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Changing the World's Energy Future

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A Review of Remote Welding & Non-destructive Examination Technologies for the DOE Standard Canister

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The U.S. Department of Energy (DOE) manages a wide variety of spent nuclear fuel that poses a unique management challenge. To help address this challenge, the DOE Standard Canister (DOESC)—designed to remain sealed during handling, storage, transportation, and disposal—was conceptualized as a standardized containment vessel to accommodate DOE-managed spent nuclear fuel. Since 1999, several welding and examination processes have yet been independently developed for the DOESC's closure welds. However, neither the DOESC nor these processes have been realized in an operational capacity. This review paper seeks to present and compare previously developed DOESC closure weld, non-destructive examination, and repair processes and technologies. Specific processes developed for the Idaho Spent Fuel Facility, in preparation for the Yucca Mountain geological repository, and the recent Road-Ready Demonstration Project will be discussed. Specific focus will be given to how different operating constraints and the American Society of Mechanical Engineers Boiler and Pressure Vessel Code drove certain welding and non-destructive examination requirements. Historical DOESC welding and examination strategies will be assessed against current regulatory and Boiler and Pressure Vessel Code requirements. The comparison of welding processes, technologies, and DOESC designs presented in this review paper will inform further construction efforts for other commercial and DOE-managed spent nuclear fuel containments, including the DOESC.

Keywords: remote, welding, spent nuclear fuel, non-destructive examination, DOE Standard Canister, storage, transportation, disposal

I. INTRODUCTION

The United States (U.S.) Department of Energy (DOE) Standard Canister (DOESC) was conceptualized as a group of standardized spent nuclear fuel (SNF) containments for DOE-managed SNF (Figure 1)[1, 2]. The DOESC was meant to remain sealed during handling (i.e., after SNF loading and closure), storage, transportation, and disposal—without the need to repackage its contents.

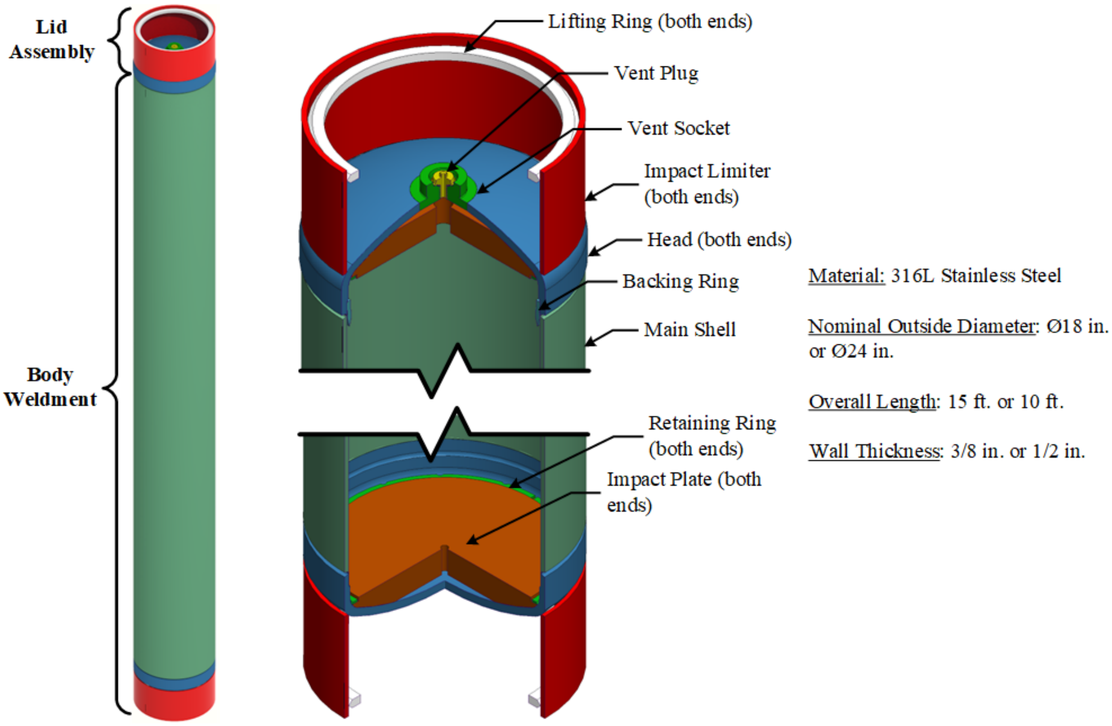
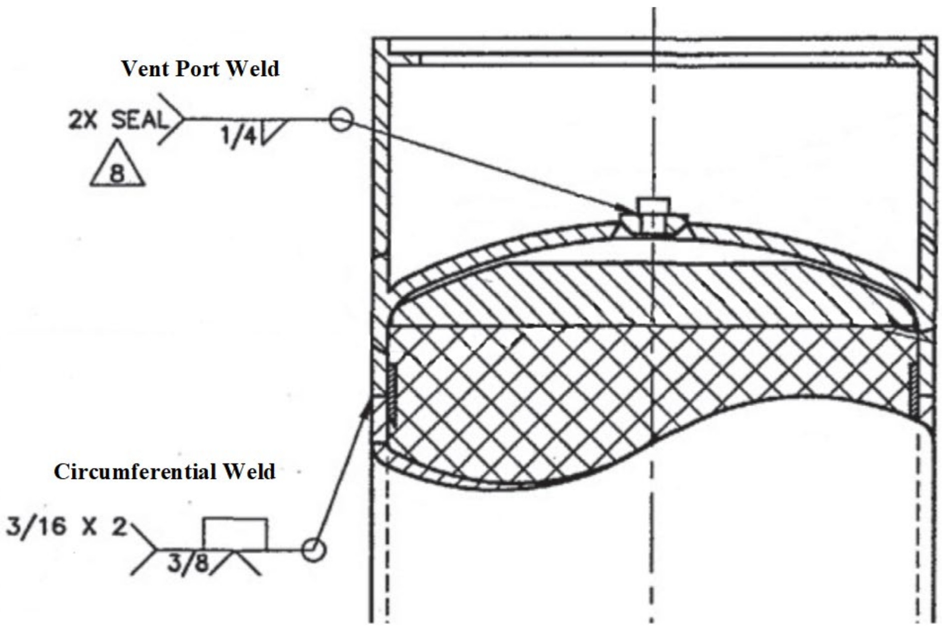


Figure 1: The Department of Energy Standard Canister (DOESC).

Similar to commercial SNF storage and transport canisters, the DOESC design includes two closure welds that are performed after the contents are loaded[3]. These closure welds are referred to as the circumferential weld and the vent port weld (Figure 2).



