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Research Program Plan for Modeling of Creep and Creep-Fatigue Crack Growth in HTGR and VHTR Materials (JCN-N6654)

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Prepared by
T.-L. Sham

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OAK RIDGE NATIONAL LABORATORY
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SUMMARY

Subcritical crack growth due to creep and creep-fatigue loading has been identified as a phenomenon that has a high importance ranking and a low knowledge level for the integrity of the NGNP RPV and IHX in the NGNP high-temperature materials phenomena identification and ranking tables (NUREG-CR-6944, Vol. 4).

Work performed in Task 1 of JNC N6654 on a review of current creep and creep-fatigue crack growth literature has concluded that the C^*-based flaw evaluation procedures in current British, French and Japanese codes and guidelines could potentially lead to nonconservative lifetime predictions. As C^* is based on the steady-state creep model, its applicability to nickel-base alloys that exhibit pseudo-tertiary creep response also requires a critical assessment. There is also uncertainty on when the information on the materials of construction (RPV, IHXs, cross vessels, and possibly steam generators) for NGNP will be available.

In order to address all of these issues, a roadmap for developing creep and creep-fatigue crack growth evaluation methodologies and analysis tools is presented. These methods and tools are needed to support an independent assessment of the structural integrity of NGNP pressure boundary and metallic components under normal operating conditions, design-basis conditions, beyond-design-basis conditions, and conditions that result in significant component degradation and failure.

The overall goal of the roadmap is to implement a qualified and validated creep-fatigue flaw growth evaluation procedure into NRC's currently evolving modular probabilistic fracture mechanics computer code where various types of uncertainties in the data and models will be accounted for. The target date for the project completion is by December 2013.

Three tasks are proposed herein to address some technical elements of the roadmap. Four additional tasks are proposed to develop plans to address the remaining technical issues identified in the roadmap. The proposed research program and task schedule presented in this report are submitted to the NRC Program Manager for approval.

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ABBREVIATIONS AND ACRONYMS

CG	crack growth
CT	compact tension
CTP	crack-tip parameter
EPRI	Electric Power Research Institute
FEA	finite element analysis
GT-MHR	Gas Turbine-Modular High-Temperature Gas-Cooled Reactor
HAZ	heat-affected zone
HTGR	high-temperature gas-cooled reactor
HRR	Hutchinson, Rice, Rosengran
IHX	intermediate heat exchanger
ISI	inservice inspection
NGNP	Next Generation Nuclear Plant
NRC	U.S. Nuclear Regulatory Commission
PBMR	pebble bed modular reactor
PCHE	printed circuit heat exchanger
PCS	power conversion system
PFM	probabilistic fracture mechanics
PIRTs	phenomena identification and ranking tables
PM	program manager
RES	Office of Nuclear Regulatory Research, NRC
RPV	reactor pressure vessel
TRISO	tri-isotopic
VHTR	very high temperature reactor

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1. BACKGROUND

1.1 INTRODUCTION

Creep and creep-fatigue crack growth are time-dependent extensions of macroscopic cracks at temperatures that exceed about 30% of the melting temperature of the metallic component in absolute temperature scale. A macroscopic crack is one that is larger than the relevant microstructural length for crack growth, e.g., grain size.

Creep and creep-fatigue crack growth of pre-existing flaws that are undetected due to the limitations in detection capability of pre-service examination techniques, or of flaws that are initiated at crevices or shape notches early in life, may predominate lifetime over creep and creep-fatigue damage of the whole cross-section. Extensions of these macroscopic cracks in components such as reactor pressure vessel (RPV), cross vessels, intermediate heat exchangers (IHXs), and steam generators that are within the primary coolant system, are of particular concern if they are not detected during inservice inspection (ISI) due to accessibility and/or other constraints. A macroscopic crack might grow to a critical size that triggers other structural failure modes such as creep rupture due to reduced section thickness, or brittle fracture of ferritic components during heatup/cooldown. It might grow through the wall thickness, which could lead to a breach of the pressure boundary or the primary/secondary boundary; causing fission product release and/or air/steam/water ingress.

Subcritical crack growth due to creep and creep-fatigue loading has been identified as a phenomenon that has a high importance ranking and a low knowledge level for the integrity of the Next Generation Nuclear Plant (NGNP) RPV and IHX in the NGNP high-temperature materials phenomena identification and ranking tables (PIRTs), Corwin (2008). Creep and creep-fatigue crack growth evaluation methodologies and analysis tools are necessary to support the independent assessment of the structural integrity of NGNP pressure boundary and metallic components under normal operating conditions, design-basis conditions, beyond-design-basis conditions, and conditions that result in significant component degradation and failure.

A literature survey to document the state of knowledge of creep and creep-fatigue crack growth processes had been performed by Sham (2009). Particular emphasis was placed on the candidate metallic materials for the NGNP RPV, cross vessels, and IHX. It was concluded that there is a general knowledge gap in the time-dependent fracture mechanics for HTGR and VHTR creep and creep-fatigue crack growth evaluation procedures. The reliance on C^*-based methods in existing crack growth evaluation procedures could potentially lead to overly optimistic safety assessment for HTGR and VHTR components. As C^* is based on the steady-state creep model, its applicability to nickel-base alloys that exhibit pseudo-tertiary creep response also requires a critical assessment.

Research and development effort was recommended in the Sham (2009) report to develop appropriate crack-tip parameters for HTGR and VHTR structural materials, and to establish the validity or transferability conditions for their use in safety assessment analysis procedures and in flaw evaluations to support ISI protocol.

A survey of the creep and creep-fatigue crack growth data for HTGR and VHTR materials was performed by Sham (2009) and data gaps for some candidate HTGR and VHTR materials were identified. A low-temperature (320 to 420ºC) creep crack growth phenomenon, Wu et al. (2005), was also identified in the Sham (2009) report on a specially heat-treated light water reactor pressure vessel steel to simulate the coarse grain structure of the heat-affected zone (HAZ).

