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ASME CODES AND SMALL MODULAR REACTORS

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ABSTRACT
Authors: Sargent & Lundy, LLC: Dennis Demoss, Stefan Janusz, and Richard Niemer. Focus: Codes and Standards. This paper will review new Small Modular Reactor (SMR) designs and implications on ASME Codes and Standards. SMR technologies which will be discussed include B&W mPower (TVA Clinch River site), Westinghouse SMR (Ameren Callaway site), NuScale/Fluor SMR (Pacific NW lab site), Holtec SMR (Savannah River site), and Non-U.S. Designs such as the Russian SMRs.

U.S. SMR reactor designs vary from 45 to approximately 225 MWe. SMRs, as defined by the International Atomic Energy Agency, have an electrical output less than 700 MW [1]; however, U.S. SMRs are typically defined as producing less than 350 MWe. SMR goals include significantly reducing plant capital cost requirements and enabling multi-reactor module construction and addition over time providing greater utility flexibility. A primary SMR advantage includes its installation in smaller grids typical of electrical power systems in developing countries. Unique aspects of the SMR technologies include integral reactor and steam generator vessel, integral pressurizer and internal piping, below-grade containment vessel, helical-coil integral steam generators, integral decay heat removal systems, modular plant construction and arrangement, in-service inspection unique requirements, special materials, and welding. SMR technologies provide unique challenges for conformance with ASME Codes and Standards.

Non-U.S. designs, such as the Russian floating ship-type configuration SMR (KLT-40S) and Russian land-based SMR (VBER-300), will be discussed from the perspective of compatibility with ASME Codes. Discussion will be provided regarding non-U.S. SMR operational safety and inspection requirements based on ASME Codes.

SMR development may require the expansion and clarification of current ASME Code design rules and requirements. For example, Section XI testing requirements and frequencies may require revision due to longer intervals between refueling. New divisions of ASME Codes may be required to address inspection of SMR inaccessible plant components and materials and plant operational differences from previous LWR designs. Additional reactor internal components and equipment may also require additional ASME Code considerations. Finally, higher design temperatures resulting from passive design shutdown considerations may require development and Code acceptance of new materials.

INTRODUCTION
Development, construction, and operation of Small Modular Reactors (SMRs) will enable the generation of electricity by non-polluting, reliable, and safe technology. SMRs are expected to generate a great deal of interest for those power producers whose generation needs match the unique advantages of SMRs. There are at least five (5) and as many as ten (10) companies worldwide that are on record stating that they are developing an SMR that will be available for commercial production in the near future, with interest from five (5) or six (6) countries.

SMRs offer simplicity, convenience, attractive economics, and, most importantly, an opportunity for the producers of electric generation to reengage the nuclear option. Site integration requirements, in-service inspection and testing, and staff operational interface expectations will need to be taken into account to ensure SMR installation success.

A different reactor design approach, tailored for this new and emerging market segment, could help meet the rising power demands associated with economic growth and urbanization while avoiding the use of fossil fuels that would otherwise be burned in coal and natural gas power plants.

This paper will explore the similarities and the differences among four (4) of the U.S. light water SMR designs most likely to move forward in the near term and Russian designs. Additionally, this paper will address the role that ASME may fulfill since it is likely that revisions to the existing ASME Code, as well as the development of new ASME Codes and Standards to support this new technology, may be required. Finally, this paper will identify the current economic and societal conditions that poise SMRs to herald the U.S.'s nuclear re-renaissance.

OUTLINE

I. SMR Features Common to Four (4) U.S. Designs
II. SMR Design Features Unique to Each of the Four (4) U.S. Designs:
 - B&W mPower SMR
 - Westinghouse SMR
 - NuScale SMR
 - Holtec SMR-160
III. Engineering Issues which may Challenge the Existing ASME Codes and Standards
IV. Russian SMR Compatibility with ASME Codes
V. Economics of SMR Technologies
VI. SMR Development Status, Advantages to U.S. Designs, and Domestic Potential

I SMR FEATURES COMMON TO FOUR (4) U.S. DESIGNS

<u>SMR designs rely on passive safety features.</u>
The SMR plant designs increase the use of passive cooling systems and passive shutdown features minimizing or eliminating required operator interaction.

