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Section III, Division 5 – Development and Future Directions

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SECTION III, DIVISION 5 - DEVELOPMENT AND FUTURE DIRECTIONS

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ABSTRACT

This paper provides commentary on a new division under Section III of the ASME Boiler and Pressure Vessel (BPV) Code. This new Division 5 has an issuance date of November 1, 2011 and is part of the 2011 Addenda to the 2010 Edition of the BPV Code. The new Division covers the rules for the design, fabrication, inspection and testing of components for high temperature nuclear reactors. Information is provided on the scope and need for Division 5, the structure of Division 5, where the rules originated, the various changes made in finalizing Division 5, and the future near-term and long-term expectations for Division 5 development. Portions of this paper were based on Chapter 17 of the *Companion Guide to the ASME Boiler & Pressure Vessel Code, Fourth Edition*, © ASME, 2012, Reference [1].

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1. INTRODUCTION

In the last several years, both domestically and abroad, there has been renewed interest in High Temperature Reactors (HTRs); in particular, the High Temperature Gas Reactor (HTGR) and the Liquid Metal Reactor (LMR). Both of these reactor types contain pressure boundary components or core support structures that operate at temperatures that exceed those covered by ASME Boiler and Pressure Vessel Code, Section III, Division 1 (BPV III, Division 1) rules that apply to Light Water Reactors (LWRs).

The HTGR is characterized by high gas outlet temperatures, 750 to 950°C (1380 to 1740°F) and moderately high pressure, about 7 MPa (1000 psi). Most of the Code pressure boundary components are shielded from the very high gas temperatures and operate at temperatures near to or somewhat greater than Light Water Reactors (LWRs). The exception is the core support structure and the heat transfer interface between the primary and secondary heat transport systems. Because of the massive core heat capacitance, thermal transients are generally quite slow.

The LMR operating temperature is generally in the range of 500 to 550°C (930 to 1020°F) and much lower pressure, about 1 to 2 MPa (150 to 300 psi). Because of the relatively low heat capacitance of the core and high heat capacitance of the liquid metal coolant, thermal transients can be quite rapid, particularly for Service Levels B and C. Although there are major differences in configuration and operating conditions between the HTGR and the LMR, the underlying design technology, materials, and fabrication and inspection requirements have much in common. A notable exception is the rules for construction of graphite core support structures for the HTGR which are unique.

Research and development to meet the needs of the HTGR and LMR has been underway for several years in the U.S. Department of Energy (DOE) national laboratories, universities, and specific tasks funded by ASME ST-LLC through support from DOE and the U.S. Nuclear Regulatory Commission (NRC). To guide these activities, a number of planning documents have been prepared; i.e. the HTGR Roadmap, HTGR and LMR White Papers and a Strategic Action Plan used by the Subgroup on High Temperature Reactors (SG-HTR). These documents address both near term, defined as through the 2015 Edition of the Code, and long term, 2017 and beyond, needs. This paper provides a summary overview of those plans.

2. Organization

With the exception of the graphite components, Division 5 is essentially an editorial compilation of existing Subsections and Code Cases addressing both elevated temperature components and conventional operation below the creep regime. This is accomplished by referencing Subsections NB, NC, NF, NG and NH. The Code Cases for elevated temperature components and the aforementioned graphite rules are included in the main text. One significant change from past practice is that only two Classes of construction are considered, Class A corresponding to Class 1 in Section III, Division 1, and Class B corresponding to Class 2.

2.1. Classification

The initial issuance of ANS-53.1 [2], expected to be published by early 2012, establishes safety classifications for modular helium-cooled reactor plants in a manner much differently than that done for light water reactors. This document creates three classifications for Systems, Structures and Components (SSCs):

(a) safety-related;
(b) non-safety related with special treatment;
(c) non-safety related.