1.2 THE NEXT GENERATION NUCLEAR PLANT

The U.S. Department of Energy has selected the High Temperature Gas-cooled Reactor (HTGR) design for the NGNP Project. The NGNP will demonstrate the use of nuclear power for electricity and hydrogen production. The reactor design will be a graphite moderated, helium-cooled, prismatic or pebble-bed, thermal neutron spectrum reactor. The NGNP will use very high burn-up, low-enriched uranium, Tri-Isotopic (TRISO)-coated fuel, and will have a projected plant design service life of 60 years. The HTGR concept is considered to be the nearest-term reactor design that has the capability to efficiently produce hydrogen. The plant size, reactor thermal power, and core configuration will ensure passive decay heat removal without fuel damage or radioactive material releases during accidents.

Preconceptual designs for the NGNP were performed by three reactor vendor teams and the key operating parameters for the NGNP preconceptual designs, along with the Fort St. Vrain HTGR, are shown in Table 1 as background information, Corwin et al. (2008). The gas outlet temperatures for the three NGNP preconceptual designs were in the range of 900 to 950ºC. The candidate materials for the RPV and cross vessels were 2¼ Cr 1Mo steel, Modified 9Cr 1 Mo steel, and SA508/533B steels. The candidate materials for the IHXs were Alloy 617 and Alloy 800H. For reference, the Fort St. Vrain HTGR had a primary loop steam generator instead of an IHX.

Through consultations with stakeholders and potential end-users, the NGNP Project had reached an agreement to reduce the gas outlet temperature of the first NGNP from the 900-950ºC range in the preconceptual designs to the range of 750 to 800ºC, in part to meet the 2021 target for initial operation. However, even with the reduced gas outlet temperature, the NGNP will be able to generate nuclear heat for electricity generation and hydrogen production; and to support process steam applications such as petrochemical processing and petroleum refining.

With the reduced gas outlet temperature, two reference configurations, one based on a pebble-bed core and the other on a prismatic core, have been planned in the NGNP conceptual design. Alloy 617 and Alloy 800H are still viable IHX candidate materials. The RPV for these two reference configurations will most likely be kept at a relatively low metal temperature in order to remove the concerns on creep-fatigue interaction during normal operations. Therefore, light water reactor pressure vessel steels could potentially be used as the materials of construction for the RPV. The cross vessels will be constructed with the same materials as the RPV. The selection of the final NGNP configuration from these two reference conceptual designs will be made at some future point.

Table 1. Key operating parameters for the NGNP preconceptual designs and the Fort St. Vrain HTGR. From Corwin et al. (2008)

Condition or Feature	Fort St. Vrain HTGR	General Atomics GT-MHR	AREVA ANTERES	Westinghouse PBMR PHP
Power Output (MWt)	842	550-600	565	500
Average power density (w/cm^3)	6.3	6.5		6.0
Moderator	Graphite	Graphite	Graphite	Graphite
Core Geometry	Cylindrical	Annular	Annular	Annular
Reactor type	Prismatic	Prismatic	Prismatic	Pebble Bed
Safety Design Philosophy	Active	Passive	Passive	Passive
Plant Design Life (Years)	30	60	60	60
Power Conversion Configuration	Direct	Direct	Indirect	Indirect
PCS Cycle Type	Reheat Steam	Brayton	Steam Rankine	Rankine
IHX Design Power Process	NA	PCHE	Shell & Tube PCHE or Fin-Plate	PCHE
Core outlet temperature (°C)	785	Up to 950	900	950
Core inlet temperature (°C)	406	590	500	350
Coolant Pressure (MPa)	4.8	7	5	9
Coolant Flow Rate (kg/s)	428	320	272	161
Secondary outlet temperature (°C)	538	925	850/875 PCS/H_2	900
Secondary inlet temperature (°C)	NA	565	450/475 PCS/H_2	NA
Secondary Fluid	Steam	He	He	He-N
IHX Pressure Drop (kPa)	NA	50	55	45
IHX Material	NA	A617	A617	A617 or A800H
Reactor Vessel Material	Prestressed concrete	2¼Cr-1Mo steel	Modified 9Cr 1Mo steel	SA508/533B
RPV Outside Diameter (m)		8.2	7.5	6.8
RPV Height (m)		31	25	30
RPV Thickness (mm)		281	150	>200

2. ROADMAP DEVELOPMENT

As reported in the state-of-knowledge review on creep and creep-fatigue crack growth processes by Sham (2009), the C^* integral is used by the British, French and Japanese codes and guidelines to determine creep crack growth. However, the crack-tip stress field of a stationary crack is characterized by C^* only when extensive secondary creep conditions prevail. Under small-scale secondary creep conditions, the crack-tip stress field is characterized by the parameter $C(t)$ which can be substantially greater in magnitude than the value of C^*. Thus the use of C^* could significantly underestimate the crack growth increments under small-scale secondary creep conditions.

It is well-accepted that the crack growth behavior is closely related to the deformation rates in the crack-tip region. Hence different crack-tip parameters would be controlling in different regimes; akin to the concept of "load parameter map" developed by Riedel (1986). As the use of C^* in flaw evaluation procedure could potentially lead to overly optimistic lifetime predictions, the development of an improved methodology to overcome the potential nonconservatism in the C^*-based flaw evaluation procedure is needed to support the NGNP license review.

As two reference configurations have been planned in the NGNP conceptual design, the timeline for information on the materials of construction (RPV, IHXs, cross vessels, and possibly steam generators) to be available is uncertain. A recent EPRI report by Marston (2008) has provided the phases for the NGNP Project and it is shown in Fig. 1. Based on the schedule of this project phases, conceptual design work could be completed some time in 2010.

