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**Safety Basis Development for the Tank Closure Cesium Removal (TCCR) Demonstration - 19596**

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## ABSTRACT

The Tank Closure Cesium Removal (TCCR) system has been installed at Savannah River Site (SRS) to supplement the existing salt waste treatment facilities and demonstrate the capability of ion exchange technology to remove Cs-137 from legacy waste. Developing the safety basis for the TCCR system and melding it with the documented safety analysis for existing facilities presented a unique challenge. Most notably, utilizing new methodologies to analyze new hazards resulted in unexpectedly high consequences and required more rigorous controls than had initially been anticipated. However, the integrated control set developed for the TCCR system should have minimal impact on its operating capabilities and will allow it to begin operating in 2019. This may lay the foundations for future utilization of similar systems at SRS and across the Department of Energy complex.

## INTRODUCTION

Savannah River Remediation (SRR) manages and operates facilities in the Liquid Waste System (LWS) at Savannah River Site (SRS) for the Department of Energy (DOE). The LWS consists of 51 underground waste tanks (eight of which are operationally closed and filled with grout), waste evaporators, treatment facilities, and solidification facilities such as the Defense Waste Processing Facility (DWPF) and Saltstone Production Facility (SPF). Using the LWS treatment and solidification facilities, SRR is continuously working to stabilize and disposition millions of liters of legacy waste stored in the remaining waste tanks. Solids removal and Cs-137 separation from waste are key steps in the stabilization of waste and ultimate closure of the tanks. To supplement the treatment capabilities of the current operational facilities, SRR has procured, installed, and is preparing to operate the TCCR system.

The TCCR system primarily consists of small modular skids that have been installed within the Concentration, Storage, and Transfer Facilities (CSTF), directly adjacent to underground waste tanks. The general layout of the system is displayed in Figure 1. Two dead-end pre-filters and four Ion Exchange (IX) columns make-up the main process components, all of which are shielded and housed in a modified sea-land container that acts as a secondary containment structure and process enclosure. The IX columns are each filled with approximately 500 kilograms of Crystalline Silicotitanate (CST) media that is designed to remove Cs-137 from radioactive waste. Flexible hose-in-hose transfer lines connect the TCCR processing equipment to Tanks 10 and 11.

Tank 10 contains approximately 750,000 liters of waste, primarily solidified into a contaminated mixture of nitrates, nitrites, and hydroxides of sodium. The hardened mixture, called salt cake, will be dissolved and mixed to liberate Cs-137 and other radioactive constituents from the matrix for processing. The resultant slurry will be pumped out of Tank 10 in successive batches, flowing through the TCCR pre-filters to remove insoluble particles and then through the IX columns to strip away Cs-137 and other dissolved radionuclides. After the slurry is processed through the pre-filters and IX columns, the effluent (decontaminated salt solution) will be sent to Tank 11. The decontaminated stream can then be further processed and dispositioned as grout at the SPF.

The TCCR process is designed to remove a total of 3.7E+15 Bq (100,000 Curies) of Cs-137 from the waste in Tank 10 over approximately 9 months. After the process is complete, each of the loaded IX columns will be disconnected from the process piping, removed from the enclosure with a crane, and transported by truck to the Interim Safe Storage (ISS) location over one kilometer away from the primary processing area. There, the IX columns will be placed in a safe configuration until further dispositioning can be performed.

During the design, fabrication, and installation of the TCCR system, SRR has worked to develop the safety basis for the new system and integrate it into the existing CSTF safety basis. This was a unique challenge given the novelty of the process technology, the variability of process conditions and performance, and the nature of the fixed priced contract by which the design and fabrication of the system was procured.

