Activity)
    1. Issue Butt Fusion section
    2. Create and issue Electrofusion section
    3. Also address Saddle Fusion and other fusion methods

I. Section V (Section V Activity)
    1. Form task group of NDE
    2. Develop NDE methods
    3. Issue NDE Section
    4. Get Flaw acceptance data for XI

J. Section II (Section II Activity)
    1. Develop Part E
    2. Develop Needed Material Tables
    3. Resolve NRC issues as data become available

K. Section XI (Section XI Activity)
    1. Develop Flaw acceptance criteria
    2. Needed for III and V activities

L. Develop a research plan to provide data and information to support implementation of HDPE in Section III and other sections of the Code. (Appendix B)

10 PROJECT FUNDING AND FINANCIAL SUPPORT

In the absence of an approved Code or Code Case, funding to conduct the research identified in this document, likely, will not materialize and the interest of Operators in HDPE piping system will diminish.

An approved Code or Code Case must be a priority of all involved.

NRC's approval of an ASME Code or Code Case for HDPE is the cornerstone to meeting the Roadmap goal, which is to advance the use of HDPE piping in nuclear plants.

Clarify the role of the NRC and the DOE in funding research and development.

An annual budget from donors, such as private and/or government entities, or an income from a trust, will impart stability and diligence to research and attract top industry researchers to get involved.

11 SCHEDULE AND MILESTONES

Develop a project plan and schedule that contains key milestones leading to the development of a complete set of Code rules for HDPE piping. Events which contain objectives for each milestone will be displayed. It is an easy tool for Stakeholders to use for frequent reviews. It serves for frequent peer reviews to ensure acceptance of the final results. A process for resolving conflicts that arise during peer review will be provided.

The absence of committed funds for the majority of the research projects leaves the schedule and milestones relatively undefined, and makes it difficult to show logic ties of milestones to predecessor activities.

The start and end dates displayed in the Gantt chart below, are arbitrary and serve to reflect their priority ranking. As this Roadmap is considered a “living-document,” these dates will be reconciled once these projects have been funded.