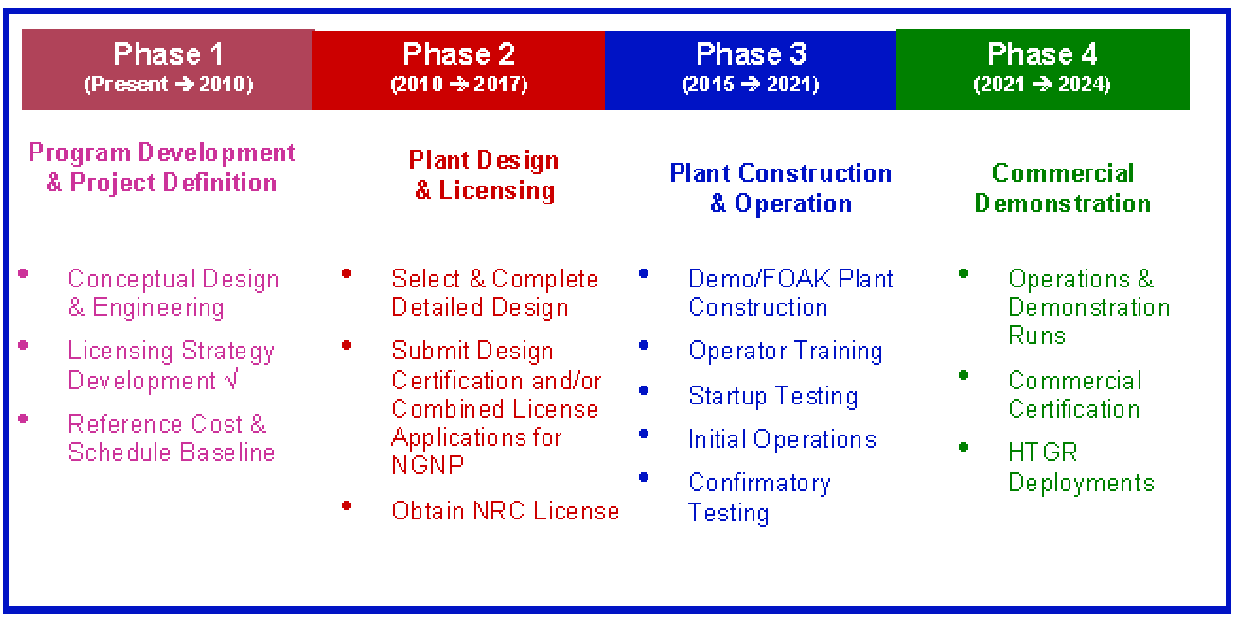

Fig. 1. Phases of NGNP Project. From Marston (2008).

In order to support a timely NGNP license review, a roadmap that addresses the technical concerns and accounts for the uncertainty on the materials of construction has been established. The goal of the roadmap is to develop a time-dependent creep and creep-fatigue crack growth predictive methodology that will be integrated into the modular probabilistic fracture mechanics (PFM) computer code that is currently under development at NRC/RES. The roadmap consists of three modules which are further divided into sub-modules (A through E), as shown in Fig. 2. Different tasks are associated with these sub-modules.

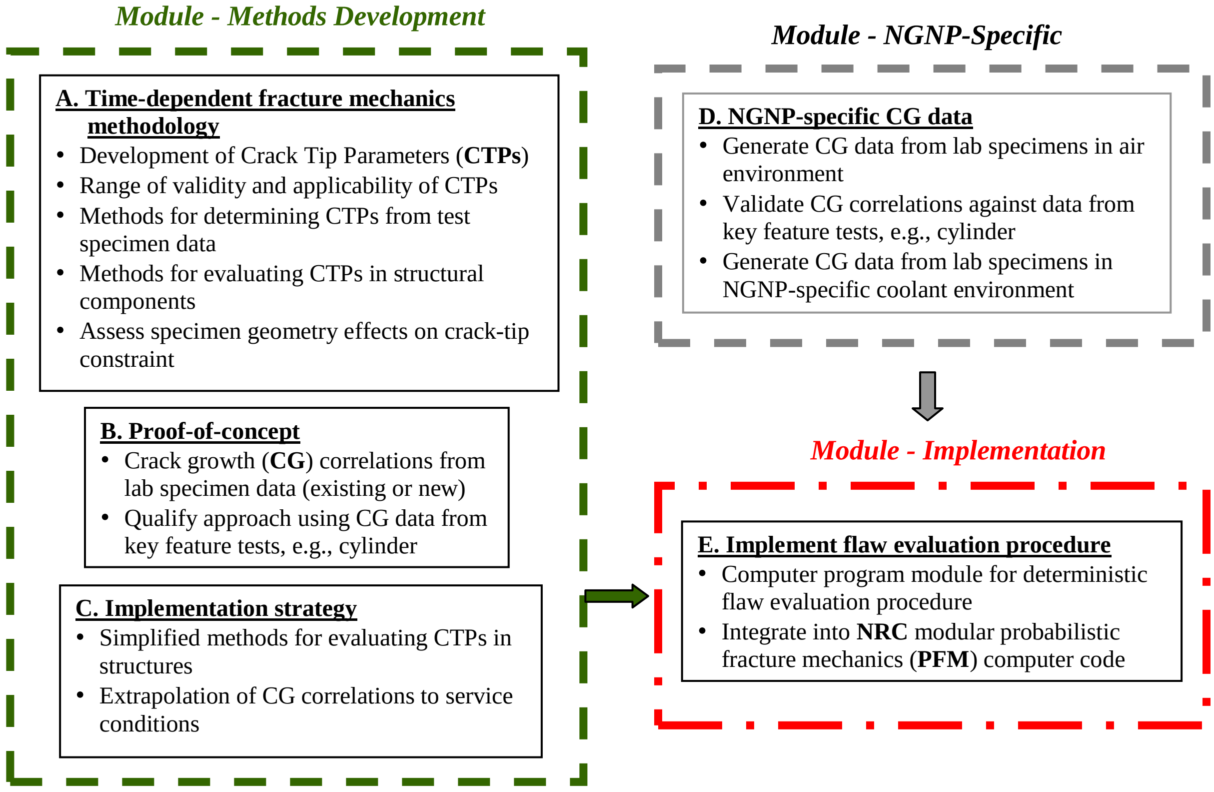

Fig. 2. Roadmap for development of creep & creep-fatigue flaw evaluation capability for NGNP Project.