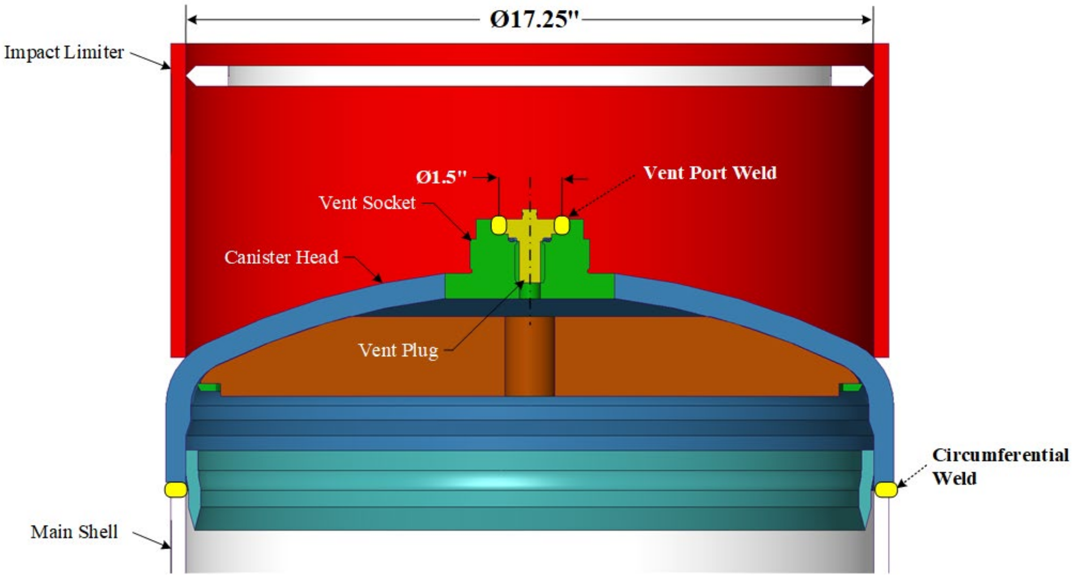


Figure 2: DOESC closure welds from NSNFP 1 design[2] (top) and RRDP design (bottom).

Since the DOESC was originally conceptualized, different welding, repair, and non-destructive examination (NDE) processes have been developed for the Idaho Spent Fuel Facility (ISFF), National Spent Nuclear Fuel Program (NSNFP), and recent Road-Ready Demonstration Project (RRDP)[4-6] (Figure 3).

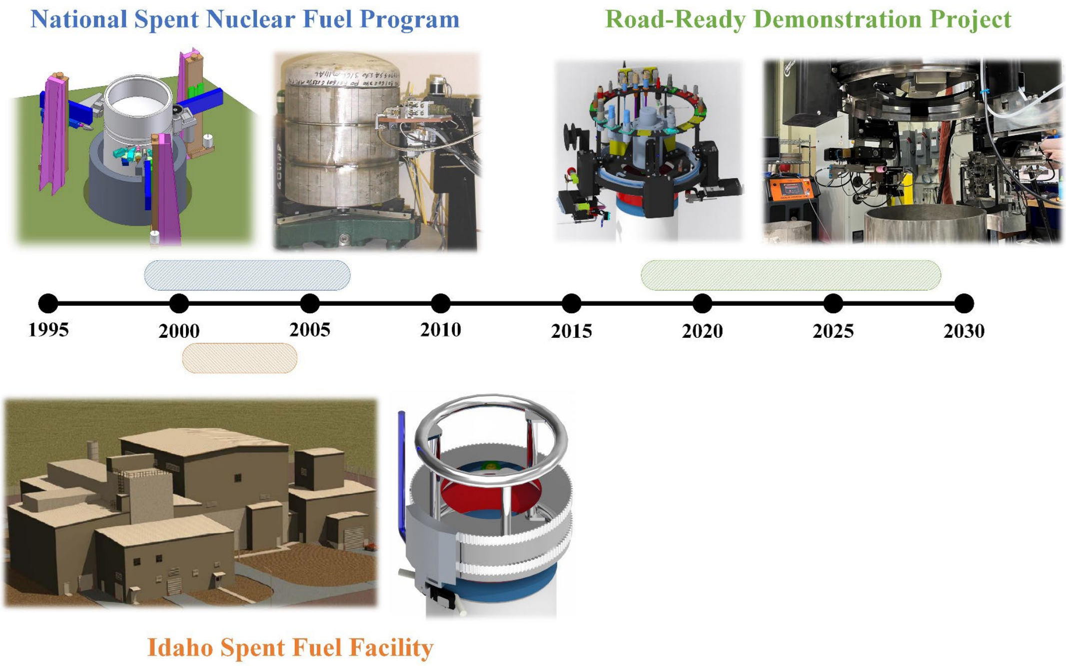


Figure 3: DOESC weld and NDE development timeline[5, 7].

Although commercial SNF canister construction has been reviewed elsewhere[3], the differences across these DOESC closure weld technologies and processes have not been documented. This review paper will compare these technologies and processes and discuss ongoing challenges to inform further construction efforts for other commercial and DOE-managed SNF containments.

Section I will provide a brief background on DOE SNF management, canister fabrication, and the recent efforts to package DOE-managed SNF for road-ready dry storage. Section II will describe the fabrication and inspection technologies for the DOESC used in the ISFF. Section III will review the DOESC canister closure system developed under the NSNFP. Section IV will present the canister closure system developed for the recent RRDP. Section V will compare these different closure weld technologies and discuss relevant design attributes and contemporary challenges. Section VI will conclude with a summary of the work, along with the path forward for DOE SNF canister welding and inspection technologies.

I.A. Background

Throughout the 20th century, the research, development, and commercialization of nuclear energy technology by the U.S. Atomic Energy Commission and DOE lead to the generation of SNF. This so-called 'DOE-managed SNF' is different from conventional light water reactor nuclear fuels in the U.S., often having different fuel geometries, fuel materials, and cladding materials[8]. The Idaho National Laboratory (INL) site manages 250+ types of DOE-managed SNF[9]. In pursuit of an integrated and long-term SNF management program for DOE-managed SNF, and for meeting the 1995 Idaho Settlement agreement, the DOE Office of Environmental Management (DOE-EM) created the NSNFP for research, development, and testing of treatment, shipment, and disposal technologies[10, 11]. One of the first challenges the NSNFP faced was the "aging" of DOE-managed SNF in containers originally designed for interim storage prior to reprocessing—not for shipment to a geological repository.

A significant portion of DOE-managed SNF lacked the rigor and pedigree of characterization that is typical of commercial SNF[12]. Retroactive characterization of DOE-managed SNF was determined to be unviable[13]. The DOE-managed SNF could therefore not be credited for performing a nuclear safety function. To address this challenge, the NSNFP conceptualized the DOESC as a sealed containment that could be credited for a containment safety function during handling, storage, transportation, and disposal (Figure 1)[1, 2].

The DOESC was rigorously tested and analyzed, including 30 ft. full-scale drop tests with surrogate fuel assemblies, baskets, and other internals[14]. These testing campaigns successfully demonstrated a robust design. However, the DOESC's fabrication and NDE strategy were outside the scope of these drop-testing campaigns. Shortly after these testing campaigns, the welding and NDE processes for the closure welds (Figure 2) were designed and developed for the ISFF (Section II) and NSNFP (Section III)[4, 5].