Safety-related SSCs are governed by rules in Division 5 that are very similar to Class 1 or Class CS rules, and these are designated as Class A rules in Division 5. SSCs that are deemed to be not safety-related but which require special treatment (alternative safety function capability and contribute to defense-in-depth) are addressed by rules that are very similar to Division 1, Class 2 rules (using either design-by-analysis or design-by-rule as appropriate). These are designated as Class B rules in Division 5. Non-safety related SSCs are treated like balance-of-plant items in the current LWR fleet, following the rules of Section VIII of the ASME BPV Code, ASME B31, etc., as appropriate. This classification system currently applies to both HTGRs and LMRs.

Note that the ANS-53.1 classifications are either safety or non-safety based. They are not like the Division 1 classifications that reflect a pressure boundary (Class 1 or Class 2), metal containment (Class MC), or core support (Class CS) function. Hence, the Class A and B terminology reinforces that distinction and allows for unique Division 5 situations that may arise in the future if additional rules beyond those in Division 1 are needed. Simply put, confusion is eliminated with different classification nomenclature since HTGRs and LMRs are different from light water reactors.

3. Origin of Division 5 Rules

As shown in Table 1, the initial publication of Division 5 does not contain new technical rules or general requirements, with the exception of the new graphite rules (both the general requirements in Subsection HA, Subpart B and the design and construction rules in Subsection HH, Subpart A). Graphite aside, Division 5 either refers to existing Division 1 rules as appropriate or directly incorporated rules contained in existing nuclear Code Cases (incorporated because ASME Code rules cannot reference Code Cases).Therefore, what may appear to be new rules are actually just reformatted rules, adjusted to meet the approved Division 5 structure and terminology where appropriate. Table 2 provides further details on the origin of rules for each Division 5 Subsection and Subpart. The only new (not previously published) rules incorporated into Division 5 are the graphite rules.

Note also that all of the Division 5 general requirements have been located in Subsection HA. This was done in order to support the current Subsection NCA re-write effort. It will be easier to move the entire Subsection HA from Division 5 once the re-write effort is ready to incorporate Division 5 general requirements into its revised Section III general requirements book. However, until that established goal is achieved, Subsection HA will exist to provide the general requirements for Division 5.

Any alterations to the existing Division 1 rules are specifically identified in the corresponding Division 5 Subsections, via the renumbered paragraphs and subparagraphs. These Division 5 Subsections HA, HB, HC, HF, and HG, Subparts A are very short (six pages or less). When incorporating the existing rules of the older Code Cases (some dating back to the early 1980s), new Division 5 paragraphs and subparagraphs were created, but the rules are essentially the same existing rules. Division 5 Subsections HB, HC, and HG, Subparts B have more pages since the existing Code Case rules were incorporated directly into Division 5.

3.1. Corrections and Clarifications

A limited number of areas exist where editorial corrections or clarifications were made. Most of the alterations made when incorporating the Code Cases into Division 5 were changes necessary to adapt to the new Division 5 structure or were deemed necessary to match the current ASME BPV Code. Since the issuance of some of the elevated temperature Code Cases, the ASME BPV Code has been revised. For example, allowable stress or stress intensity values used to be in the Section III Appendices but now appear in Section II, Part D. Beyond the issue of where material data currently exists, material data callouts have changed. For example, material callouts no longer in Section II (e.g., SA-430) were deleted. Material groupings used in the Code Cases were updated to reflect how Section II is currently published, using nominal composition callouts. In addition, the older Code Cases contained dated or erroneous references that were corrected and grammar and misspellings were also corrected. Interim metrication of these older Code Case tables and figures was accomplished by inserting SI values next to the US Customary values or creating new tables with SI unit headers. Excluding the stress tables of Subsection HG, Part B, Appendix HGB-II, exacting metric conversions were used to avoid affecting any critical temperature and stress data relationships that could adversely affect creep evaluations. The Appendix HGB-II stress tables were previously metricated as part of a revision effort for Code Case N-201-5, using interpolation to achieve stress values at the proper Celsius temperature intervals.