<u>SMRs are located below grade.</u>
SMRs provide enhanced safety and security over conventional nuclear units. Their below grade location renders them relatively immune to weather extremes such as hurricanes, floods, and tornadoes and less accessible to terrorists.

<u>SMR investment costs are less and construction schedules shorter.</u>
Factory assembly and modular construction enable SMRs to be manufactured in a controlled environment setting offsite. These conditions generally enable greater opportunities to improve quality and reduce cost than on-site construction. SMRs require lower total capital costs and shorter construction schedules due to modular construction. SMRs also offer utilities the opportunity to match load growth by incremental additions of generation capacity.

<u>SMR MW output is relatively small compared to large, more conventional units.</u>
The smaller SMR enables utilities with smaller capacity grids to have greater flexibility to more easily follow load growth or capacity replacement. The cost per kW-hr capacity is higher, however, due to the effect of economies of scale.

<u>SMR fuel is long lived.</u>
Candidate features include fuel designs that offer very long-life fuel loads (possibly ones that can last the entire life of the reactor so that refueling is not needed). Most designs incorporate two (2) or four (4) year fuel-cycles.

II SMR UNIQUE FEATURES COMPARED TO TRADITIONAL LWR DESIGN

A. Electrical Output

The electrical energy provided by the four U.S. SMRs selected for discussion ranges for individual modules from 45 MWe for NuScale to 225 MWe for Westinghouse [2]. Russia's KLT-40S and VBER-300 provide 35 MWe and 295 MWe, respectively [3,4]. Since multiple units can be added at a given site these individual unit sizes are not as significant as the comparatively larger units of 1000 to 1600 MWe for traditional nuclear plants. The smaller size enables custom fitting to individual and very specific needs, including cogeneration.

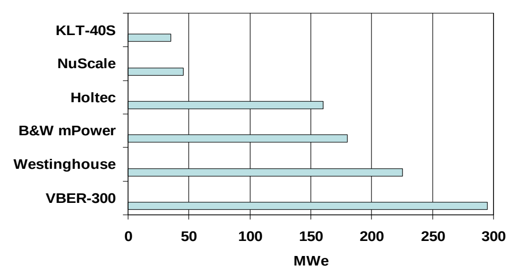

Figure 1: COMPARISON OF SMR ELECTRICAL GENERATION

B. Reactor Vessel Design

The B&W mPower SMR utilizes a hybrid, three (3) piece reactor vessel design with the nuclear core, steam generators, and pressurizer integral within a single vessel. The approximate dimensions are 80 feet in length and 13 feet in diameter. The active core region is approximately 6 feet. [2]

The Westinghouse SMR utilizes a hybrid, three (3) piece reactor vessel design with the nuclear core, steam generators, and pressurizer integral within a single vessel. The approximate dimensions are 80 feet in length and 12 feet in diameter. The fuel design will incorporate conventional 17X17 PWR fuel assemblies with an active core of approximately 8 feet. [5]

The NuScale SMR utilizes a hybrid reactor vessel design with the nuclear core, steam generator, and pressurizer integral within a single vessel. The approximate dimensions are 45 feet in length and 9 feet in diameter. The fuel design will incorporate standard 17X17 fuel assemblies with an active core of approximately 6 feet. The NuScale reactor will incorporate a helicoil steam generator. [2,4]

The Holtec SMR utilizes a design where the steam generator and pressurizer are separate from the reactor vessel. The approximate dimensions of the reactor vessel are 100 feet in length and 45 feet in diameter. The fuel design will incorporate conventional 17X17 PWR fuel assemblies with an active core of approximately 12 feet. [2,6]

C. Containment Design

All four designs feature underground containment structures.