There have been many developments in SNF canister welding and examination since the DOESC closure weld systems were developed for the ISFF and NSNFP. Process development efforts have been made by Oak Ridge National Laboratory to carry out remote repair of welds for dry SNF storage systems[15, 16]. Recent advancements in quality assessment include integrating robust machine learning capabilities for in-situ quality and construction code compliance[17, 18]. Separate from the DOESC, DOE-EM developed the multi-canister overpack (MCO) as a containment for Hanford's N-reactor SNF. The MCO containment was constructed and certified (i.e., N-stamped) in accordance with the rules of Section III, Division 1 of the American Society of Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), including the first application of BPVC Code Case N-595 for its closure welds. The BPVC is a standardized construction code for pressure vessels, including SNF storage and transportation containments. A Gas Tungsten Arc Welding (GTAW) machine process was used for the MCO closure weld[19]. The MCO closure weld examination included liquid dye penetrant examination (PT) of the root, intermediate and cover weld passes. While the DOESC closure process has been developed to different degrees, none have been executed in an operational capacity similar to the MCO.

The current DOESC design has a circumferential and vent port closure weld that would be performed after the contents (i.e., SNF, basket(s), and shielding device(s)) are loaded (Figure 2). Similar to other SNF containments, these closure welds are primarily performed remotely[20]. The circumferential weld is performed first, which attaches the Ø18" Schedule 40S or Ø24" Schedule 80S pipe to the DOESC head, followed by a vacuum drying process of the DOESC's contents. The vent port weld is performed after backfilling the loaded DOESC with helium. These closure welds are critical to the DOESC's containment safety function. Special attention to the design, fabrication, examination, and failure mechanisms of these closure welds is required to assure adequate performance of this safety function[21].

The first generation of the DOESC design was completed by the NSNFP, which established Section III, Divisions 1 and 3 of the BPVC as the construction code of record for the DOESC (including N-stamping)[2, 22, 23]. The ASME BPVC contains rules for materials, design, fabrication, examination, and testing of welds of SNF storage and transportation containments, such as the DOESC's closure welds. Under the BPVC, both closure welds required volumetric and surface NDE. For volumetric NDE, ultrasonic examination (UT) was preferred over radiographic examination (RT) due to the possibility of high radiation fields during SNF loading[1]. No surface NDE technique was originally specified, although the ASME BPVC only permitted PT[23]. The DOESC closure welding, examination, and repair processes have been previously and independently developed, to different degrees, for ISFF[24], under the direction of the NSNFP[5], and most recently, for the INL's RRDP[6]. This paper seeks to comprehensively compare these different DOESC closure welding technologies and processes.

I.B. DOE SNF Road-Ready Demonstration Project

Given the wide variety of DOE-managed SNF at the INL site, one SNF management concept is to package the DOE-managed SNF at the INL site into dry, sealed canisters, which are then placed in onsite storage for later removal. The canisters and associated packaging are designed to facilitate SNF removal from the intermediate SNF storage facility and allow long-term dry storage before shipment to alternative storage or eventual disposal when an appropriate facility becomes available. This management concept is known as "road-ready dry storage" (RRDS)[25]. The RRDP is the most recent effort to use DOESCs, which aims to develop and demonstrate the designs, technology, processes, and regulatory framework for packaging DOE-managed SNF into a RRDS system[26] (Figure 4).

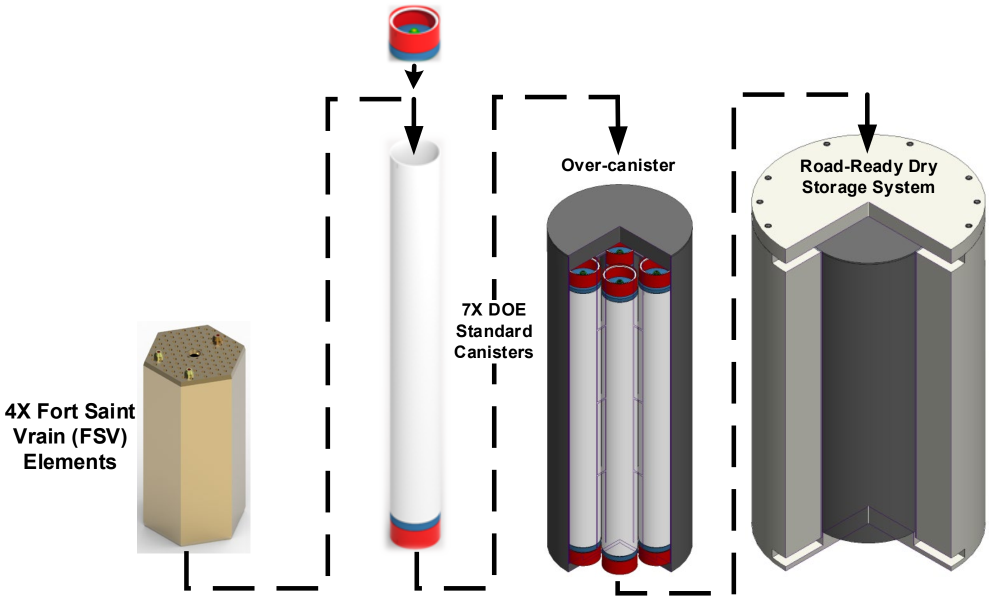


Figure 4: RRDP objectives schematic.

The specific type of SNF chosen for the RRDP is Fort Saint Vrain high-temperature gas-cooled reactor SNF currently stored at the INL's Idaho Nuclear Engineering Technology and Engineering Center (INTEC). This SNF will be loaded at INTEC into an ∅18" × 15 ft. DOESC[27, 28]. Multiple DOESCs will be loaded into a commercial welded over-canister[3] and transportable overpack for interim storage (Figure 4).

The RRDP's canister closure system, which includes welding and NDE equipment for the DOESC's circumferential closure weld, has recently been designed and developed[6], moving beyond the previous ISFF and NSNFP efforts. Vent port welding and NDE equipment design and development is still ongoing.

II. IDAHO SPENT FUEL FACILITY'S WELDING AND NDE SYSTEM

The ISFF was designed and licensed by the Nuclear Regulatory Commission (NRC) as a dry SNF interim storage facility at the INL[24]. Although never realized as an operational facility, the ISFF was intended to repackage DOE-managed SNF into DOESCs for interim storage prior to shipment to a repository. These DOESCs were to be loaded, welded, and inspected using a combination of automated and manual equipment and techniques.

Because construction rules for storage containments had not yet been defined in Division 3 of the BPVC during design of the ISFF, the ISFF established the DOESC's code of record as Section III, Division 1, Subsection NB of the ASME BPVC (1998 ed. With 2001 addenda), with Code Case N-595[29]. Because Subsection NB is a construction code for nuclear reactor pressure vessels, Code Case N-595 was required to modify requirements typical for reactor pressure vessels, such as replacing the hydrostatic pressure test of the closure welds with a helium leak test. The circumferential weld was classified as a structural weld subject to the ASME BPVC's fabrication and examination (UT and PT) requirements. The vent port weld was considered a seal weld and only subject to PT examination.