4. Graphite Rules

The graphite rules in Division 5 are new and will be discussed in some detail here. Graphite is a brittle and porous material. It is essentially pure graphitized carbon manufactured in a variety of ways with different raw materials (mined coal or a blend of crude oil stocks). Different manufacturing processes result in different grades of graphite with different orientations of crystallites, size and distribution of pore spaces, and varying degrees of graphitization. Graphite can withstand very high temperatures and still retain necessary functionality as a core support structure material. Graphite does not experience thermal creep until temperatures exceed 3600°F (2000°C). It is a nuclear moderator. Therefore, graphite has significant uses in high temperature reactors. Figure 1 shows some typical graphite components.

4.1 Graphite Committee History

The genesis of the ASME Section III Subgroup on Graphite Core Components resulted from a workshop at Oak Ridge National Laboratory (ORNL) in 2003. As a result of the workshop and discussions between ORNL and ASME, the first meeting of the new graphite committee was held in February 2004. Since that initial meeting, committee members have been actively developing Code rules for graphite core components, which comprise the graphite core assembly. In May 2005, a charter for the committee was approved and the committee became known as the Subgroup on Graphite Core Components (SG GCC), reporting to the BPV III Standards Committee.

In October 2009, the SG GCC began the process of balloting the proposed graphite rules they had developed to the BPV III Standards Committee. Approval for both the graphite general requirements and the graphite design and construction rules by the BPV III Standards Committee and the Board on Nuclear Codes and Standards was achieved in May 2010. Since that time, the SG GCC has continued to revise the graphite rules by developing additional editorial and technical improvements.

4.2. Graphite Technical Approach

Rather than simply duplicating the existing Code rules for metallic materials, the SG GCC considered the unique material properties and environmental responses of graphite during operational use in order to develop proper rules. One major driver is the fact that graphite's mechanical and thermal properties change with temperature and irradiation. The changes to graphite's mechanical and thermal properties influence the performance lifetime of graphite components in the core, and the variation in properties must be used to determine when graphite components must be replaced. A second driver is the inherent variability of graphite material properties. A probabilistic approach has been adopted as a basis for the development of Code design rules to cover this variability. For this initial publication, the graphite rules are limited to high temperature, graphite moderated, gas cooled fission reactors containing either a prismatic or pebble bed core.

4.3. Graphite General Requirements

The new graphite general requirements developed by the SG GCC did not follow exclusively the philosophy of the Subsection NCA, Division 1 scope for metallic core supports structures, but also adopted portions of the Division 2 general requirements to develop a hybrid graphite general requirements subsection, currently identified as Subsection HA, Subpart B in Division 5. The format of the graphite general requirements does follow the Subsection NCA format, but the uniqueness of graphite still has to be addressed.

For example, the Designer, who is responsible for the design of the graphite core components and the graphite core assembly and for generating the Design Drawings, Construction Specification, and the graphite material data, must be a G Certificate Holder. A G Certificate Holder may also have other scope including the ability to design, construct, manufacture material, machine graphite core components, and install the core assembly (if each activity is allowed per the certificate). This G Certificate Holder can also prepare the construction procedures, shop and field drawings, Construction Report, and qualifies the Graphite Material Organization while retaining overall responsibility, including certification. A Graphite Quality Systems Certificate Holder is established and is able to manufacture material, perform machining, and complete the core assembly installation, with the G Certificate Holder authorized for construction still having overall responsibility. The graphite general requirements also establish the Authorized Nuclear Inspector for Graphite Supervisor and the Authorized Nuclear Inspector for Graphite and their associated duties.

4.4. Graphite Design and Materials

Article-2000 addresses the general material requirements, the material property data needed for design, sampling requirements, examination and repair details, and packaging, transportation, and storage requirements for the graphite billets.

Graphite material properties are surprisingly different from the material properties of steel with which most engineers are familiar. Graphite presents many unique challenges. In addition, mechanical strengths can vary within a single billet of graphite as does the strength from billet to billet. There is additional strength variation in billets manufactured in different furnace charges. ASTM D7219-08 specifies the minimum mechanical strength and thermal properties for the different nuclear grades of graphite based on grain sizes and manufacturing method. The Division 5 graphite rules have adopted ASTM D7219-08 and ASTM D7301-08 and require that mechanical and thermal property data required for the graphite core assembly design be obtained via prescribed testing. The graphite rules also clarify that the Designer is responsible for obtaining the necessary graphite design data.