The B&W mPower SMR is similar to a conventional PWR steel containment vessel; approximate dimensions are 120 feet in height and 80 feet in outer diameter. [2]

The Westinghouse SMR utilizes a modular, all-steel containment vessel; approximate dimensions are 90 feet in height and 30 feet in outer diameter. [5]

The NuScale SMR utilizes a steel containment vessel; approximate dimensions are 65 feet in height and 20 feet in outer diameter. [4]

The Holtec SMR utilizes a steel containment vessel; approximate dimensions are 91 feet in height and 45 feet in outer diameter. [6]

D. Refueling Frequency

The B&W mPower SMR and Holtec SMR-160 are designed for a fuel cycle of 48-months [2,6]. The Westinghouse SMR and NuScale SMR are designed for a fuel cycle of 24-months [4,5].

E. Reactor Coolant Pumps

The B&W mPower and Westinghouse SMRs will each utilize eight (8) reactor coolant pumps and motors per reactor [2,5].

The NuScale and Holtec SMRs will be designed using natural circulation with no active pumps and motors [4,6].

F. Pressures and Temperatures

The light-water SMR designs will operate with primary coolant conditions of approximately 2000 psig and 600°F and steam conditions of 850 psig and 530°F. These values are similar to existing LWR designs. [2,4-6]

G. Extended Capacity Fuel Pools to Accommodate 60 Years of Operation

The SMR designs under development are based on extended capacity spent fuel pools of up to 100 years of storage capacity [6]. This provides operators considerable flexibility managing their spent fuel.

III ENGINEERING ISSUES WHICH MAY CHALLENGE EXISTING ASME CODES AND STANDARDS

<u>ASME Considerations</u>

Similar to the existing nuclear power plant designs, SMRs will rely extensively on ASME Codes and Standards to address U.S. Nuclear Regulatory Commission (NRC) design and licensing requirements. Initially, all SMR designs will require an NRC Design Certification. Later on, SMRs will require additional NRC regulatory approvals to proceed with construction and operation. ASME Codes have provided significant leadership to designers and constructors seeking to develop safe and economical nuclear power generation and to obtain required regulatory approvals. The smaller and passive designs of these SMRs will challenge existing ASME Codes and Standards in several areas, potentially requiring the development of unique ASME Code Divisions. Four examples include the following:

A. Primary System Components Configured into one Vessel.

This design feature improves safety and offers lower capital investment cost. It also introduces complications associated with internal vessel components and piping, operating inspections, repair, and replacement of internal components. The reactor internals design complexity, involving integrated pressurizer, steam generator, and piping channels, will require additional analyses for flow induced vibration and fatigue. ASME Code design issues to consider include the following:

- Fatigue analysis and ASME Class I Design of reactor internal equipment and piping. Can the ASME Class I design rules be applied to the hybrid reactor vessels and equipment? Will additional design margin be required due to uncertain design conditions?
- Accident analysis requirements and load conditions for internal equipment and piping for internals.

- Use of new materials and welding processes.
- The multi-segment reactor vessel will require additional analyses and support considerations.

B. Inspection Requirements

Regulations, Codes, and Technical Specifications require a variety of periodic surveillances including weld examinations, leak rate tests, steam generator tube inspections, and component operability tests, to name a few. Appropriate measures for inspection and testing are essential to sustain improvements in SMR plant safety, resource optimization, operations, and maintenance, resulting in cost savings.

Current outage-related surveillance frequencies are based on a 24-month fuel cycle. With extended, 48-month fuel cycles and integral reactor components and welds, requirements for In-Service Inspection (ISI) and component In-Service Testing (IST) will likely require changes or expansion. The use of multi-segment reactor vessels may result in multiple levels of inspection standards and requirements with limited or minimal accessibility [7].

Systems and components integral to the reactor vessel, i.e., integral pressurizer and steam generator tubes, will require special inspection and monitoring considerations. Typical steam generator surveillance requirements for operating plants are based on inspection of 100% of the tubes every 60 Equivalent Full Power Months (EFPM) [7]. SMR designs utilizing a 24-month fuel cycle can satisfy this surveillance requirement through the inspection of 50% of the steam generator tubes every outage. For SMR designs with the longer 48-month fuel cycle, such as the B&W mPower SMR and Holtec SMR-160, 100% of the steam generator tubes will require inspection during each outage.

