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Analysis and Design Considerations for Piping and Support Systems in Elevated Temperature Reactors

George Antaki[1], Taha Al-Shawaf[2]

[1] Chief Engineer Nuclear Services, Becht, Aiken, SC, USA
[2] Technical Consultant, Orano Federal Services, Charlotte, NC, USA (taha.alshawaf@orano.group)

ABSTRACT

Elevated temperature reactors are subjected to operating conditions that have not been evaluated in the operating fleet of light water or heavy water Generation III reactors. These include the use of coolant other than light water, such as liquid sodium, operation at elevated temperature in the creep regime;; different heat transfer, thermal mixing, and thermal shock effects; different dynamic properties at elevtade temperature; different damage mechanisms; and different creep-fatigue assessment methods. ASME Section III Div. 5 is a relatively new code which, currently, does not provide sufficient guidance to design, analyze, and qualify elevated temperature piping and support systems. This paper consists of two parts. The first part discusses design and operational experience of Generation III reactors that should be considered in advanced reactors. The second part provides elevated temperature reactor design considerations which includes a gap analysis of ASME Section III Division 5 as well as tools needed to perform the analysis and design of these systems.

INTRODUCTION

The methods and criteria for the operating fleet of Generation III light water reactor analysis and design of piping and support systems are well established. In addition to the design, the Generation III piping systems have undergone decades of operation and in-service inspections which have brought additional know-how as to their performance. However, the nuclear industry does not have the same depth of experience for piping and support systems for the new Generation IV advanced reactors which operate at elevated temperatures (400^{o}C and above) and may be cooled by fluids other than light water such as liquid sodium. This paper discusses the challenges that need to be considered in the design, analysis and qualification of the elevated temperature piping systems and some of the lessons learned for the design of Generation III reactors design process.

DESIGN AND OPERATIONAL EXPERIENCE

The design methods of Generation III reactors are well established. During the design process several activities are performed in sequence to establish the final piping system and support configuration. The design steps that are intended to ensure a safe and reliable design in compliance with ASME Section III, Div. 1 (2021(a)&(b)), include but not limited to those listed in Table 1:

Table 1: Design Steps Complying with ASME Section III Div. 1

1. Layout	4. Documentation
2. Design and Service Loads	5. Interface and Construction
3. Analysis and Qualification	6. Hot Function and Startup Testing

Layout

The correct layout of nuclear power plant piping systems is not simply a matter of marking-up 3D CAD models of the plant and placing commodities first-come first-served. Layout is a multi-discipline function to accommodate the needs of all the disciplines to achieve a good arrangement to fulfill the plant's (a) safety requirements, (b) functional requirements, and (c) structural qualification requirements.

- Safety requirements include separation, single failure, and the prevention of adverse interactions (cascading failures). Separation and single failure will require that certain redundant systems be installed at opposite ends of the building. Adverse interactions will require that electrical cable trays be run above the piping and ducting, and the question of high energy line breaks (with its consequential whipping, jetting, etc.) be resolved early in the design. It is at this early stage that piping systems are classified as Class 1, 2, 3, or non-safety. Depending on whether the piping system has a function following an earthquake, it is categorized as Seismic Category I or non-seismic or II/I if it is non-seismic but its failure could affect the function of a Seismic Category I Structure, System or Component (SSC).

- Functional requirements include close collaboration between civil-structural, systems-hydraulics, and piping engineering to correctly place pumping stations, valve stations, and large equipment such as heat exchangers. It also requires experience in layout of specific piping systems. For example, there are specific rules to pipe pump suction and pump discharge: where to place strainers (if required), how many diameters of straight pipe at pump suction and discharge nozzles, what type of reducers to use, what type of fittings to avoid, etc. Functional requirements include the layout of piping systems to comply with the thermo-hydraulic requirements of the system in terms of pressure drops, thermal mixing, etc., in addition to the corresponding power supplies, as well as instruments and controls. Functional requirements also include accessibility for in-service inspections, maintenance, and replacements.

- Structural qualification requirements will dictate close collaboration of the piping engineering discipline with the civil-structural discipline to place cast-in-place anchors, embedded plates, gang structures and racks for pipe supports, dynamic restraints, pipe whip restraints, and jet shields. This is also the stage where seismic interactions are verified, and non-seismic commodities will have to be restrained to prevent adverse interactions.