Each closure weld would have been performed via a manual or automated GTAW process. The circumferential weld was a full penetration butt weld formed by a single j-groove, while the vent port weld was an autogenous (i.e., a weld without filler) single pass weld [30]. The circumferential weld and vent port weld would be performed manually using a standard hand torch if the automated techniques were unable to perform the welds, or if repairs had to be made. Nominally, the circumferential weld was performed using a commercial orbital weld head equipped with a water-cooled 300A torch, remote-controlled wire feed nozzle manipulators, and live video feed of the weld zone[4, 31] (Figure 5). The wire feed manipulator mechanism would adjust the weld wire height relative to the electrode, moving the wire across the weld seam, and adjusting the wire's entry angle. The vent port weld was performed using a commercial orbital tube welder designed for joining tubes to tubesheet in high production applications[4] (Figure 5).

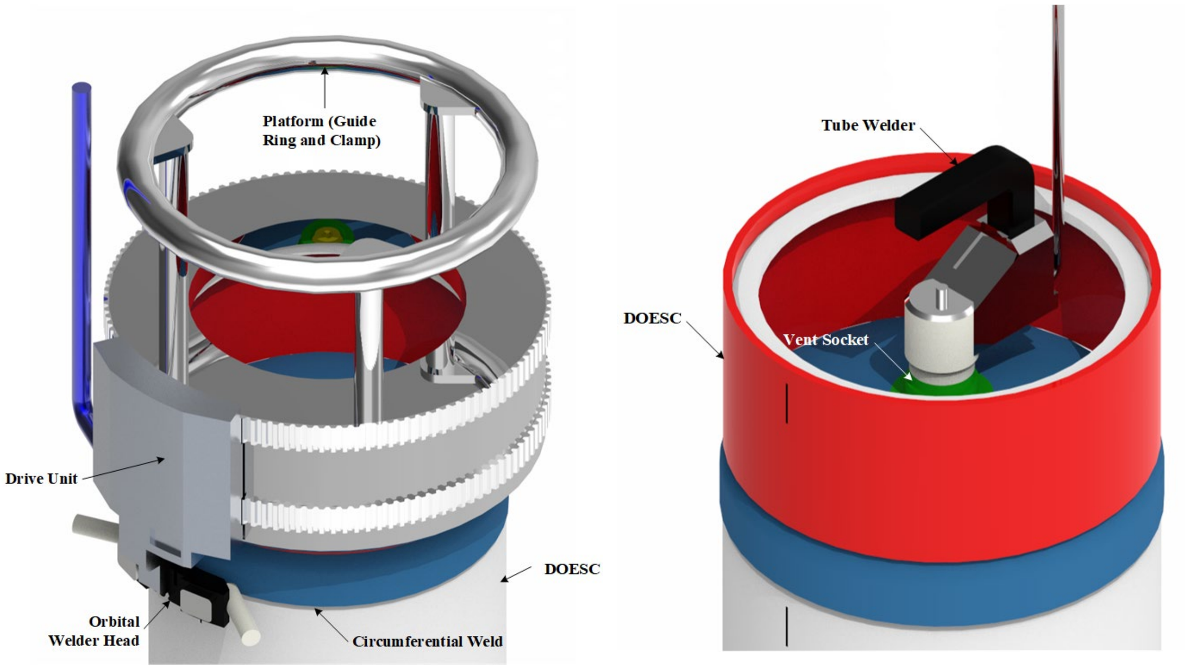


Figure 5: ISF circumferential orbital welder (left) and vent port tube welder (right). Adapted from[31].

This tube welder was equipped with a 150 Amps-DC torch, completely enclosed purge chamber, and pneumatic mandrel. The pneumatic mandrel engaged a centerhole drilled within the DOESC's vent plug. The tube welder then performed a single pass autogenous weld to join the vent plug to the vent socket.

PT of both the circumferential and vent port welds was performed manually using standard equipment (e.g., light meter, penetrant and developer sprays, cleaning materials). UT was performed for the circumferential weld either manually or with the drive unit from the orbital welder.

There is little information available on the development of the ISFF welding and examination processes for the DOESC. Development testing was planned for the UT equipment, with particular attention given to the distinct UT response from where the DOESC pipe's longitudinal seam weld intersects the circumferential weld.

The concept of the ISFF utilized commercial hardware, which likely would have been developed had the ISFF been constructed and operated. The phased array UT sensors, scanning technique, defect repair, or couplant recovery, were not designed in detail.

III. NATIONAL SPENT NUCLEAR FUEL PROGRAM'S CANISTER CLOSURE SYSTEM

After the ISFF received its NRC license, researchers from INL completed the detailed design and development of a canister closure system for remote and semi-automated welding, NDE (visual, eddy current (ET), and UT), and repair of the DOESC's circumferential weld within a hot cell environment[5]. This canister closure system was not designed to perform, examine, or repair the DOESC's vent port weld. Each of these circumferential weld subsystems were mounted on a rotating carousel that surrounded the DOESC (Figure 6). A stationary shield tube surrounded all but a small portion around the DOESC's circumferential weld. This shield tube provided a barrier for all subsystems to be safely stowed when not in use.

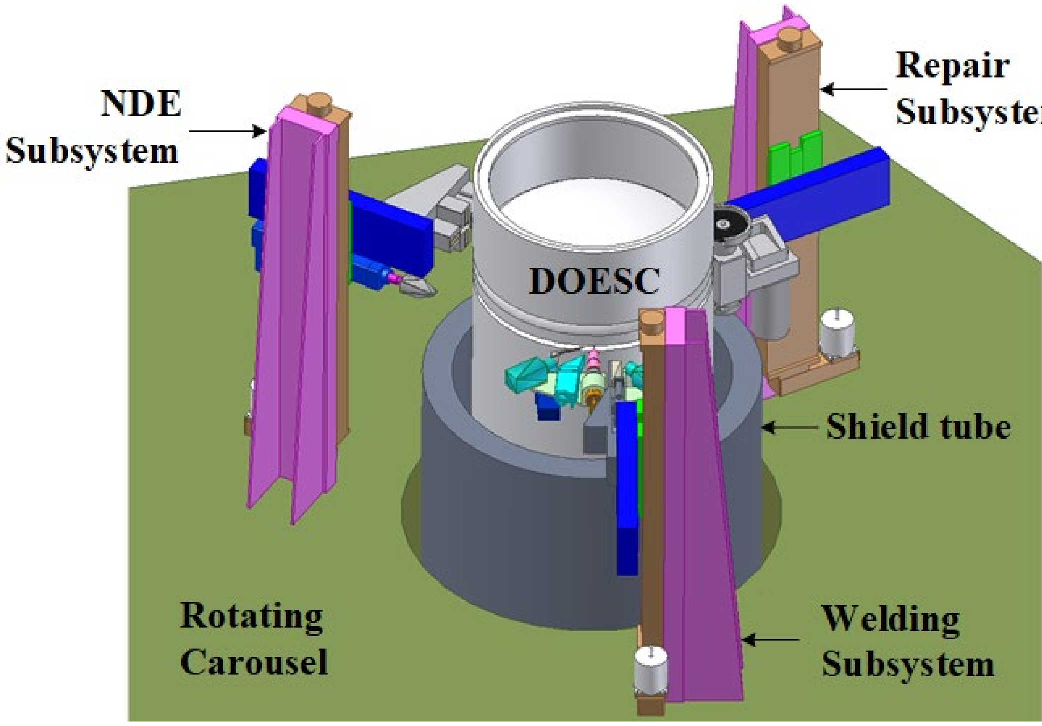


Figure 6: NSNFP canister closure system. Adapted from[5].