2.1 MODULE – METHODS DEVELOPMENT

As was concluded in the report by Sham (2009), the establishment of a link between the crack-tip stresses and deformation rates in test specimens and structural components through the crack-tip parameters (CTPs) is important; since it provides a technical basis for applying the crack growth correlations, which are developed from specimen data, to structural components. Without such a fracture mechanics basis, prototype testing would be necessary to develop crack growth correlations. Since not all possible scenarios could be considered through prototype testing, safety related structural integrity issues could not be assessed fully.

2.1.1 Sub-module A - Time-dependent Fracture Mechanics Methodology

The development of CTPs that can be used to correlate with crack growth data is the main focus of the research and development efforts of this sub-module. The consideration of all three creep deformation regimes (primary, secondary, and tertiary creep) is important as the conditions for the transition of the crack-tip fields associated with these regimes are required to ascertain that the appropriate CTPs are used in the operative creep regimes during crack growth. The inappropriate use of the CTP and crack growth correlation obtained under extensive secondary creep conditions in the primary and tertiary creep regimes would lead to nonconservative crack growth predictions.

Furthermore, without the consideration of the tertiary creep regime, the range of applicability of the crack growth behavior in the secondary creep regime could not be established. The consideration of crack growth behavior in the tertiary creep regime is particularly important for some safety assessment scenarios where a design flaw is assumed to grow undetected from the beginning of life. For example, as a crack grows through the wall of a component, load is shed continuously to the remaining ligament, leading to enhanced creep damage in the cross section ahead of the crack.

Time-dependent fracture mechanics methodology needs to be developed to address the potential non-conservatism of the C^*-based approaches. The analytical results are needed to guide the development of test matrices and methods to extract the appropriate CTPs from test data. The work in the following Tasks 1, 2 and 3 is the basic foundation upon which all other modules/sub-modules in the roadmap depend on, and hence will be started first at the earliest time and all other tasks are planned to continue till July 2010. This would position the program to consider the NGNP-specific metallic materials for the NGNP RPV, cross vessels, IHX and steam generators when they are finalized in 2010. The tasks under this sub-module are as follow.

2.1.1.1 Task 1 - Development of crack-tip parameters

This task involves the investigation of crack-tip fields and the CTPs for creep deformations that include primary, secondary and tertiary creep. The initial emphasis is on the stationary crack geometry and power-law descriptions of the creep rates, which in one dimension under tension, are given by:

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + B_1 \varepsilon_{cr}^{-p_1} \sigma^{n_1} + B_2 \sigma^{n_2} + B_3 \varepsilon_{cr}^{p_3} \sigma^{n_3} \quad , \quad p_1 > 0 \ , \quad p_3 > 0$$

where $\dot{\varepsilon}$ is total strain rate, σ and $\dot{\sigma}$ are the stress and stress rate, E is the Young's modulus, ε_{cr} is the creep strain, and B_1, B_2, B_3, n_1, n_2, n_3, p_1, and p_2 are creep parameters.

The similarity crack-tip field analysis approach of Riedel and Rice (1980), and of Riedel (1981), will be applied to each creep deformation mode. Different combinations of embedding of these crack-tip fields and the transition from one type of crack-tip field to another will be investigated. The form of the material model to be used is general enough to describe the creep behavior of the candidate NGNP materials (Alloy 617 and Alloy 800H). The asymptotic crack tip analyses will be performed with the material constants as parameters, and the sensitivity of predictions to their values will be assessed.

Once the structures of the asymptotic fields are established, the range of validity of these time-varying asymptotic crack-tip fields and the nesting of these fields as functions of time need to be determined. Finite element analyses (FEAs) of the stationary crack problems will be carried out to address these issues. Since the objective is to understand the evolution of the time-dependent crack-tip fields rather than to perform correlation with specific test data, the use of representative values of material parameters will suffice. It is noted that some creep curve data for Alloy 800H are available from the literature. Attempt will be made to use material parameters that are representative of these Alloy 800H data in the FEAs.

As summarized by Sham (2009), the work by Riedel (1981) has laid the ground work for the development of CTPs for a stationary crack. The case of a growing crack is more challenging, and FEA is needed to compliment the analytical considerations. However, considerable insight had been gained from some of the early calculations such as those performed by Hui and Riedel (1981) and Wu et al. (1986); thus these results will be leveraged in addressing the crack growth phenomena. FEAs of the growing crack problems will be carried out to determine the crack-tip fields that accompany the growing crack, and to determine their range of validity. The finite element crack growth calculations will be performed by applying different crack growth histories systematically, i.e., forcing the crack to grow in the FEA according to realistic crack length versus time histories, without the use of specific crack growth criterion. This is equivalent to mapping out a "solution" space numerically in order to gain an understanding of the time evolution of the crack-tip fields for the growing crack. Material parameters that are representative of the Alloy 800H creep curve data will also be used in these finite element crack growth analyses.

2.1.1.2 Task 2 - Methods to determine crack-tip parameters

Crack-tip parameters govern the crack-tip stress and deformation rates at the crack tip. But the availability of methods to extract the CTPs from the load/load-line displacement records of a compact tension specimen is a pre-requisite for the development of crack growth correlations. A methodology to determine the C_t parameter from load/load-line displacement data was developed by Saxena (1986). This method will be investigated to determine the potential of its extension to the CTPs that are to be developed in Task 1.