Design and Service Loads

The ASME III Code requires that a Design Specification be prepared for each piping system to specify, among other things, the loads and load combinations that apply for the piping system. The loads and load combinations are grouped into six categories, which are defined in ASME III:

- Design, which is typically the maximum internal pressure during normal operation (Service Level A), plus deadweight.
- Service Level A are normal operating loads such as pressures, temperatures, weight.
- Service Level B are loading that the piping system must sustain without damage. They typically include anticipated pressure transients, and the operating basis earthquake.
- Service Level C are typically anticipated pressure transients, with fewer than 25 stress cycles above a certain stress threshold. The piping systems must be designed to sustain Service Level C load combinations without loss of pressure boundary and without loss of flow capability.
- Service Level D are often described as one-time events that the piping system must be able to sustain without loss of pressure boundary. Additional limits may be imposed to assure flow capability. They typically include pipe break in combination with the safe shutdown earthquake.
- Test loading include initial pressure tests (hydrotest or pneumatic tests), and periodic tests.

Analysis and Qualification

Once the layout is set and isometrics are developed, and the Design and Service load combinations are specified in the ASME III Design Specification, the piping system is analyzed to determine that it meets the ASME III qualification criteria. This is an iterative phase to achieve a layout and restraint arrangement that will meet the qualification criteria. The qualification criteria are to be specified in the ASME III Design Specification and typically involves compliance with eleven requirements:

1. Qualification of wall thickness and pressure ratings for internal design pressure and concurrent temperature.
2. Qualification of stress limits in various forms: primary stress limits for sustained and occasional loads, secondary stress limits for thermal expansion and anchor movements, stress limits for postulation of breaks in high energy lines, and fatigue usage factors for Class 1 lines.
3. Qualification of pipe supports and restraints.
4. Qualification of equipment nozzle loads.
5. Qualification of stresses at welded attachments.
6. Qualification of loads on flange joints.
7. Qualification of loads and movements at mechanical joints other tha flanges.
8. Qualification of wall and containment penetrations.
9. Qualification of in-line active components, such as acceleration limits on valve actuators.
10. Compliance with design details in ASME III (weld types and sizes, types of branch connections, use of threaded joints, use of socket welds, etc.).
11. Compliance with deflection criteria

Documentation

Documentation must be in accordance with Part 10 of the Code of Federal Regulations 10CFR50 Appendix B (2019) and ASME NQA-1 (2022(a)) program, but it must also comply with the nuclear industry practice, i.e., it must be correct, complete, clear, concise, current, compliant, and consistent (the 7 C's). Every input to a calculation must have a clear and specific reference. The calculations must use verified and validated software, and must be prepared, checked and approved by qualified individuals.

Interface and Construction

The design process is iterative. The interface with civil-structural must include constructability, and installation tolerances. This interface is communicated through isometrics and the 3D CAD plant layout.

Hot Function and Startup Testing

Once the piping system is installed, there are key activities to be completed prior to power operation**:**

- As-built reconciliation to verify that the installed configuration is consistent with the design configuration, here the tolerance limits of ASME III Appendix T (2023(b)) capture the experience gained through the 70's and 80's.
- Pre-operational thermal expansion testing to verify, as the pipe heat-up, that they expand in the direction and with the magnitude expected as specified in ASME, OM, (2022 (b)) Operation and Maintenance Standard - Part 7.
- Pre-operational vibration testing to verify that the pipe vibration is within limits such as those specified in ASME, OM, (2022(b)), Operation and Maintenance Standard Part 3.
- Functional testing of pumps, valves, vessels, and completed piping systems to verify that the measured flow rates and pressure drops are within the design values.

ELEVATED TEMPERATURE REACTORS - DESIGN CONSIDERATIONS

Elevated temperature reactors are subjected to operating conditions that have not been evaluated in the operating fleet of Generation III reactors. These include the use of coolant other than light water, such as liquid sodium. This environment exposes the piping system to creep damage; different heat transfer, thermal mixing, and thermal shock effects; different dynamic properties; different damage mechanisms; and different creep-fatigue assessment methods.