Article-3000 addresses the general design requirements, the “design by analysis” rules for the graphite core components, and the requirements for the design of the graphite core assembly.

Graphite core components develop stresses from mechanical loads and from interactions with the fast neutron flux in the reactor. The distributions of temperature and fast neutron fluence create thermal and radiation-induced strains and multiaxial residual stresses as well as variations in mechanical properties in the component. In addition, the graphite component can experience viscoelastic creep due to energetic neutron interactions with the graphite crystal structure. The creep strains affect the coefficient of thermal expansion. This interaction results in the development of nonlinear viscoelastic relationships between long-term stresses and strains.

Because the material properties change with operating time, the designer must calculate and track stresses over the lifetime of the graphite component. Low temperature operations, such as refueling and maintenance, also must be considered for the analyses. Graphite design rules in Division 5 do not differentiate between primary and secondary stresses, and only combined stresses are considered. Therefore, the design rules have separate design stress limits based on safety importance and absorbed neutron fluence rather than limits based on stress classifications.

The variability of material properties requires probabilistic assessment methods in graphite design. The graphite rules introduce three Structural Reliability Classes (SRCs) that prescribe differing statistical distributions for the expected mechanical tensile strength. Each SRC assigns an upper limit of probability of failure. Material strength and brittleness is modeled using Weibull statistics to describe the probability that, within each portion of the graphite billet, the strength will meet or exceed some minimum value. This evaluation, along with a stress analysis, is used to predict the probability of failure.

The evaluation of analytically determined stresses in graphite core components can be performed using either a simplified or a full assessment method. Both of these methods require appropriate material property data that are obtained from tests, including irradiation tests. Stress and deformation limits are included in the assessment.

No margin of safety or safety factor is used in the assessment of component stresses. The probability of failure is determined for crack initiation in the component, which is not necessarily component failure. Graphite core components must be evaluated to ensure that safety functionality is achieved with expected cracks throughout their lifetime.

The simplified assessment is the initial method the Designer should use to determine if the component stresses exceed the limit assigned by the SRC probability class. This method compares the component stresses to a uniaxial tensile strength distribution by means of a two-parameter Weibull distribution. The strength value (S_g) is determined from the Weibull distribution established by material strength tests. If the component stresses exceed the SRC limits for the simplified assessment, the component can be re-evaluated using the full assessment.

The full assessment method uses a probabilistic design approach incorporating Weibull statistics to determine the probability of failure. Failure is determined by comparing the calculated probability of failure with the allowable failure probability for the assigned SRC. The allowable failure probability is based on the safety function of the component and expected temperatures and stresses during transients.

An optional third assessment method is based on testing full-scale graphite components. The tests must be designed to envelop all design and service loadings and to provide a 95% confidence level that the component will not fail. Note that not all parts and loadings are suitable for design by the testing option, since it may not always be possible to reproduce complex loadings and environmental effects.

4.5. Graphite Machining, Examination and Testing

Graphite machining requirements include proper material identification for traceability, good practices to prevent contamination of the graphite, dimensional examination of finished components, examination of finished components for material defects or damages, and packaging needs after machining.

Nondestructive testing methods still need to be developed for the examination of graphite components. The development of effective test methods is complicated by the disparate nature of expected microstructures and defects, including variations in grain size, the appearance of porosity and the presence of internal cracks. This is an active area of research.

The requirements for proof testing of machined graphite core components are also provided in Division 5. This testing is normally specified in the Construction Specification.

4.6. Graphite Installation and Examination

Article-5000 provides the requirements for storage of graphite core components at the site, the unpacking and examination of the graphite core components, the installation of the components into the graphite core assembly, and the examination requirements for the core assembly, including required examinations during installation and post-installation.