Containment leak rate testing will be simplified with the new smaller steel containments. However, leak rate testing frequencies will require adjustment or allow for exemption to accommodate extended fuel cycles. Containment penetration designs will require special features for submerged water designs and shorter clearance dimensions to accommodate thermal expansion issues.

Increased design margins and use of higher quality shop fabrication (improved tolerances) may justify longer inspection intervals.

The current development of the four (4) proprietary SMR designs account for the in-service inspection challenges intrinsic with SMRs; specifically, current designs have identified potential degradation mechanisms, selected resistant and resilient materials, and attempted to provide adequate access for examination and testing. With integral components within the reactor vessel, accessibility for inspection and testing becomes paramount.

Traditional inspection access has required sufficient space for physical and visual access and elimination or mitigation of environmental hazards. Holtec SMR-160 premeditated weld locations for in-service inspection and testing accessibility. Equivalent examination and assessment capabilities must be provided similar to current Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs) capabilities, depicted below.

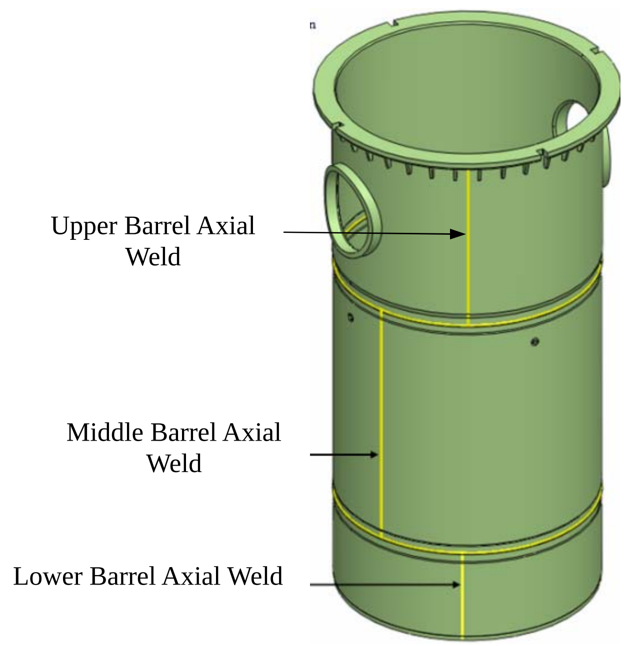

Figure 2: CORE SUPPORT BARREL ASSEMBLY

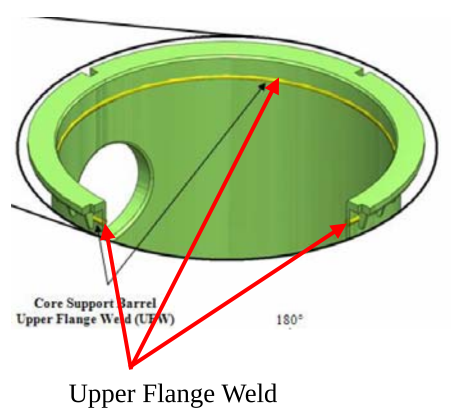

Figure 3: UPPER FLANGE WELD

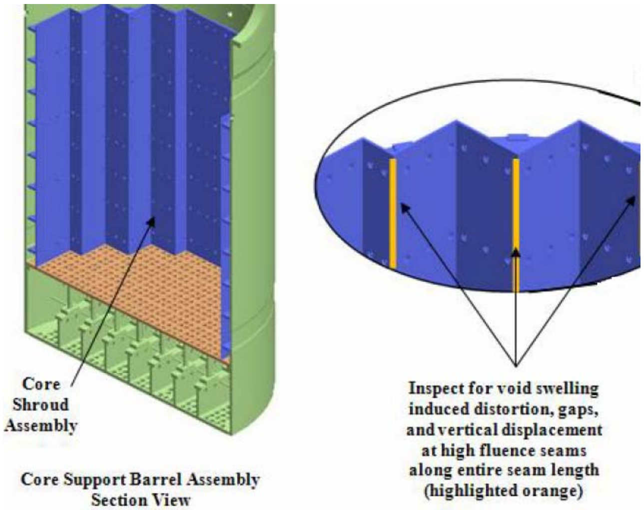

Figure 4: CORE SHROUD ASSEMBLY

Flow Induced Vibration (FIV) testing and monitoring may be performed similar to existing BWR monitoring of steam dryers with cable penetration and in-vessel instrumentation. Further analytical evaluations are required to hypothesize the introduction of unique flow paths or vortices associated with SMR designs.