ASME Section III, Div. 5 (2021 (c)) is a relatively new code providing requirement for material, design, construction, and testing of nuclear component subjected to elevated temperatures. The cutoff to classify a component as elevated temperature is provided in Table HAA-1130-1 and corresponds to 700ºF (370ºC) for carbon steel and 800ºF (425ºC) for austenitic stainless steel.

The code structure of Section III, Div. 5 for metallic material and its Div.1 equivalent is summarized in Table 2. Class A & B of Div. 5 corresponds to class 1 & 2 of Div. 1, respectively. The subsections in Div. 5 start with the letter H to denote High Temperature replacing the letter N in Div.1. The last letter in the subsection numbering is either A or B referring to low temperature service range (A) and elevated temperature service range (B) respectively. It should be noted that the requirements for low temperature service are essentially the same as those from Division 1.

Table 2 : Code Structure of Section III, Div. 5 and its relationship to Div 1 for Metallic Material

Division 5			Division 1	
Class	Subsection	Title	Subsection	Class
Class A & B	HAA	General Requirements	NCA	Class 1 & 2
Class A	 HBA HBB	Pressure Boundary Components Low Temperature Service Elevated Temperature Service	NB	Class 1
Class B	 HCA HCB	Pressure Boundary Components Low Temperature Service Elevated Temperature Service	NCD	Class 2
Class A & B	HFA	Supports	NF	Class 1 & 2
Class A	 HGA HGB	Core Support Structure Low Temperature Service Elevated Temperature Service	NG	Class 1

ASME, Section III, Div. 5 low temperature design (HBA-3600) refers back to Div.1. For elevated temperatures, Section HBB-3651 refers to Div. 1 requirements and stress indices as an acceptable method and states that finite elements analysis method is acceptable for finding detailed stress distribution. An example on implementation of the Div.5 design by pipe stress analysis approach with its Div.1 stress predictions is provided in Adibi-Asl (2023). More numerical examples are needed to illustrate, achieve consensus, and test drive the Div.5 piping design by analysis rules.

For design by finite element at elevated temperature, a hopper diagram is provided in Table HBB-3221-1, with load-controlled stress limits, and strain and deformation limits. As an option, the strain and deformation limits can be evaluated using linear elastic models if a strain of 1% maximum is permissible for the particular component analyzed.

Structural Failure Modes and Design-by-Rules

The ASME code, Section III, Div. 5 takes into account the failure modes that are considered in Section III, NB plus the modes that are dependent on the creep mechanism. The combined failure modes are as follows:

1. Ductile rupture from short-term loading,
2. Gross distortion due to incremental collapse and ratcheting,
3. Loss of function due to excessive deformation,
4. Buckling due to short-term loading,
5. Creep rupture from long-term loading,
6. Creep-fatigue failure, and
7. Creep-buckling due to long -term loading.

The last three items are related to the creep effect caused by elevated temperature. Adibi-Asl (2022) provided a design-by-rule approach utilizing piping formulae adopted from ASME Section III, Div. 1 and augmented by the requirements in Section III, Div. 5 related to creep. He detailed the proposed procedure to perform Class A piping. The intent is to provide a design-by-rules that is simplified and conservative approach.

Adibi-Asl (2023) used the above design-by-rules procedure to analyze an example problem. Based on the results of his analysis, the following conclusions were made:

- Although the elastic analysis procedure is cost-effective, the conservative design may not be competitive.
- The use of stress indices from Div. 1 contains and intrinsic assumption that these indices do not change at elevated temperature. This assumption requires validation.
- Under elevated temperatures, elastic follow-up is expected to be a concern in piping system. This phenomenon needs to be accounted for in the context of design-by-rules.

Recent ASME Code Development

Recently ASME BPV III, Task Group (TG) on High Temperature Piping Design as part of SG High Temperature Reactor was formed with the following charter: “Develop design by analysis rules for Class B elevated temperature piping systems in cyclic service with variable design lives as part of the new Section III, Division 5 Class B Code Case effort.” The task group studied several methods to perform the analysis of piping systems under elevated temperature service loading.

The Omega Method

When a bar is subjected to constant stress at elevated temperature, the strain varies with time as shown in Figure 1. After an instantaneous strain the bar will elongate with time due to creep. The primary creep starts at a rapid rate and slows with time. The secondary creep has a uniform rate. The tertiary creep: has an accelerated creep rate and terminates when the material breaks or ruptures. It is associated with both necking and formation of grain boundary voids.