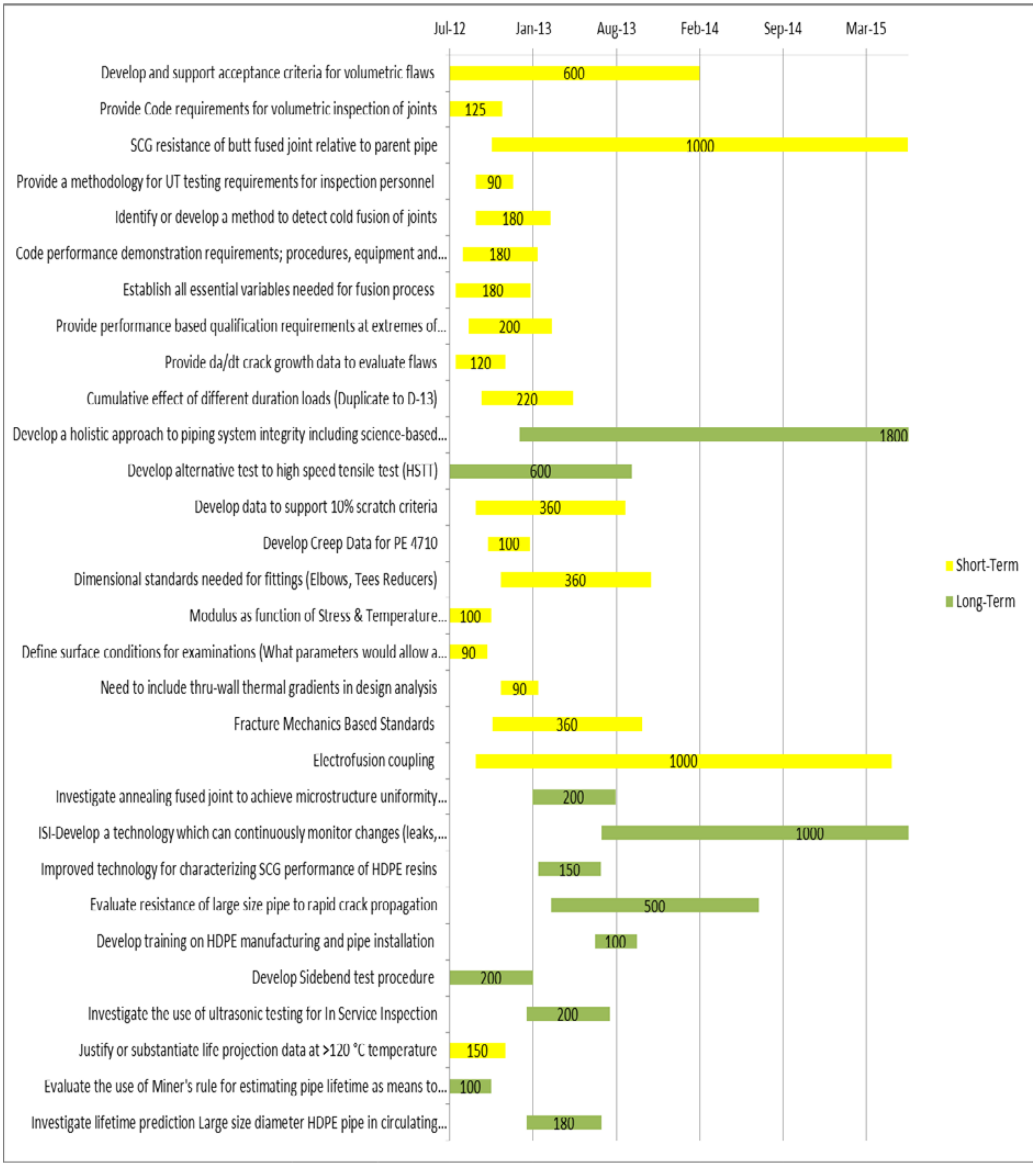

Figure 2 - Bar Chart of Events and Milestones

12 CONCLUSIONS AND RECOMMENDATIONS

The ASME Code Development Roadmap for HDPE Pipe in Nuclear Service has been an excellent exercise in identifying plans and strategies aimed at providing solutions to issues and concerns facing the HDPE pipe application. Ultimately, resolving issues with HDPE design and short and long-term performance, and understanding HDPE piping characteristics, will lead to a safe and profitable use of HDPE.

The Roadmap is summarized in a multi-layer chart which identifies the prevalent issues and milestones to execute. These involved design, fusion integrity, slow crack growth (SCG), regulatory and standardized testing to a greater degree and legal and financial to a lesser degree.

To successfully execute the Roadmap, the WG on HDPE R&D must subdivide into working cells and collaborate with other ASME Sections' Experts to address relevant issues in the proposed strategies. Those smaller working groups will be nimble and efficient toward reaching their goals.

ASME should map the future needs of HDPE piping in nuclear applications on average, every year, especially since the process is in its infancy, and maybe longer when the process matures. The purpose of this exercise is to identify the key technology and infrastructure developments required to assure the safe use and continued growth of HDPE piping in nuclear plants over the next decade.

ASME must maintain and administer an electronic record or database of all studies, research reports, findings, rulings, etc… relating to HDPE piping in nuclear service. Such must be available to be accessed by members to study and reference. Additionally, the administrator will manage the Roadmap's Actions and Milestones until they are completed and filed.

As stated in the Introduction, the roadmap is a flexible and living document. It must be administered and updated continuously. An annual meeting must be held during Code Week to review the Roadmap status, introduce new ideas or modify existing positions of its content. To that end, contributors are encouraged to submit practical or futuristic ideas and research proposals to the Roadmap administrators at any time of the year. Additionally, the Working Group of HDPE R&D in Section III is proposed to be the guardian of the Roadmap process and serve as a look-out for needs and opportunities to maintain a stream of innovative ideas and research, forecast and contrast trends and trends in research and technology areas to meet the anticipated needs of HDPE piping in nuclear applications.

ASME should coordinate with other roadmapping organizations to synchronize timelines, agree on, and refine, product sector definitions, identify common elements, facilitate cross-functional groups, and coordinate roadmapping schedules [1].

REFERENCES

[1] National Electronics Manufacturing Initiative, Inc. [Online] [Cited: August 15, 2011.] http://www.nemi.org.

[2] M. Garcia and O. Bray, *Fundamentals of Technology Roadmapping*, SAND97-0665, Sandia National Laboratories, Albuquerque, NM, 1997.