The custom weld head was equipped with a 300A, air-cooled GTAW torch, arc viewing cameras, laser seam tracker, wire feed positioner, and arc voltage control (Figure 7). Two arc viewing cameras were placed forward and aft of the torch that could observe both the joint while in low light and the weld pool during welding. The weld head's laser seam tracker was used for tracking the electrode with the seam and for visual examinations of the weld before initiating the ET and UT examinations.

Figure 7: NSNFP weld head (left) and repair grinding wheel (right) [5].

The repair subsystem removed defects in the closure welds created during welding and subsequently identified by the NDE subsystem. The restriction of cutting fluid in a hot cell environment and imprecision of arc-gouging led to grinding with a conventional grinding disc as the selected technique for making these repairs (Figure 7). Following a weld, the repair subsystem wire brushed the weld and heat affected zone to remove oxides produced during welding. If defects were discovered during examination, the repair subsystem would grind out the previous pass. The repair subsystem developed a cutting toolpath based on the NDE's determination of the defect's size and location within the weld.

The NDE subsystem included surface and volumetric examination according to the ASME BPVC. Given the requirement of remote operation in a hot cell environment, ET was selected as the technique for performing the surface examination. INL researchers acknowledged an ASME BPVC case was needed to permit ET in lieu of the PT that is required by the ASME BPVC. The ET subsystem used an array of probes that would contour over the weld and a separate array for the narrower repair cavity. Remote volumetric NDE was performed using two pairs of phased array ultrasonic transducer (PAUT) sensors. To identify the size and orientation of defects required by the ASME BPVC, one pair of sensors was oriented longitudinally (i.e., across from the weld seam), and the other pair was oriented circumferentially (i.e., in line with weld seam). An expert panel review was performed of the canister closure system, with a recommendation to move forward with development, especially regarding performance under the harsh radiological environment[32].

IV. ROAD-READY DEMONSTRATION REMOTE CLOSURE SYSTEM

As part of the RRDP, a new effort to design, develop, and construct a DOESC remote canister closure system was initiated. This canister closure system would specifically be operated at INTEC. The remote closure system is comprised of five platforms that interface with the top of the DOESC (Table 1). These platforms include modules capable of remotely performing, examining, and repairing the DOESC's circumferential and vent port welds. The design and development efforts for this canister closure system have been reported in detail elsewhere [6, 33, 34]. These platforms are compared against the ISFF and NSNFP technologies below.

Table 1: RRDP remote canister closure system weld platforms.

Platform Number	DOESC Closure Weld	Weld Equipment	NDE Equipment	Repair Equipment
1	Circumferential	Air-Cooled GTAW Torch	ET, PAUT	—
2		—	ET	Side Milling Cutter
3	Vent Port	Air-Cooled GTAW Torch	ET	—
4		—	PAUT	—
5		—	—	Annular Cutting Wheel

IV.A. Circumferential Weld Platforms

Two circumferential weld platforms have been designed and developed by INL and Liburdi Dimetrics® for use in the RRDP[6]. Platform number 1 (Figure 8) is designed to perform the circumferential closure weld and weld NDE. Platform number 1 is equipped with a semi-autonomously controlled, 600A, air-cooled GTAW torch, which can run a pre-programmed weld routine, or welding using manual user input. The circumferential welds are formed by a single u-groove butt joint and created by a series of four or six weld passes for Ø18” and Ø24” canisters respectively. A pair of ET and PAUT sensors are mounted to the platform to perform the surface and volumetric NDE. Platform number 2 (Figure 9) is designed to remove any potential weld defects in the circumferential weld using a pneumatically driven high-speed steel cutting wheel. A cutting wheel was selected because the finer debris could be collected easier than coarser debris from a grinding disc. A vacuum module is located adjacent to the cutting wheel to collect debris during the repair process. An ET sensor is also mounted to platform number 2 to perform ET after a weld repair.

These platforms are based around a frame and module architecture[6]. The center frame allows the platform to be pneumatically clamped to the DOESC lid assembly and has a rigging attachment point. The center frame is fixed. A rotating frame is attached to the center frame via a track and bearing system and is rotated around the track by a pinion gear. The welding torch, NDE sensors, and repair head are attached to the rotating frame on modules. The weld, ET, PAUT, and repair modules are equipped with servo motors that allow each end effector to be positioned around the weld groove, as well as high-definition cameras and lights to view the operations.

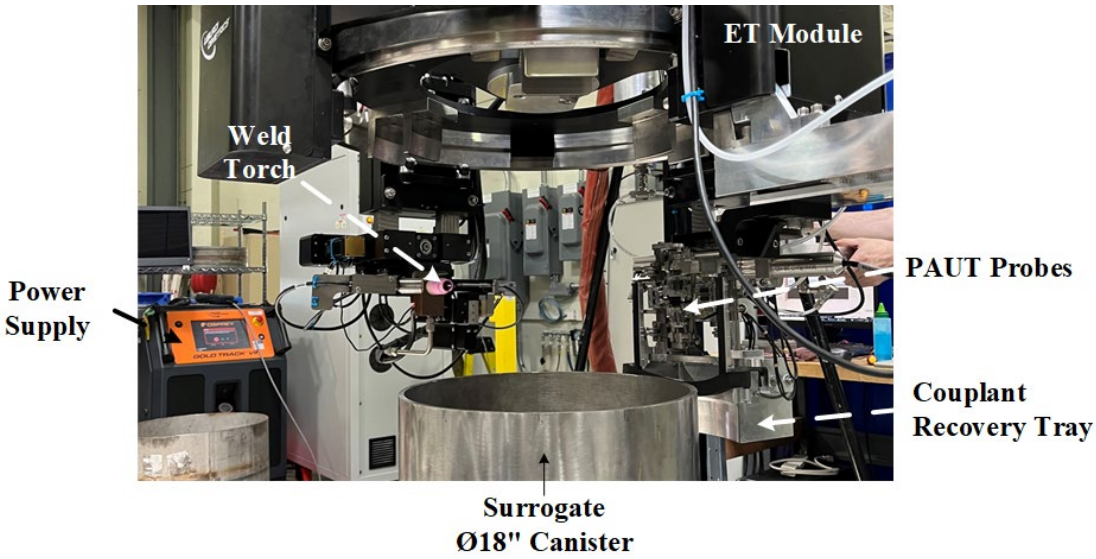


Figure 8: RRDP remote canister closure system platform number 1 (circumferential weld & NDE platform) being lowered onto a surrogate Ø18” DOESC.