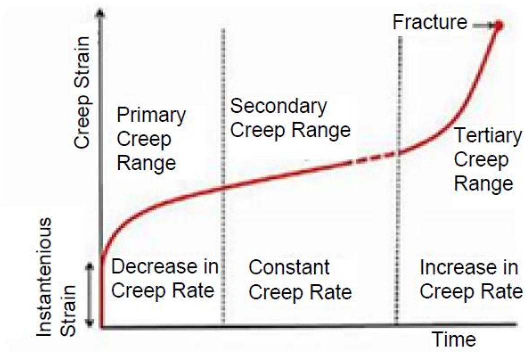


Figure 1. Phases of Creep

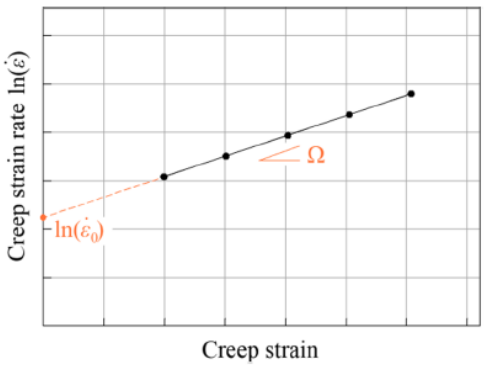


Figure 2. Creep Strain Rate as a function of Creep Strain

The Omega method was developed by the Material Properties Council (MPC) and has been used in ASME 2605-3. Prager (2000) provided a good discussion about the Omega method and is applied as the Level 2 assessment method in American Petroleum Institute API 579-1/ASME FFS-1 Part 10 (2021). The method assumes that the primary creep phase is negligible compared to the secondary creep and the tertiary creep as shown in Figure 1. The method stems from the fact that when test data are plotted as natural log of strain rate in y-axis vs. creep strain in the x-axis in the secondary and tertiary creep range, a linear relationship is produced as in Figure 2, The slope of the line is **Ω** (thus the Omega Method) and the y-axis intersect is equal to $Ln(\acute{\varepsilon}_o)$ where $\acute{\varepsilon}_o$ is the initial creep strain rate, Thus, the fitting function is:

$$\ln(\acute{\varepsilon}) = \ln(\acute{\varepsilon}_o) + \Omega\varepsilon$$

It follows that the remaining creep life (t_R) is given by:

$$t_R = 1/(\Omega\ \acute{\varepsilon}_o)$$

Hence, given the slope of the curve and the initial strain rate, one can find the remaining life of the component.

The petrochemical industry has extensive experience in the design and operation of elevated temperature piping systems. API 579-1/ASME FFS-1 Part 10 (2021) provides a three-level approach for the assessment of creep damage and creep life. In the Level-1 approach, charts are provided so that for a given applies stress, a damage rate can be calculated in units of 1/hr, which when multiplied by the duration of operation in the creep regime provides a use fraction. The Level-2 approach uses the Omega method to permit the detailed calculation of the creep life. An advantage of API 579-1/ASME FFS-1 is the clarity of its step-by-step approach, as well as the companion guide API 579-2/ASME FFS-2 which provides example problems.

An Important Challenge for Elevated Temperature

An important challenge in design at elevated temperature is the fact that the predicted design life is highly dependent on the exact prediction of the temperature profile. A small change in operating temperature, in the order of 10^{o}F can change the component life by 30%. The refining industry addresses this challenge by an exacting program of temperature inspections during operation through thermography, with access through thermographic windows. The prediction of the exact temperature profiles at the design stage, its confirmation during prototype testing, and access for in-service monitoring of the temperature profile during operation should be addressed.

Development of a Code Case

The piping TG is also developing a code case for the design of Class B piping systems. The elements of the code case includes the following:

- Provide time dependent allowable stress for primary loading.
- Account for cyclic loading
- Avoid stress classification

New Primary Load Rules will be established to evaluate the following load condition:

(a) The Design Conditions using Design-by Rule using ASME NCD-3300, 3400, 3500 and 3600. Alternatively Design-by-Analysis can be used utilizing FEA limit load, Elastic-Perfectly-Plastic (EPP) material model.
(b) Service level limits are performed using Design-by-Analysis utilizing FEA limit load EPP material model.