The extraction of the CTPs from FEA results is a pre-requisite in applying the crack growth correlation to determine crack growth in structural components. Contour integral, interaction integral, and crack-tip extrapolation methods for computing the CTPs from FEA results will be investigated in order to develop an effective methodology to compute the CTPs that are to be developed in Task 1.

2.1.1.3 Task 3 - Specimen geometry effect on crack-tip constraint

Crack-tip constraint effect is related to the effect of higher order terms in the crack-tip field that would lower the crack opening stress or triaxial stress state ahead of the crack tip. These effects are quantified by the elastic T-stress, Rice (1974), and the elastic-plastic Q-stress, O'Dowd and Shih (1991), in linear elastic and rate-independent elastic/plastic materials, respectively. The practical implication of crack-tip constraint for these time-independent material models is that for geometries that give rise to negative T-stress or Q-stress, there is an apparent increase in the fracture toughness because of the reduction in the maximum principal stress or the triaxial stress state ahead of the crack tip. Therefore, the use of fracture toughness values determined from specimens that have negative T-stress or Q-stress would be nonconservative if they are applied to crack geometries in structural components that involve high crack-tip constraint, i.e., structural crack geometries that give rise to zero or positive T/Q-stresses.

There is an analog for crack-tip constraint in time-dependent fracture mechanics. Under C^*-controlled crack growth conditions, it was shown by Budden and Ainsworth (1999) that the crack growth rate is slower for low crack-tip constraint geometry as compared to the crack growth rate for high crack-tip constraint geometry. Generally, cracks are observed to tunnel through the thickness of a specimen under creep conditions.

The effect of crack-tip constraint under creep conditions can be rationalized by considering the cavity growth process ahead of a macroscopic crack. The loss of crack-tip constraint corresponds to a decrease in the triaxial stress ahead of the crack tip, and this leads to a retardation of the cavity growth rate ahead of the crack tip. Thus, it takes a longer time for the crack-tip cavity to grow to a critical size to coalesce with the macroscopic crack tip, resulting in a slower crack growth rate.Therefore, using a crack growth correlation obtained from test specimens with low crack-tip constraint to predict crack growth in high crack-tip constraint component for safety assessment is nonconservative.

The CTPs to be developed in Task 1 correspond to the dominant singular term of the crack-tip fields. However, unlike linear elastic fracture mechanics and elastic-plastic fracture mechanics where the influence of the higher order terms (T-stress and Q-stress, respectively) on the crack-tip stress and deformation states have been characterized for different geometries, such is not the case for the crack-tip stress and deformation state associated with the CTPs to be developed in Task 1 for both stationary and growing cracks. The influence is expected to be more complex because of the time dependence. It is important to quantity this effect for different specimen geometries. The crack-tip constraint effect will be investigated by performing FEAs to obtain full-field finite element solutions on geometries such as edge crack and center-cracked panel. Both stationary and growing crack FEAs will be performed. Similar to Task 1, different crack growth histories will be applied systematically in the finite element crack growth analyses according to realistic crack length versus time histories. Material parameters that are representative of the Alloy 800H creep curve data will also be used in the FEAs.

2.1.2 Sub-module B - Proof-of-concept

The work to be performed in Tasks 1, 2 and 3 involves the development of CTPs and the establishment of criteria for their use in different creep deformation regimes to predict crack growth in structural components. Also included in the effort is the development of methodologies to determine the CTPs from experimental data typically collected in the form of crack length, load, and load-line displacement histories. This analytical foundation will establish a technical basis for the use of the CTPs to characterize the crack-tip stress and deformation states in specimens and structural components; and the methodologies to determine the CTPs from test data (crack length, load, and load/line displacement). Once these are established, the following proof-of-concept efforts are required.

A. Laboratory Specimens

- Determine the CTPs using scoping creep crack growth data in the form of crack length, load, and load-line displacement histories from compact tension specimens. Creep curve data are also required in establishing the material paramters in the creep models. These material parameters are needed in determining the CTPs.

- Establish that the CTPs determined from crack length, load, and load-point displacement data can be used to correlate creep crack growth rate data.

- Establish creep-fatigue crack growth correlation model in terms of the CTPs. An initial attempt could be based on a superposition model where the creep-fatigue crack growth within a creep-fatigue cycle is consisted of a fatigue crack growth term and a creep crack growth term during hold time. Scoping tests data required are creep crack growth, fatigue crack growth and creep-fatigue crack growth data.

- Based on the review performed by Sham (2009), Alloy 800H would be a good candidate for the scoping crack growth tests since Alloy 800H has good creep strength in the temperature range of 750 to 800°C.

B. Key Feature Tests

The purpose of the key feature tests is to qualify the creep-fatigue crack growth correlation established from laboratory specimens. This is accomplished by comparing the amount of creep-fatigue crack growth in a structural component as predicted from the creep-fatigue crack growth correlation against the measure crack growth data. A suitable candidate for the key feature test is the creep-fatigue crack growth of a surface flaw in a cylinder. The material for the structural component in the key feature test should be the same as that used to generate the creep-fatigue crack growth correlation in Part A above. Thus, Alloy 800H is recommended.

2.1.3 Sub-module C - Implementation Strategy

Generally, CTPs for a structural component can be determined by nonlinear time-dependent finite element crack growth analyses. While accurate, it involves a lot of computational resources. Thus, development of simplified but adequately conservative calculation procedures for determining the CTPs would be necessary in order to reduce the need to perform many nonlinear time-dependent finite element crack growth analyses in flaw evaluations.