The incorporation of enhanced risk monitors (ERM), as promoted by the U.S. Department of Energy, will aid inspection and testing requirements in addition to aligning with operation and maintenance economic goals of SMRs [8]. The direction of SMR design incorporates fewer components with the accessibility for offline inspection, testing, and maintenance opportunities with longer refueling cycles. Therefore, ERM would provide continuous metrics for equipment status and degradation. Additionally, implementation of advanced non-destructive examination (NDE) methodology would aid in the unique inspection challenges for SMRs.

C. Structural Materials

Reactor and structural materials must perform over an extended design life and longer operating cycles. Plants will be designed for a 60-year operating life. Increased design margins and use of high-quality shop fabrication will provide greater life cycle assurance.

D. Advanced High-Temperature Reactors

Advanced High Temperature Reactors are also under consideration for future SMR applications. This will require additional ASME Code approval for high-temperature metallurgy and ceramic materials.

In recognition, it is known that an entirely new Division 5 of ASME Section III [9] has been issued to incorporate Section III NH and Code cases, plus rules for graphite and ceramics, to address all high-temperature reactor needs.

These future high-temperature SMRs will have materials, design, and ISI issues that will rely on the updated ASME Code rules, or the development of new ASME Code Divisions. While the four (4) SMRs referenced earlier are not in the high-temperature category, continued ASME Code improvements for advanced high-temperature reactors are required and, thus, relevant to understand what Code issues are under consideration. It is likely that similar issues exist for at least some of the proposed Code revisions under consideration. The following summation was reported by the DOE in August of 2012:

E. Section III, Div 5

- Graphite and composite issues
- Creep-fatigue, negligible creep, and weldment rules
- Incorporate recommendations from ASME-LLC
- Simplified and “all-temperature” rules
- Environmental rule considerations (corrosion, irradiation, graphite, etc.)

F. Extension of Allowables for Current and New Materials

- Alloy 800H, 617, improved SS (316LN/FR, HT-UPS), modified grade 92, Hastelloy N, etc.
- Graphites and Composites

G. Section XI

- More reliance on advanced techniques (UT for volumetric exam, AE for crack or leak monitoring, phased arrays for micro-cracking, etc.)
- Creep-crack growth evaluation procedures
- Rules for compact heat exchangers (joint with Section III)

IV RUSSIAN SMR COMPATIBILITY WITH ASME CODES

The two (2) Russian SMR designs to be addressed are the OKBM KLT-40S and the OKBM VBER-300. The KLT-40S is a ship-based, floating SMR utilizing the 35 MW KLT-40 reactor design originally developed for ice breakers and other marine vessels. The VBER-300 is a larger PWR SMR compared to the KLT-40S. It is more similar in layout to a typical PWR nuclear plant. Russia’s KLT-40S is currently under construction and the VBER-300 is currently in the Russian licensing stage. [3,10]

The KLT-40S operates with the primary at approximately 1800 psi, a fuel cycle of 36-months, and 30-year design life. The VBER-300 operates with the primary at approximately 2300 psi, an overall fuel cycle of 72-months with partial refueling at either 12-months or 24-months, and design life of 60-years. [3,10]

The KLT-40S was developed in conformance with Russian laws and rules for nuclear-powered vessels. It is likely the KLT-40S would encounter the same challenges with the ASME Code as the B&W mPower and Holtec SMR-160. However, considering the fuel enrichment (< 20%) is significantly greater than currently licensed nuclear plants in the U.S., it is unlikely the KLT-40S could be licensed to operate in the U.S. [3,10]