The strain limits and ratcheting check evaluation

This evaluation is based on Class A Code Case N-861-2, ASME (2023(a)). This evaluation uses FEA EPP material model with composite cycle load definition. Pseudo stress at yield (PSY) based on 1% strain in base metal and 0.5% in welds at local temperature and design life. If shakedown to plastic cycling is achieved, then no ratcheting will occur.

Figure 3 which is based on a flow chart in Mahajan et al. (2023) report illustrates this method. The flow chart is summarized into the following steps:

1. Define a design life (t_{design}) with composite cycle.
2. Define PSY's based on the minimum yield strength of the material and the time-temperature dependent stresses from the isochronous stress stain curves (ISSCs) based on total time duration (t_{design}) of high temperature service and a target inelastic strain at 1%.
3. Perform a small strain thermo-mechanical EPP finite element analysis (FEA) where the yield stresses of the material are replaced with PSYs. The FEA model must include detailed component geometry to simulate stress raisers and corner radii.
4. If strain histories of all integration points achieve shakedown, the strain limit check pass.
5. If strain limit check does not pass, load cycle and component geometry are redefined and all the steps are repeated.

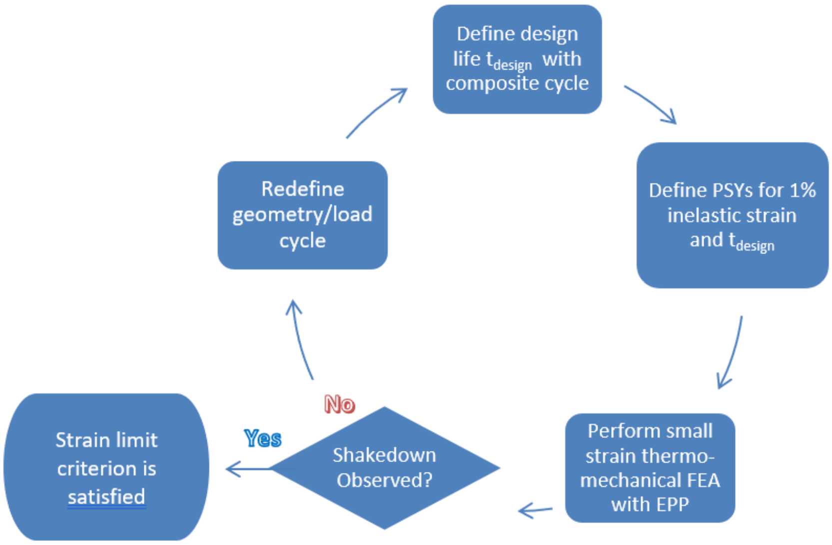


Figure 3. Proposed Strain Limit Evaluation Flow Chart,
Ref. Mahajan et al. (2023)

Creep-fatigue damage Criteria and Evaluation

The allowable creep-fatigue is obtained from damage diagram shown on Figure 4. The vertical axis represents the summation of creep damage fractions while the horizontal axis is the summation of the fatigue damage fractions for all cycles. The intersection point of the damage envelope lines is at (0.2,0.2). This value is chosen to be a conservative lower bound for most piping materials. For a given load cycle, the damage line follows a certain slope such as the blue dashed line starting from the origin as shown in Figure 4. The intersection of the dashed blue line with the creep vs. fatigue damage envelope is considered the point of failure.

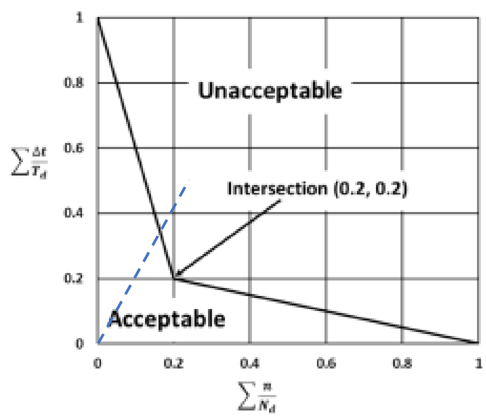


Figure 4. Creep vs. Fatigue Damage Envelope

Without considering stress classification, obtain peak stress ranges using elastic FEA in accordance with XIII 2400 and 3500(e). The stress history is determined from ISSCs. The method is analogous to Class A relaxation using ISSCs but adjusted for elastic follow-up using q=2 for normal material and q=6 for sharp stress concentration. The elastic follow-up can be represented by Figure 5.