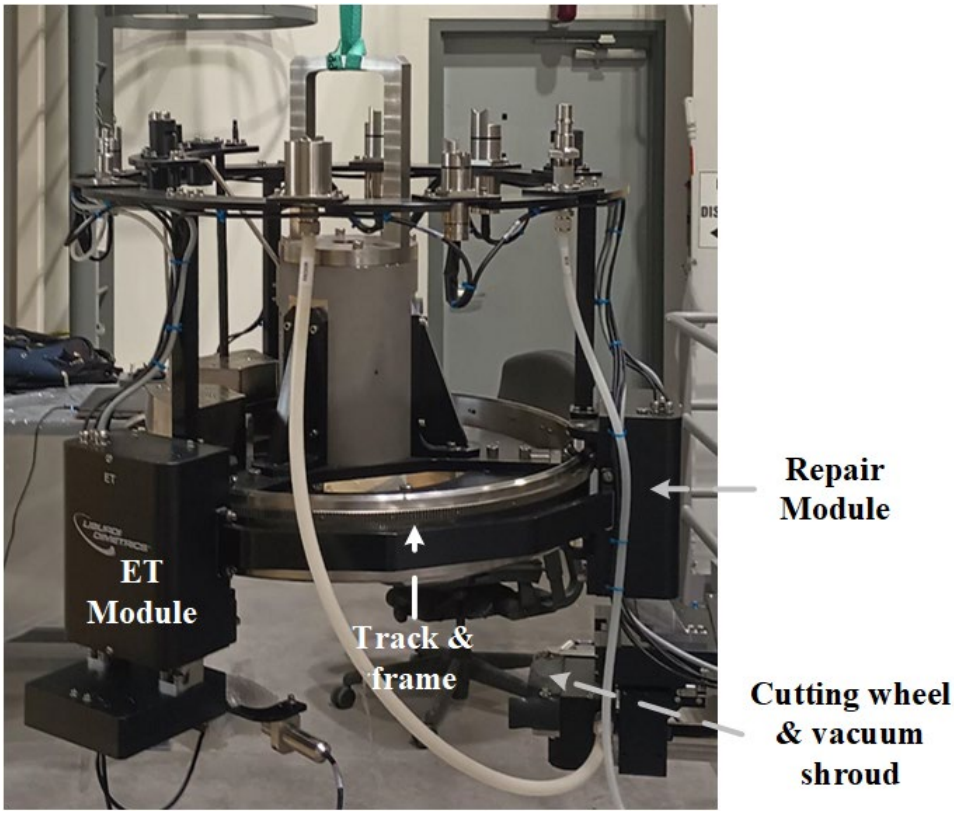


Figure 9: RRDP remote canister closure system platform number 2 (circumferential weld repair platform) suspended from rigging attachment point.

The weld platforms are powered and operated by a GoldTrack VII power supply, Liburdi Canister Closure Console (LCCC) cabinet, and Fireview user interface all developed by Liburdi Dimetrics®. This is the same power supply used for the MCO's closure weld[19]. The control console is equipped with screens that can display selected camera views, allowing the operator to observe and control platform operations in real-time. During the semi-automated welding process, the control console executes a pre-programmed welding routine with buttons for manual adjustments to critical welding parameters such as amperage, voltage, wire feed rate, and travel speed. For NDE and repair tasks, the operator directly controls the platform through the console, pausing and continuing NDE as needed.

IV.B. Vent Port Weld Platforms

The RRDP has also designed three platforms (numbers 3, 4, and 5) for the vent port weld (Table 1, Figure 10). Although detailed design and development is still underway, the platforms will clamp to the DOESC the same way and use the same Gold Track VII power supply, LCCC cabinet, and the Fireview user interface as platforms 1 and 2. In addition, the same weld torch, wire feed mechanism, cameras, PAUT probes, and eddy current probe array will be used. The vent port weld uses the same u-groove butt joint as the circumferential weld, but on a Ø1.5" seam within the confined space of the Ø17.25" impact limiter (Figure 2). This enclosed space reduces the available space for equipment, which is why the vent port weld requires three platforms.

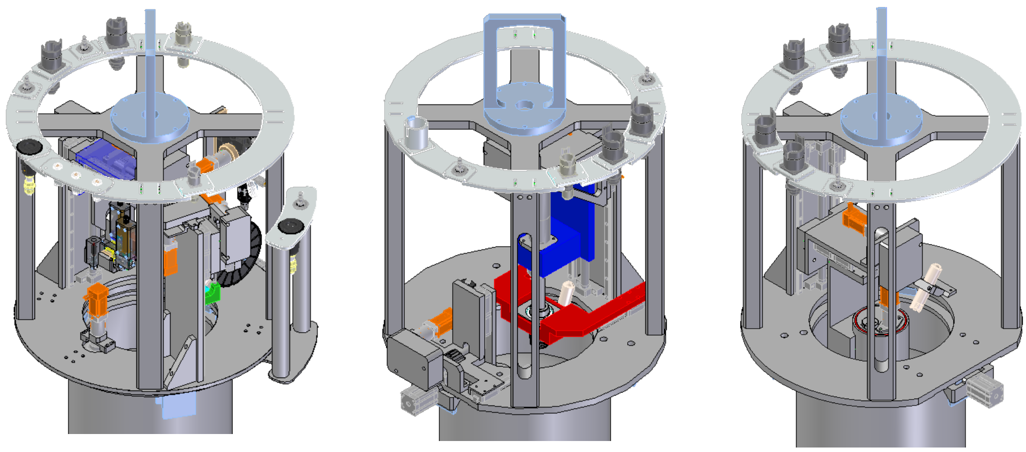


Figure 10: RRDP canister closure system platform number 3 (left), number 4 (middle), and number 5 (right)

Although generally the same equipment as platform number 1 and 2 will be used for the vent port weld, the vent port weld's geometry requires customized brackets and linkages for welding, NDE, and repair. Platform number 3's weld torch and eddy current probe array will be vertically oriented and include motorized vertical plunge and cross-seam motion relative to the weld. Platform number 4 will solely be for performing PAUT of the vent port weld. This PAUT module will require a customized couplant delivery and recovery system. The PAUT module design is of particular interest given the challenges with compression wave scanning and dry couplant previously reported for the circumferential weld[6].

Platform number 5 will utilize a custom annular cutting wheel sized to the vent port's u-groove. Unlike platform number 2, platform number 5 will only be capable of vacuuming debris as a separate step after the repair cut is made.