Simplified methods to determine C^*, either through the use of the EPRI fully plastic J integral solutions or the R5 reference stress approach, are quite well established. The success stemmed from the fact that C^* depends only on load and crack length; and thus, is essentially time independent. The development of simplified methods for new CTPs that are truly time dependent will be challenging. However, the crack-tip stress fields to be developed in Tasks 1, 2 and 3 for a stationary crack would likely be of the HRR type. Thus the concept of transition times developed by Riedel and Rice (1980) and Riedel (1981) could possibly be exploited in the development of simplified but conservative methods to determine the new CTPs.

Crack growth in weldment is much more complex. The complexity is partly due to the inhomogeneity of the microstructure, which varies from the weld metal, through the HAZ to the base metal. Mismatches in the creep deformation and creep rupture properties occur due to microstructural inhomogeneities. However, welding processes and post weld heat treatments also can have significant effect on the microstructure of the weldment. Thus, while it is tempting to develop crack growth procedures that can be applied to many different types of weldments, it would be more realistic to concentrate on the development of crack growth procedure for NGNP-specific weldments in order to account for the specific microstructures and the interaction of the specific mismatched properties. It is expected that the effort has a very strong testing component. It is important that well thought-out scoping experiments to identify potential problem are considered.

Tasks 1, 2 and 3 address the development of CPTs that are appropriate for the operative and evolving regimes of creep deformations; and the conditions that govern the range of their applicability. These tasks also address the issue of crack-tip constraint effects. Thus, an understanding would be established in dealing with differing loading conditions, from test specimens to component geometries. However, microstructures could evolve when a material is kept at high temperatures for long times. Phenomena such as grain coarsening, formation of secondary phases, redistribution of carbides, migration of grain boundaries, etc. could occur. To understand whether the evolving microstructures could affect the crack growth behavior is important. Because of the complexity of the phenomena, it is recommended that only phenomena that are relevant for NGNP-specific materials are to be addressed. Again, well thought-out scoping experiements to identify potential problem are recommended.

To illustrate the type of considerations that might be required to address such issues, consider Alloy 617. Generally, laboratory test data are generated under short-term and high stress conditions. However, service conditions are typically long-term and involve low nominal stress. Data show that the Charpy impact energy for Alloy 617 decreases after it has been subjected to thermal aging. The transition from a creep ductile behavior in the unaged condition to a possible creep brittle behavior in the aged condition could affect the crack growth behavior. Thus well thought-out key crack growth experiment should be conducted to determine if the crack growth rates are accelerated due to thermal aging. If the results from the experiment show that the crack growth rates were indeed enhanced, additional crack growth data would be required to support the development of models to describe the crack growth behavior of Alloy 617 in the aged condition.

Whether or not such considerations are required depends on the specific materials of construction to be selected by the NGNP Project. Thus early interaction between NRC and the NGNP Project to obtain information on materials of construction is critical.

2.2 MODULE – NGNP-SPECIFIC

This module is involved with the development of crack growth correlations specifically for the materials of construction for NGNP RPV, IHXs, cross vessels, and possibly steam generators (pending on the final configuration). Both base metal and weldments should be included. The testing effort could begin once these NGNP-specific materials are identified, and the results from the work in sub-module A - Time-dependent Fracture Mechanics Methodology, and sub-module B - Proof-of-concept, are available.

2.2.1 Sub-module D - NGNP-Specific Crack Growth Data

Confirmatory or new crack growth data for the development of crack growth correlations are required to support NGNP license review. The coolant environment that these materials will be exposed to during service is impure helium, and possibly steam; although the precise NGNP coolant chemistry has not been specified.

One option to develop NGNP-specific crack growth correlations is to perform crack growth tests in the appropriate NGNP coolant environment. However, since many test conditions such as temperatures and loads are required to establish a robust database in order to develop adequately conservative crack growth correlations, such an approach is very resource intensive because of the complexity in performing crack growth tests in a coolant environment. Instead, the approach recommended is to generate the crack growth data in air so that a robust database can be generated with much less resources as compared with testing in an environmental test loop.

After the crack growth correlations for the NGNP-specific materials are established in air, key feature test such as surface flaw in a cylinder is recommended to qualify these crack growth correlations. This validation is important for gaining added confidence in using these correlations in safety assessments.

Any potential material degradation mechanisms in impure helium, and possibly in steam, that could accelerate the crack growth rates as compared with those in the air environment will need to be addressed. Scoping tests for NGNP materials in impure helium (and possibly steam) that covers the expected range of NGNP coolant chemistry will be required to determine whether these environmental degradation mechanisms are operative. If the environmental effects are confirmed, testing will be required to develop the so-called environmental degradation factors for the flaw evaluation procedure.

Selective conditions from the air tests can be employed for crack growth testing in the NGNP-specific coolant environment. The concept is to use these data to establish environmental degradation factors (by taking ratios) and apply them conservatively in design. Design of experiment approach should be considered so that a statistically meaningful sampling scheme is used in selecting the test conditions. Only a relatively small set of coolant chemistry that bounds the characteristics of the plant operational environment is employed for the environmental crack growth tests. The concept of an environmental degradation factor is similar to the weld strength reduction factor, or the grain-size reduction factor for creep rupture strength, where ratios of properties are employed to establish the penalty factors.

Xu and Bassani (1999) had investigated the problem of elevated temperature cracking associated with embrittlement from intergranular diffusion of impurities, using cohesive zone model for small-scale creep, diffusion and damage. The constitutive equation for the cohesive zone was coupled with stress-assisted diffusion of impurities into the grain boundary. A Kachanov-type damage model was used to describe the effect of impurity concentration on grain boundary strength. Similar modeling approach can provide guidance to the crack growth test effort in the NGNP-specific coolant environment.