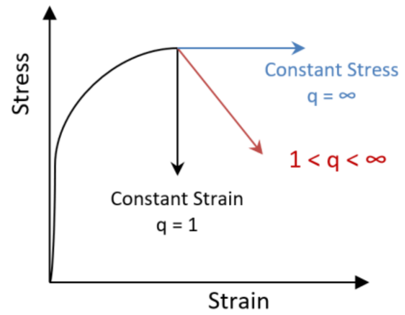
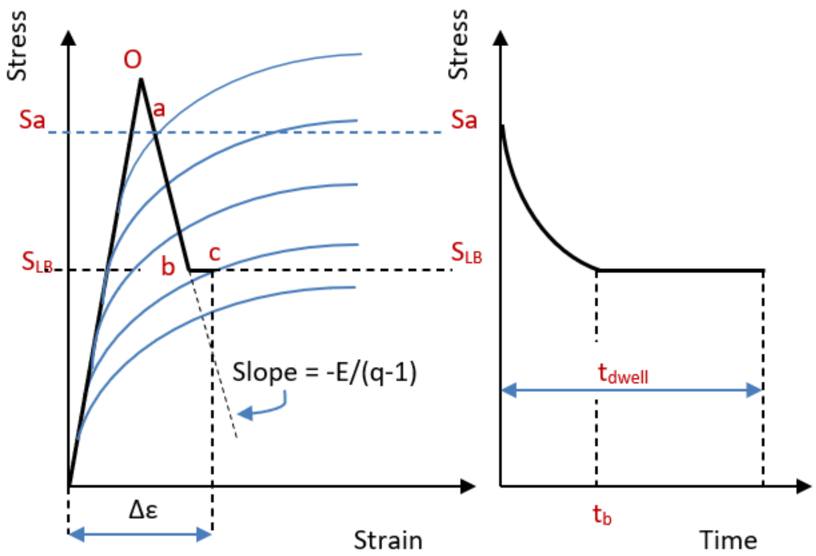


Figure 5 Elastic follow-up Diagram,

The creep damage is determined from stress history using an analytical expression provided and subject to a lower bound stress value.

Mahajan et al. (2023) provides a method of evaluation consisting of the following steps:

1. Elastic analysis with all loads using temperature dependent material properties, elastic moduli, Poison's ratio, and thermal expansion coefficient. thermo-mechanical FEA using all geometric feature of stress concentration regions is conducted to produce the total stresses at all integration points.
2. The maximum alternating stress intensity (S_{alt}) for all integration points are used to calculate the maximum peak stress (σ_{peak}), i.e., σ_{peak}= 2 S_{alt}.
3. Stress relaxation is performed by using σ_{peak} as a starting point for the stresses to relax as shown in Figure 6(a). For a given elastic follow-up, q, the stress is relaxed among the family of ISSC's along the slope –E/(q-1) where E is the elastic modulus at peak temperature during the load cycle. The point 'a' is the intersection with the hot tensile curve and the corresponding σ_a is the starting relaxation stress that follows the curve shown in Figure 6(b) until reaching the lower bound stress S_{LB}, which remains constant until t_{dwell}.



(a) (b)

Figure 6 (a) Stress-strain path (black line) on the ISSC's and the respective relaxation and total strain range (b) Stress relaxation history, based on Mahajan et al. (2023)

Analytical expressions will be provided in the code case to calculate Sa, time to reach Sa, and stress at time t, σ(t). In addition, creep-fatigue damage equations and methodology will be provided.

Additional Considerations:

The piping TG will be investigating the following aspects:

1. Effect of elevated temperature on flexibility factors and stress indices.
2. The use of pipe and elbow elements instead of shell elements for Class B piping.
3. Piping analysis software required development improvement.

Sumary and Conclusions:

Lessons learned from the analysis and design of generation III nuclear power plants as well as the experience gained in their operations can be used in the design of advanced NPP piping systems operating at elevated temperatures. ASME Section III, Div, 5 piping TG is developing a new code case for the analysis and design of Class B piping systems. Alternative methods in the analysis and evaluation are being studied and adopted in the evaluation of piping systems in elevated temperatures. Several other considerations are being studied in the code case development.

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