V. DISCUSSION

The circumstances under which the abovementioned welding and NDE technologies were developed somewhat influenced their design. The ISFF welding and NDE systems and NSNFP canister closure system were each developed when the Yucca Mountain geological repository was due to receive DOE-managed SNF packaged within DOESCs[35]. Given the decision to suspend Yucca Mountain construction, the recent RRDP focuses more on near-term storage, with suitability for eventual off-site transportation and disposal[26]. In addition, the only function of the DOESC in the ISFF license was for interim storage. The NSNFP considered storage and transportation requirements from the ASME BPVC[32]. Finally, although transportability of the DOESCs was an objective for the ISFF[36], no NRC certification of a transportation package was required for the ISFF. Similarly, no transportation package certification is currently required for the RRDP[37].

V.A. Differences

The abovementioned welding and NDE technologies utilize different processes and techniques to fabricate and examine the DOESC's closure welds (Table 2). These technologies are also designed to varying constraints, stemming from their operating environments and construction code.

Table 2: Comparison of DOESC welding and NDE techniques.

DOESC Program	DOESC Closure Weld	Volumetric NDE	Surface NDE	Weld Technique	Repair Technique	Code of Record
ISFF	Circumferential	UT	PT	GTAW (Manual & Automated)	Machining, Grinding, or Thermal Gouging	Section III, Division 1[29]
	Vent Port	None				N/A
NSNFP	Circumferential	PAUT	ET	GTAW (Semi-Automated)	Grinding Disk	Section III, Divisions 1&3[29, 38]
RRDP	Circumferential & Vent Port	PAUT	ET	GTAW (Semi-Automated)	Cutting Wheel	Section III, Division 3[39]

The ISFF was built and designed to specifically allow collocated personnel during DOESC closure in its canister closure area, which permitted manual operations. The NSNFP did not have a specific operating environment defined for its welding and NDE processes. When design of the RRDP's remote canister closure system began, a facility at INTEC had been identified, but operating constraints had not been defined in significant detail. Conservative constraints were given to moderator control and remote operation for the NSNFP and RRDP systems. One specific way these differences were manifested in the design is in the weld torch. While the ISF orbital weld torch is water-cooled, both the NSNFP canister closure system and RRDP weld platforms use air-cooled torches for compatibility in moderator-controlled environments. While the RRDP system did originally consider a 'dry couplant' PAUT wheel probe, the RRDP platforms now ultimately uses limited couplant (i.e., water) between the PAUT sensors and DOESC's closure welds to achieve the coverage required by the BPVC[6]. The PAUT module includes a couplant delivery and recovery system.

In addition to different technologies, the weld joint geometry of the circumferential and vent port welds differs across the ISFF, NSNFP, and RRDP DOESC designs (Figure 11). The original NSNFP DOESC used a v-groove circumferential pipe weld with an optional threaded plug for the vent port. Per the original DOESC design, the NSNFP assumed a threaded plug would be added, removed, and welded (if required) in a hot cell to form a containment to meet BPVC requirements[2, 32]. This design was adapted by the ISFF program, which utilized a single-sided j-groove circumferential weld—likely driven by its suitability to semi-automated welding. Additionally, the ISFF modified the vent port weld by inserting a metallic mechanical seal beneath the vent plug to temporarily seal it until the final vent port seal weld was completed (Figure 11). The RRDP has further modified both weld joints. The RRDP circumferential weld groove has a single-sided u-groove with a steeper angle than previous iterations to limit each weld pass thickness to 3 mm (0.12”). This weld pass thickness was selected to maximize coverage provided by ET, while the steep angle precludes the need for multiple weld stringers in each layer. The vent port weld utilizes an identical weld joint to the circumferential joint. Furthermore, the RRDP has modified the backing ring, which does not contact the root of the weld for more consistent PAUT inspection. This backing ring is only used as a barrier to protect the SNF from any slag potentially produced while performing the circumferential closure weld (Figure 11).

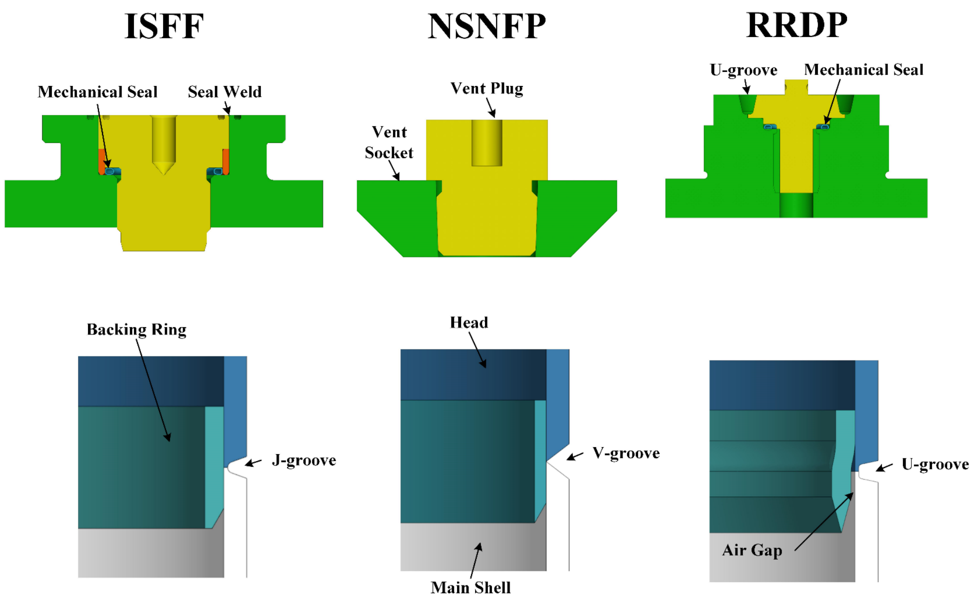


Figure 11: Weld joint geometry of ISFF[40], NSNFP[1], and RRDP DOESC vent port welds joining the vent plug to the vent socket (top) and circumferential closure weld joining the head to the main shell (bottom).

Construction code requirements are another driver for the technology and process differences. The ISFF classified the vent port weld as a seal weld. This placed it outside the scope of the ASME BPVC and removed the volumetric NDE requirement. PT was suitable for the ISFF because of the operating environment and its common application in weld NDE of commercial SNF containments[41]. As mentioned above, the optional threaded vent plug in the NSNFP DOES design required welding of its exposed threads to meet ASME BPVC requirements. The RRDP has classified the circumferential and vent port closure welds as structural welds[42], meaning both require volumetric (PAUT) and surface (ET) examination are required. The NSNFP welding equipment did not include equipment for performing or examining the DOESC's vent port weld.

V.B. Alternative DOESC Closure Weld Techniques

Although the ISFF, NSNFP, and RRDP design efforts selected GTAW as the closure weld process, other weld processes were considered during the RRDP design effort. In the category of arc welding, shielded metal arc welding (SMAW), gas metal arc welding (GMAW), and submerged arc welding (SAW) were potential candidates[43]. Friction welding (FRW) and friction stir welding (FSW) were two solid state welding processes that were also considered during the RRDP design effort[44].