The VBER-300 has operational characteristics that are similar to current-generation U.S. PWRs. The VBER-300 design is an evolution of Russian marine propulsion reactors. With partial fuel cycles available at either 12-months or 24-months, and a layout similar to a typical PWR, it is not likely the VBER-300 would experience inspection-related issues related to the U.S. SMRs; however, it would certainly require in-depth review for compliance with U.S. codes and standards as well as design certification. Considering that both the operational characteristics and fuel enrichment (< 5%) are similar to currently licensed U.S. PWRs, the VBER-300 has the potential to be licensed to operate in the U.S. However, please note that the Russian designs have not been certified for use in the U.S. by the U.S. NRC and, additionally, the Russian designs are based on older technology and certainly not as modern or up-to-date as the U.S. SMR designs. [3,10]

V ECONOMICS OF SMR TECHNOLOGIES

A. Lower Capital Cost

Perhaps one of the greatest advantages to SMRs is their lower capital cost compared to large-scale nuclear power plants. New nuclear power plants can cost in the range of $5 to $10 billion to construct, which many utilities and investors see as very cost-prohibitive. SMRs can cost a little as a few hundred million dollars, which reduces financial risk and allows for more favorable financing. Current estimates predict approximately $300 million for a 100 MWe SMR. [11]

With their smaller size, fewer components, simpler nature, and factory fabrication, the risk of cost overrun during construction is reduced. In addition to the reduced capital cost, as compared to traditional LWR power plants, SMR design and modular factory construction provide increased price certainty.

It is estimated that the cost per kilowatt installed for SMRs is higher than that of large-scale power plants, but, as with any new technology, that price will likely decrease as manufacturing processes become streamlined.

B. Scalability, Shorter Construction, & Mass Production

Shorter construction times and the potential for mass production provide a quicker revenue stream for owners of SMRs. With their scalability, SMRs allow for the generation of electricity (and, thus, revenue) incrementally. Revenue is generated immediately after each unit is completed, which allows for reduction of debt or retirement of debt prior to construction of the next unit. As the demand for a community's electricity increases, a utility could add another SMR to its modular facility without significant risk or financial burden. [11]

C. Risk Reduction

The smaller nature of SMRs affords simpler solutions. In addition to reduced complexity in SMR design, many SMR design features utilize proven technology and design methodology licensed and tested by the NRC. Some designs have the reactor vessel located in a pool of water and underground, thereby lessening the susceptibility to natural disasters such as earthquakes, tornadoes, and floods.

Many of the SMRs are designed such that they automatically shutdown should a problem arise. Holtec's SMR-160 relies on gravity, requiring no pumps or motors to circulate coolant; therefore, inherently and passively safe. If power is lost, the SMR-160 would not need electricity to safely shutdown the reactor and cool the core. [6]

Additionally, as SMRs are scalable, if one unit of the modular facility encounters an issue and needs to be brought offline, electricity and revenue can continue to be generated from the remaining units.

D. Site Selection

Many domestic power plants are beginning to shut down permanently, whether due to financial reasons or they are nearing the end of their licensed operation. Many nuclear power plants will begin retiring in the next couple of decades due to the expiration of the operating licenses. SMRs could be sited on these existing plots, taking advantage of the existing infrastructure, transmission lines, and connection to the grid.

E. Alternative to Power Uprate or New Units

Utilities are often looking to take advantage of existing power plant sites by generating as much power as possible from their units. Often times, utilities will accomplish this through power uprates and subsequent license amendments. Other times, though more infrequently, utilities will make plans for new, additional units and expand the existing site. SMRs can be a cost-effective alternative to new, large-scale units or power uprates that can require extensive modifications. SMRs also provide the potential to generate additional revenues due to dual-use through hydrogen production or water desalination, in addition to electricity generation.

VI SMR DEVELOPMENT STATUS, ADVANTAGES TO U.S. DESIGNS, AND DOMESTIC POTENTIAL

All four (4) of the U.S. designs are in pre-application design certification status. Design certification is expected 3rd quarter of 2014 for the B&W mPower SMR, 2nd quarter 2014 for the Westinghouse SMR, 3rd quarter 2015 for the NuScale SMR, and 4th quarter 2016 for the Holtec SMR-160. The DOE has allocated approximately $100 million of development funds to the B&W mPower and TVA SMR project in 2013. [2]

U.S. Designs have distinct advantages over non-U.S. designs that could enable the U.S. to lead in SMR development and deployment worldwide.