2.3 MODULE – IMPLEMENTATION

2.3.1 Sub-module E - Implement Flaw Evaluation Procedure

This sub-module is involved with the implementation of the deterministic flaw evaluation procedure in the computer program module. It is anticipated that flaw evaluations using either best estimate or statistical upper limits for the crack growth rates could be performed by the computer program. After verification and validation, the deterministic flaw evaluation computer program module can be incorporated into NRC's PFM computer code that is planned to be available in the next 3 to 5 years.

2.3.1.1 Task 4 - Test plan to assess low-temperature creep crack growth mode

A low-temperature (320-420ºC) creep crack growth mode, Wu et al. (2005), in a specially heat-treated light water reactor pressure vessel steel to simulate the coarse grain structure of the HAZ was indentified from the literature during the preparation of the review performed by Sham (2009). It is not known if the observed low-temperature creep crack growth phenomenon in the simulated RPV coarse grain HAZ material would persist in the base metal. However, it is not expected that microstructure of the base metal would be as drastically affected as in the simulated coarse grain HAZ material tested by Wu et al. (2005); since the temperature experienced by the bulk of the base metal during welding is lower than the temperature in the RPV HAZ. The post-weld stress-relief temperature should not be high enough to produce the kind of microstructure that is similar to the simulated RPV HAZ material. It is not certain at this time if there is a similar concern for the weld metal in the weldment. It is noted that the materials of construction for the NGNP RPV and cross-vessels would most likely be light water reactor pressure vessel steels. Their metal temperatures would most likely be below 370ºC during normal operations; thus they would be within the temperature range of this low-temperature creep crack growth phenomenon.

Scoping test of specimens made from the coarse grain HAZ of a prototypical weldment would be necessary to either refute or confirm this low-temperature creep crack growth mode. Since such testing would require a lot of resources and planning, it is proposed to develop a test plan for such a scoping test so that the NRC Program Manager would have sufficient information on the scale and scope of such effort if it is determined that the resolution of this issue is of high priority at some point in the future.

2.3.1.2 Task 5 – Plan for the completion of Methods Development Module of roadmap

It is recommended that a plan be developed to outline if existing data are available; and if not, the type of scoping tests that are required, to support the efforts discussed in Sub-module B - Proof-of-Concept. The efforts as discussed in Sub-module C - Implementation Strategy will also be included in the plan. The goal of the plan is to provide the NRC Program Manager with information on the technical paths that would be required to complete the Methods Development Module so that the requisite methods could be in place to support the generation of crack growth data for the NGNP materials of construction.

2.3.1.3 Task 6 - Test plan for crack growth generating data for Alloy 800H in air environemnt

It is recommended that a test plan be developed to detail the test requirements for generating crack growth data from laboratory test specimens and key feature test geometries in the air environment in order to address the issues discussed in the NGNP-Specific Module of the roadmap in Fig. 2. The test matrices will be developed for Alloy 800H, or for the NGNP material of construction if the information is available at the start of the task effort. The intent is to provide the NRC Program Manager with the scope of the data generation requirements so that decision can be made on whether the required testing is confirmatory in nature or it should be considered as part of the design data generation effort.

2.3.1.4 Task 7 - Research and Development Plan for Implementing Deterministic (Best Estimate)/Probabilistic Flaw Evaluation Procedure

A research and development plan will be developed to implement a deterministic (best estimate) creep-fatigue flaw growth evaluation computer code, followed by its implementation in the NRC's currently evolving PFM computer code where various types of uncertainties in the data and models will be accounted for under the Implementation Module in Fig. 2. The goal is to complete this project by December 2013.

3. PROPOSED TASK SCHEDULE

The proposed schedule for Tasks 1 to 7 and the manpower distribution for each task are given in Fig. 3. The total efforts are 2,422 hours. The break-down of the manpower distributions is summarized below:

- Task 1: 1,070 hours, ORNL staff and subcontractors (Hui and Bassani)
- Task 2: 510 hours, ORNL staff and subcontractors (Hui and Bassani)
- Task 3: 442 hours, ORNL staff and subcontractor (Hui and Bassani)
- Task 4: 40 hours, ORNL staff
- Task 5: 120 hours, ORNL staff
- Task 6: 60 hours, ORNL staff
- Task 7: 120 hours, ORNL staff
- Finalize report for Tasks 1 to 3: 30 hours, ORNL staff
- Finalize report for Tasks 4 to 7: 30 hours, ORNL staff