Based on the radiation dose rates expected, the quantity of canisters expected during the RRDP, and the length of the circumferential weld, manual welding was considered unacceptable and automated, semi-automated, or at least mechanized weld application was required. SMAW does not generally accommodate these application methods, and available mechanized applications for SMAW such as gravity welding would not be usable in the DOESC orientation[43]. SMAW was thus quickly eliminated from consideration. GMAW has better applicability to automated application methods and can produce clean, repeatable welds and thus could be an acceptable weld process for the DOESC. However, the GMAW modes appropriate for structural welds, spray transfer and pulsed spray, produce excessive heat in the welding torch and require water cooling. Due to restrictions on neutron moderating materials in the work area requiring the use of a gas cooled torch, and with no other clear benefit versus GTAW, GMAW was removed from consideration. SAW was not given much consideration due to the weld positions, as implementing the flux bed around the circumferential weld and removing excess flux from the impact limiter around the vent port would be difficult, without any clear benefit versus GTAW.

Both FRW and FSW offered some advantages over arc welding processes. The heat and resulting stresses in the base metal can be less than that of arc welding, improving resistance to stress corrosion cracking. The welds are applied quickly in a single pass, resulting in reduced process time compared to a long, multi-layered GTAW weld. However, several requirements currently prevent implementing either of these processes for the DOESC. FRW for the DOESC lid would require very large holding and turning machinery, which would be difficult to incorporate in the designated INTEC workspace. Using FSW for the circumferential weld requires very high tool force against the wall of the DOESC with no internal support in that area, which would likely deform the canister. Although there is ongoing research to reduce these tool forces, FSW is currently not feasible[44]. For these reasons, both FRW and FSW were eliminated.

V.C. DOESC Closure Weld Code and Regulatory Compliance

The RRDS's storage function, which is its most near-term application, will be regulated by DOE[37]. The RRDS's specific transportation and disposal regulatory requirements for the RRDP are not yet defined. However, compatibility with the NRC's 10 CFR 71, "Packaging and Transportation of Radioactive Material" is expected[45]. The DOESC will only be a subsystem of the broader RRDS system for storage, transportation, and disposal. For the RRDP, the construction code of record for the DOESC has been established as Section III, Division 3[42]. Division 3 has not yet been endorsed by the NRC for storage or transportation containments[46, 47]. Commercial storage and transportation containments are typically constructed according to Section III, Division 1[48], while documenting alternative requirements in their system-specific safety documentation. Full compliance with the ASME BPVC is not a necessary condition to obtain a certificate or license for an NRC transportation or storage system. The development of the regulatory framework for RRDS is as notable a challenge as the engineering and development efforts associated with the RRDP. Defining the degree of DOE and NRC regulatory compliance is ongoing.

1. UT in lieu of RT in NRC transportation and storage containments

While compliance with the BPVC is not required, the NRC has identified certain BPVC Cases that are, and are not, approved for use in nuclear reactor, SNF storage, and SNF transportation applications[49, 50]. For the RRDP, DOESC construction applies UT in lieu of RT, as permitted by Division 3 of the BPVC[39]. However, the NRC does not approve of this substitution citing the UT technique's inability to examine the full thickness of the weld volume in austenitic stainless steels[49].

Austenitic stainless steel weld NDE is a unique challenge for the UT technique. The grain structure of austenitic stainless steel is coarse, particularly in the weld zone. This creates difficulty for ultrasonic beams to penetrate and focus in the as-welded state. This difficulty arises from increased attenuation and beam spread on the transmission path as well as the return path. The ultrasonic inspection industry has made progress tuning systems for these inspections using PAUT focusing techniques and software filtering to reduce the external noise displayed during inspection[51]. While the challenge is not eliminated, the resultant output is significantly improved over conventional UT technology and techniques.

For PAUT of the DOESC closure welds, acceptance is dependent on satisfying the specified ASME BPVC acceptance criteria[39]. The threshold for investigation of discontinuities in the weld zone is 20% of the full screen height reference level. For indications with amplitude greater than the investigative threshold, the inspector maximizes the response and measures the length of the indication to determine if the acceptance criteria have been met. Indications exceeding the reference level and maximum length, inclusive, are rejected. During evaluation, indications dispositioned by showing characteristics of cracks, lack of fusion, or incomplete penetration shall be rejected—regardless of length.

Although the RRDP is developing the DOESC's PAUT procedure according to the requirements of the ASME BPVC to address these issues, its acceptability in lieu of RT in an NRC-regulated transportation package needs to be addressed further.

2. ET in lieu of PT in NRC transportation and storage containments

The BPVC Code typically requires RT and PT for welds on austenitic stainless steel welds[39]. PT is commonly used in NRC and DOE applications[19, 41]. However, the anticipated high radiation fields and high volume of DOESCs anticipated for SNF packaging make a remote technique, such as ET, more attractive. For the RRDP, DOESC construction applies ET in lieu of PT, as permitted by BPVC Code Case N-748 under Division 3 of the BPVC[39]. The acceptability of code case N-748 has not been established by the NRC[49, 50].

VI. CONCLUSION

The closure welding and NDE processes of the DOESC have been designed and developed three separate times, to varying degrees. The DOESC design has also evolved along with the closure welding technology. Development activities were based on different operating environments and construction codes. The ISFF had defined constraints as a dry SNF storage packaging facility that permitted collocated personnel during closure, and its certification to the ASME BPVC. While licensed by the NRC as a dry SNF storage facility, certain details regarding the development and qualification of its welding, repair and NDE processes were not available. The NSNFP documented its development efforts of its canister closure system for the circumferential weld, particularly of the PAUT process. Even though the original DOESC design required the vent port weld to be performed after loading SNF, the NSNFP did not develop a weld or NDE process for it. The RRDP is currently developing and qualifying its weld processes for the circumferential and vent port closure welds.

While the design of the ISFF and NSNFP closure weld systems have concluded for the time being, the RRDP remote canister closure system is still being developed at the INL. The RRDP remote canister closure system platforms, especially for the vent port weld, need further development before deployment at INTEC. The repair and NDE functions of the circumferential weld platforms will continue on coupons and full-length DOESC mock-up(s) to qualify personnel and processes. The vent port weld platforms are still being designed but will also be subject to the same development and testing. These development activities will also include verification of their welding, NDE, and repair functions in a radiological environment. The circumferential and vent port closure weld platforms must reliably perform, examine, and repair (if necessary) the closure welds to the requirements of the ASME BPVC.

Separate from the development activities, confirmation is also needed on the acceptability of PAUT and ET NDE for any DOESC functions regulated by the NRC (e.g., transportation and/or disposal). The DOESC includes closure welds whose design and examination differ from typical commercial SNF storage confinements welds. The RRDP is currently applying a surface and volumetric NDE scheme that meets the requirements of the ASME BPVC, but further development may be necessary to address potential NRC concerns regarding use of PAUT and/or ET in nuclear reactor construction.

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