5. Future Expectations for Division 5

Research and development efforts necessary to meet the needs of the HTGR and LMR have been underway for several years in the DOE national laboratories, universities, and specific tasks funded by ASME ST- LLC through support from DOE and the NRC. International efforts have also contributed. To guide these activities, a number of planning documents have been prepared; i.e., the HTGR Roadmap, HTGR and LMR White Papers and a Strategic Action Plan used by the Subgroup on High Temperature Reactors (SG HTR). These documents address both near-term, defined as through the 2015 Edition of the Code, and long-term, 2017 and beyond, needs.

5.1. Strategic Issues

Near-term goals focus on improvements to the rules to address gaps in the materials data and design criteria while maintaining the current structure of Division 5. The long-term goal is to provide rules for use and adoption by worldwide regional jurisdictional authorities. Stakeholder input and recent developments in the new draft Section XI, Division 2 are suggestive of a system-based approach for design as well as for fitness for service evaluations, thus blurring the line between the traditional roles of Sections III and XI. Currently, the planning documents identify this as an issue for further consideration. A closely related issue is whether or not the current provision of two versus three classes of construction will be compatible with worldwide use. Informal discussions suggest that it will but further consideration is required. Also under consideration is development of rules for environmental degradation, i.e., corrosion, carburization and decarburization, and irradiation. Another long-term objective is to have self-contained, consolidated, "all-temperature" rules that eliminate the step change in allowable stresses and design procedures of the current rules.

5.2. Design and Materials Issues

For the near-term, materials issues focus on correction of inconsistencies in current allowable stress levels, extension of the design life from 300,000 to 500,000 hours, and provision of allowable stresses at higher temperatures to accommodate HTGR needs. Revisions, corrections and updates to the rules for Class B components have also been given a high priority. Design rule improvements for the near-term have been and continue to be focused on clarification and improvement of the rules for creep-fatigue evaluation and determination of when creep effects become significant, primarily for supporting the use of 9Cr-1Mo-V (Grade 91).

For the longer term, development of a suite of new simplified rules (which do not require stress classification) for evaluation of primary stress loading, strain limits, and creep-fatigue is a high priority item and a key enabling factor in the development of an "all-temperature" set of design rules. Another high priority issue is improvement of the design evaluation and fabrication rules for weldments. In the materials area, the goal is to add Alloy 617 to the approved materials for Class A (and probably Class B) construction to support the very high temperature (850 to 950°C) version of the HTGR. The addition of high strength, low carbon, high nitrogen 316 stainless steel, advanced 9Cr ferritic/martensitic steel, and advanced austenitic stainless steel HT-UPS (high temperature, ultrafine precipitation-strengthened) are also being considered.

Graphite properties and environmental effects are required by the Code to produce a design. Work is ongoing within the Next Generation Nuclear Plant Project and Generation IV International Forum (GIF) to produce the data. The current Code rules are structured to address this data acquisition process. It is the intent that the data obtained from this work will be adopted by the Code. This is a priority Code issue.

5.3. Fabrication and Examination Issues

In this area, the focus is on longer term issues. The fabrication concerns are mainly directed toward improvement of the post-weld-heat treatment of 9Cr-1Mo-V (Grade 91) and further restrictions on cold work and the use of partial penetration welds. Improvements in examination take advantage of recent technology improvements. For example, more reliance on ultrasonic examination (UT) for flaw detection, acoustic emissions for cracking or leak monitoring, ultrasonic phased arrays to detect creep micro cracking, and UT crack tip diffraction for macroscopic creep cracks.

6. Conclusions

The new BPV III, Division 5 establishes a single-volume Code framework for high temperature reactor design, fabrication, inspection and testing, and provides a home for the new graphite rules. In the near-term, the ASME committees will focus on accommodating near-term stakeholder needs in Division 5, including corrections to allowable stress tables, extension of design life to 60 years and updating the Class B rules. Long-term activities will be stakeholder driven, and it is anticipated there will be needs for new materials, less conservative and simplified analysis methods, consistent rules and allowable stresses over the full temperature range of operation, and, perhaps, a risk-informed, system-based Code.