A. U.S. Technology and Equipment Reliability

- The U.S. has a proven record of equipment reliability from an extensive fleet of operating light water reactors.
- Access to U.S. nuclear technology, operations, and training.
- Utilities/Owners of U.S. designs would be afforded design bases, drawings, calculations, etc. to own and use.

B. Robust Strength of U.S. Regulatory License Process

- NRC licenses are globally considered to be the regulatory "gold" standard due to transparent and rigorous review process.
- NRC-licensed U.S. designs would have a distinct advantage in terms of commercialization worldwide.

C. Domestically Available Components and Modular Construction

- The small size of SMRs enables the preclusion of ultra-heavy equipment/components that often require import for large power reactors.
- Many components of SMRs, including steam generators, are comparatively small and can be easily manufactured in a relatively small facility.
- The majority of equipment/components, including the reactor vessel and other large forgings, can be supplied by domestic vendors, utilizing existing supply chains.
- Modular construction enables competitive bidding, mass manufacturing, shorter lead times, and shorter construction time.

D. Domestic Market Potentials for SMRs

- The near future licensing of SMRs provides tremendous momentum, precedent, and predictability in the future licensing of advanced reactors.
- SMR design, development, and construction will likely generate substantial interest in a new generation of academia and engineering through classroom, laboratory, and field experience.
- SMR construction will likely bring increased investment in domestic manufacturing capacity. Manufacturing is essential to innovation with a close link to a nation's economic health and national security. According to the Bureau of Economic Analysis, the investment of $1 in manufacturing generates $1.48 in economic activity, the largest contributor of the major economic drivers [12].
- Finally, and most importantly, the U.S. must pursue SMR design and construction in order to establish leadership and dictate design. According to the National Diet of Japan, in their official, independent report of the Fukushima nuclear accident, the international advances in knowledge and technology were disregarded by the Owners of the plants as they felt that the U.S. no longer led the forefront in the nuclear industry. Unlike similar industry segments, the nuclear industry is inexorably connected with international accidents projected on domestic fleets. Therefore, it is essential that the U.S. exerts design leadership to ensure the safety and viability in the future of nuclear energy. As Senator Lamar Alexander stated in the Senate Hearing 112-216 "An Examination of the Safety and Economics of Light Water Small Modular Reactors", the U.S. should pursue SMR design otherwise "the world will be deprived of our safety regime and our technology," and that arguably "the world needs our technology and our safety standards as much as we do" [13].

SUMMARY

SMR development discussions and subsequent consideration as viable options for the creation of zero-carbon production electricity have become common. Work is proceeding with multiple vendors to obtain U.S. Nuclear Regulatory Commission design certification.

SMR design attributes are desirable and offer the following benefits:

(1) All U.S. designs offer increased safety and security due to their below ground installation and passive cooling approaches.
(2) U.S. nuclear technology is proven, the most modern, and benefits from a robust regulatory and license process.
(3) All U.S. designs offer significantly reduced initial capital costs and development schedules.
(4) All U.S. designs offer opportunities to improve quality and product delivery since units will be manufactured in a controlled shop environment.
(5) ASME Codes and Standards will require modification or development of new Code Cases and Code Divisions to allow for alternative inspection intervals.
(6) Finally, SMRs will enable utilities, municipalities, and even industrial companies to become involved in the nuclear age with a relatively smaller financial investment.

ASME has a valuable, timely, and challenging opportunity to support development of SMRs by refining existing Codes and developing new Code Divisions as needed to ensure the realization of this very safe, non-polluting, and economically attractive nuclear generation technology.

NOMENCLATURE

American Society of Mechanical Engineers (ASME)
In-Service Inspection (ISI)
Light Water Reactor (LWR)
Megawatt (MW)
Small Modular Reactor (SMR)
U.S. Department of Energy (DOE)
U.S. Nuclear Regulatory Commission (NRC)

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