[3] R. Phaal, C. Farrukh, and D. Probert, *Technology roadmapping—A planning framework for evolution and revolution*, University of Cambridge, Elsevier Inc., pp. 5–26, 2004.

[4] R. Phaal, C. Farrukh, and D. Probert, *Technology Roadmapping: linking technology resources to business objectives*, University of Cambridge, 2001.

[5] A. Haddad, *Tensile-Creep Behavior of Polypropylene Block Copolymer Resin*, Plastic Pipes Conference Association, N. Vancouver, BC, 2010.

[6] *Generic Butt Fusion Joining Procedures For Field Joining of Polyethylene Pipes.* Plastics Pipe Institute, TR-33. Irving, TX, 2006.

[7] *Standard Specification For Polyethylene Plastics Pipe and Fittings Materials,* ASTM International, West Conshohocken, PA, D 3350, 2008.

[8] G. Pintera, et al., *Cyclic crack growth tests with CRB specimens for the evaluation of the long-term performance of PE pipe grades,* Parkstrasse 11, A-8700, Polymer Competence Center, Leoben, Austria.

[9] S. Boros and M. Mamoun, *Development of an Accelerated SCG Cyclic Pressure Fatigue Test Method for Polyethylene (PE) Pipe and Correlation with Hydrostatic Stress Rupture Test Method, ASTM D 1598.*

[10] L. Kureleca, M. Teeuwenb, H. Schoffeleersb, and R. Deblieckb, *Strain hardening modulus as a measure of environmental stress crack resistance of high density polyethylene*, Plastic Pipes Conference Association, Vancouver, BC , 2010.

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ABBREVIATIONS AND ACRONYMS

AE	Architect-Engineer
ASTM	American society of Testing Methods, or ASTM International
ASME	American Society of Mechanical Engineers
ASME ST-LLC	ASME Standards Technology, LLC
BPV	Boiler and Pressure Vessel
Cell Classification	Per ASTM D3350: A series of numbers, each denotes a range of properties. A Cell Classification of 445574C has the following properties:
	1st Digit: Denotes Density, e.g., >0.947 to 0.955 g/cc
	2nd Digit: Denotes Melt Index, e.g., 0.40 to 0.15 g/10 minutes
	3rd Digit: Denotes Flexural Modulus, e.g. 110,000 – 160,000 psi
	4th Digit: Denotes Tensile Strength, e.g., 3,500 - 4,000 psi
	5th Digit: Denotes PENT, e.g., ≥500 hrs. SCG resistance
	6th Digit: Denotes HDB, e.g., ≥1,600 psi hoop stress at 23°C
	1st Letter: Denotes color: C - for Black
DR	Dimension Ratio (OD/t)
DOE	Department of Energy
EPRI	Electrical Power Research Institute
GTI	Gas Technology Institute
HDB	Hydrostatic Design Basis
HDS	Hydrostatic Design Stress
HDPE	High Density Polyethylene
ID	Inside Diameter
ISO	International Organization for Standardization
LTHS	Long Term Hydrostatic Stress
MI	Melt Index. It measures the fluidity of HDPE at 130 °C. expressed in g/10 minutes
MIC	Microbiologically Induced Corrosion
MPa	Mega Pascal
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
OD	Outside Diameter
PDB	Pressure Design Basis

PE100	A pipe rating used by ISO. PE100 means a PE pipe that meets 10 MPa hoop stress
PE4710	Pipe rating in ASTM for “High Performance” HDPE resins which meet: (a) >500 hours PENT, (b) 50 years substantiation of 73°F LTHS data. (c) >90% LCL/LTHS ratio. These resins qualify for an increased DF which is 0.63 for water and 0.4 for gas applications.
	PE = Poly-Ethylene
	4 ≥ 0.947 – 0.955 g/cc density range
	7 = 500 h PENT
	10 = 1000 psi HDS at 73°F (1600 psi [HDB]*0.63 [DF] = 1008 psi HDS])
PENT	Pennsylvania Notch Test. Measures the resistance of HDPE material to slow crack growth in air at 80 °C and 2.4 MPa stress
PPI	Plastics Pipe Institute
PSI	Pounds per square Inch
RCP	Rapid Crack Propagation
SCG	Slow Crack Growth

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