7. Acknowledgment

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8. References

[1] K. R. Rao, ed., *Companion Guide to the ASME Boiler & Pressure Vessel Code*, Fourth Edition, (to be published in 2012).

[2] ANSI/ANS-53.1-201X draft, "Nuclear Safety Design Process for Modular Helium-Cooled Reactor Plants" (August 12, 2011 Draft for Reference with Recirculation Ballot).

Table 1. Code Structure for Section III, Division 5

CLASS	SUBSECTION	SUBPART	SUBSECTION CALLOUTS	TITLE	SCOPE
-	HA	-	-	General Requirements	-
Class A & B		A	HAA	*Metallic Materials*	Metallic
Class A		B	HAB	*Graphite Materials*	Graphite
Class A		C	HAC	*Composite Materials*	Composites
Class A	HB	-	-	Metallic Pressure Boundary Components	Metallic
		A	HBA	*Low Temperature Service*	
		B	HBB	*Elevated Temperature Service*	
Class B	HC	-	-	Metallic Pressure Boundary Components	Metallic
		A	HCA	*Low Temperature Service*	
		B	HCB	*Elevated Temperature Service*	
Class A & B	HF	-	-	Metallic Supports	Metallic
		A	HFA	*Low Temperature Service*	
Class A	HG	-	-	Metallic Core Support Structures	Metallic
		A	HGA	*Low Temperature Service*	
		B	HGB	*Elevated Temperature Service*	
Class A	HH	-	-	Non-Metallic Core Support Structures	-
		A	HHA	*Graphite Construction Rules*	Graphite
		B	HHB	*Composites Construction Rules*	Composites
Class A & B	Appendices	None	Appendices	Mandatory and Nonmandatory Appendices	All

Notes:

1. Subsection ID has three characters for referencing flexibility to address low / elevated temperature concerns or varying materials under the same Subsection.
2. Two Section III Classes [A and B] were chosen for high temperature reactors, reflecting (1) safety-related and (2) non-safety related with special treatment classification categories, respectively, for SSCs. Non-safety related SSCs will use non-nuclear standards such as BPV Section VIII, B31, etc.
3. Appendices may be generally applicable (as shown above) or Subsection specific and attached to those Subsections (like Subsection NH).

Table -2. Origin of Division 5 Rules

Division 5 Subsection	Refers To Rules In	Incorporates Rules From
Subsection HA – General Requirements		
Subpart A – Metallic	Subsection NCA	
Subpart B – Graphite		New rules
Subpart C – Composite	TBD	TBD
Subsection HB – Class A Metallic		
Subpart A – Low Temperature	Subsection NB	
Subpart B – Elevated Temperature	Subsection NH	
Appendix HBB-I		CC N-499-2
Subsection HC – Class B Metallic		
Subpart A – Low Temperature	Subsection NC	
Subpart B – Elevated Temperature	-	-
HCB-1000		CC N-253-14
HCB-2000		CC N-253-14
HCB-3000		CC N-253-14
HCB-4000		CC N-254
HCB-5000	Subsection NC-5000	
HCB-6000		CC N-467
HCB-7000		CC N-257
Appendix HCB-I		CC N-253-14, Appendix B
Appendix HCB-II		CC N-253-14, Appendix C
Appendix HCB-III		CC N-253-14, Appendix E
Subsection HF – Supports		
Subpart A – Low Temperature	Subsection NF	
Subsection HG – Class A Metallic CSS		
Subpart A – Low Temperature	Subsection NG	
Subpart B – Elevated Temperature		Revised CC N-201, Part B
Appendix HGB-I		Revised CC N-201, Part B, Appendix Y
Appendix HGB-II		Revised CC N-201, Part A
Appendix HGB-III		Revised CC N-201, Part A, Appendix XVIII
Appendix HGB-IV		Revised CC N-201, Part A, Appendix XIX
Subsection HH – Class A Non-metallic CSS		
Subpart A – Graphite		New rules
Subpart B – Composite	TBD	TBD

Notes:
CC – Code Case TBD – to be developed CSS – Core Support Structures

Figure 1. Representative graphite core components