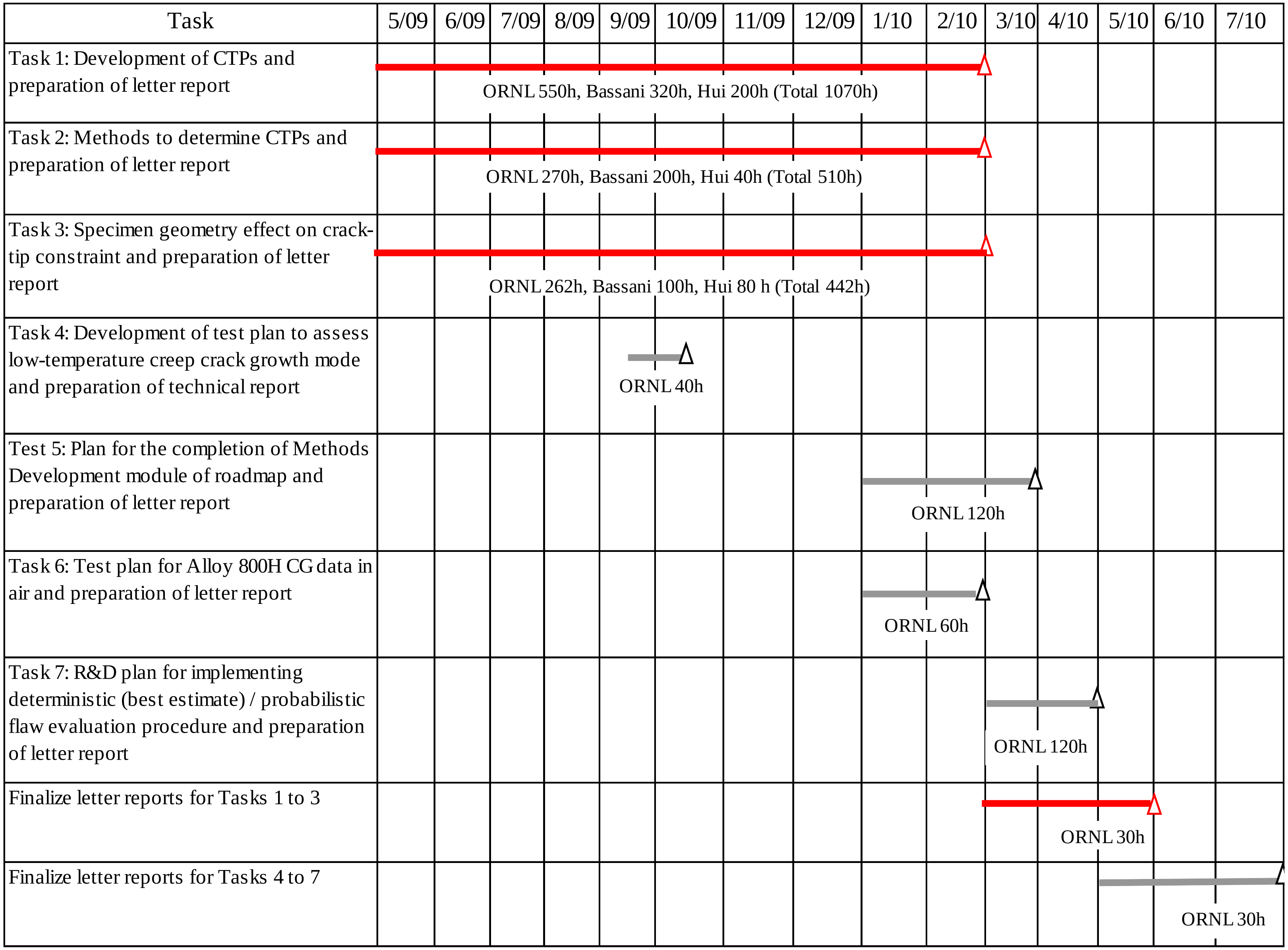

Fig. 3. Proposed schedule for Tasks 1 to 7 and the corresponding manpower distributions.

4. PROPOSED REPORTING REQUIREMENT AND SCHEDULE FOR TASKS 1 TO 7

Task 1: Submit a draft letter report on the development of CTPs; May 1, 2009 to February 28, 2010

Task 2: Submit a draft letter report on the development of methods to determine CTPs; May 1, 2009 to February 28, 2010

Task 3: Submit a draft letter report on the study of specimen geometry effect on crack-tip constraint; from May 1, 2009 to February 28, 2010

Task 4: Submit a draft letter report on the development of a test plan to assess low-temperature creep crack growth mode; from September 10, 2009 to October 9, 2009

Task 5: Submit a draft letter report on the development of a plan for the completion of Methods Development Module of the roadmap; from January 1, 2010 to March 31, 2010

Task 6: Submit a draft letter report on the development of a test plan for crack growth generating data for Alloy 800H in air environment; by from January 1, 2010 to February 28, 2010

Task 7: Submit a draft letter report on the development of a research and development plan for implementing deterministic (best estimate)/probabilistic flaw evaluation procedure; March 1, 2010 to April 30, 2010

Tasks 1 to 3: Receive NRC PM comments on draft letter reports by April 30, 2010

Tasks 1 to 3: Submit finalized letter reports by May 31, 2010

Tasks 4 to 7: Receive NRC PM comments on draft letter reports by June 30, 2010

Tasks 4 to 7: Submit finalized letter reports by July 31, 2010 (30 days from the date NRC comments are received on each task)

5. PROPOSED PERSONNEL

T.-L. Sham, ORNL, Project Manager, Tasks 1 to 7 leader
C. Y. Hui (subcontractor), Tasks 1 to 3
J. L. Bassani (subcontractor), Tasks 1 to 3

5.1 SUBCONTRACTOR/CONSULTANT INFORMATION AND CONFLICT-OF-INTEREST STATEMENT

5.2 DR. C. Y. HUI

Dr. C. Y. Hui will assist in the development of CTPs and their evaluation methods and the study on constraint effects in Tasks 1 to 3. Dr. Hui is a professor in the Department of Theoretical and Applied Mechanic at Cornell University, Ithaca, NY. His research interest is in areas generally connected with mechanics and materials. He had developed the Hui-Riedel crack-tip field for a growing crack, Hui and Riedel (1981). He had contributed many papers on creep crack growth problems. He has published over 190 papers.

<u>Conflict-of-interest statement:</u>

Dr. Hui is assisting the U.S. Department of Energy (Grant No. ER46463) in investigating the design of two level biomimetic fibrillar interfaces. The aims are to fabricate, study, and model two-level biomimetic fibrillar structures with enhanced adhesion, friction, and contact properties.

5.3 DR. J. L. BASSANI

Dr. J. L. Bassani will assist in the development of CTPs and their evaluation methods and the study on constraint effects in Tasks 1 to 3. Dr. Bassani is the Richard H. and S. L. Gabel Professor of Mechanical Engineering of the Department of Mechanical Engineering and Applied Mechanics at the University of Pennsylvania, Philadelphia, PA. His research interest is in the general areas of mechanics and materials (including bio-materials); from atomic, to nano, to continuum scale. He had made many contributions to the creep and creep-fatigue crack growth literature; from continuum crack-tip solutions to micromechanical modeling of crack growth. He has published over 100 papers and edited a number of books.

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