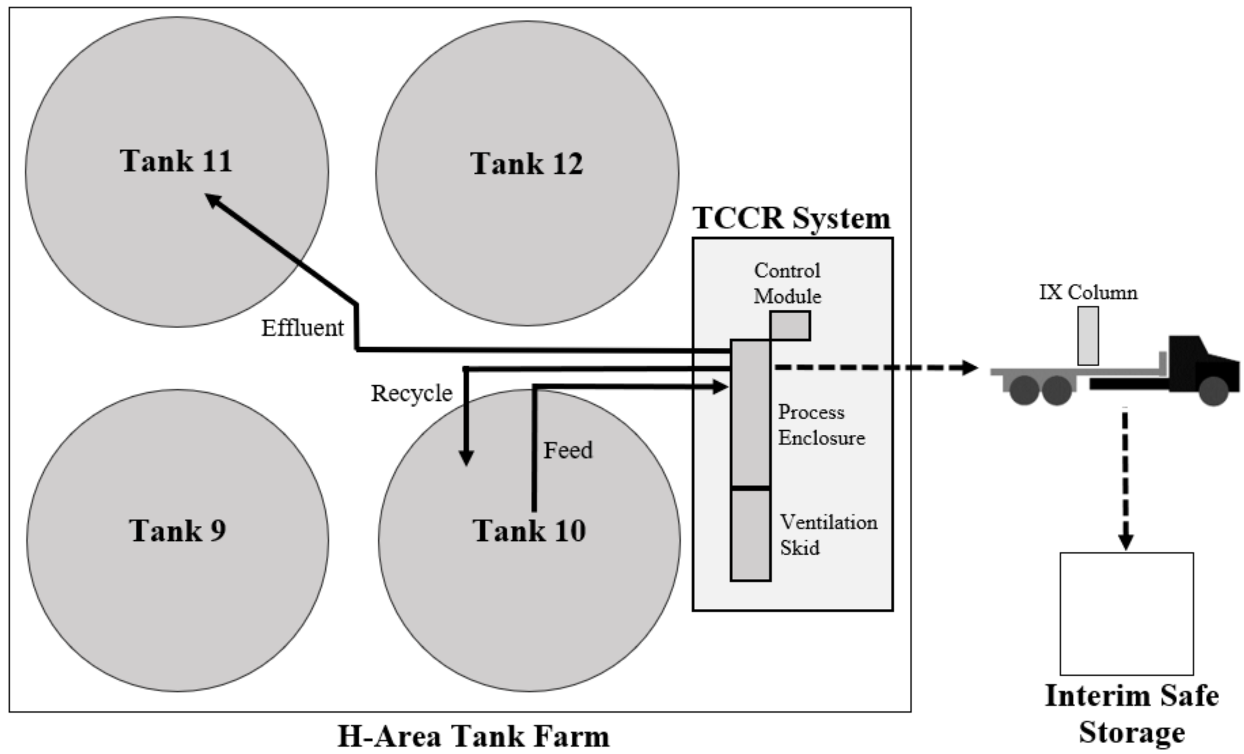


**Figure 1: TCCR Process Layout**

## DISCUSSION

### Safety Basis Strategy

A safety basis strategy [1] was developed in 2016 to document the planned approach for the development of safety documentation and related analyses to support the operational activities associated with the TCCR system.

The CSTF is classified as a Non-reactor Nuclear Facility (Hazard Category [HC] 2) and its current DSA was first developed in 2002 to meet the requirements of DOE-STD-3009-94 [2]. In the interim, the CSTF has been modified via multiple projects of equal or greater scale to the TCCR system. The safety bases for these modifications have been governed by DOE-STD-3009-94 and the resulting analyses have been successfully incorporated into the CSTF DSA. However, in light of newer DOE regulations, supplemental justification was required to treat the TCCR safety analysis in the same manner. Specifically, the scope of the TCCR project needed to be evaluated to determine whether it would be classified as a major modification to the CSTF and would hence be obligated to satisfy new safety requirements established in DOE-STD-1189 [3].

The requisite evaluation was documented during the initial design phases of the TCCR system; the evaluation highlighted the unique function of the TCCR system (to demonstrate the feasibility of IX technology for nuclear remediation) and its limited service life (approximately 9 months) as justification that the TCCR system did not constitute a major modification. This enabled the TCCR safety analysis to be performed and documented in a manner that would more readily integrate with the current CSTF DSA Specifically, the TCCR analysis was beholden to the same DOE-STD-3009-94 requirements and methodologies that are currently employed in the CSTF DSA. However, in preparation for upcoming renovations of the DSA, hazard and accident analyses for the TCCR system were performed using some updated methodologies (i.e., safety equipment design criteria, atmospheric dispersion modeling, hazardous chemical release analysis) associated with the requirements of new DOE standards.

Determination as a non-major modification was expected to be especially beneficial given the results of the initial hazard identification process for the TCCR system. Using preliminary designs and process inputs, the significant hazards in Table I were identified and evaluated. Provided that the TCCR system was fed qualified batches of salt solution and the process performed as designed, identified hazards were not anticipated to require new safety controls. Safe operation would instead be maintained by existing controls associated with the connected tanks and transfer systems. There would consequently be minimal impact to the CSTF DSA. As the project developed, this approach was impeded due to the complexity of the batch qualification process and the variability of the performance of the TCCR unit operations. This drove the hazard analysis to be performed in a much more conservative manner.

**TABLE I: Hazard Identification Summary**

| Hazard Type | TCCR Hazard | Bounding CSTF Hazard |
|---|---|---|
| Hazardous Material (Radiological/Toxic) | Tank 10 Dissolved Salt Solution | The concentrations of radiological and toxic materials in Tank 10 are bounded by those in other CSTF waste streams (i.e., sludge slurry sent to DWPF for vitrification) |
| | Loaded IX Media (CST) | N/A; see below |
| Flammables | Diesel fuel in portable generator or truck | Diesel generators provide back-up power at many locations throughout the CSTF |
| Explosives | Hydrogen gas generated from liquid waste | Hydrogen gas is analyzed and/or controlled in vessels, piping, and secondary containment structures throughout the CSTF |
| Kinetic/Potential Energy Sources | Motors/fans/pumps | Existing CSTF motors/fans/pumps are similar or equivalent to TCCR equipment |
| | Vehicles/<br>Crane loads | Vehicles and cranes are common in CSTF and TCCR is not uniquely vulnerable to vehicle impacts or crane drops |
| Natural Phenomena Hazard | Tornado/High Winds,<br>Seismic,<br>Wildland Fire | Existing administrative controls govern the shutdown/de-inventory of process equipment and vessels in CSTF transfer facilities prior to or immediately following an NPH event |

Using conservative inputs based on the total radiological inventory of Tank 10, the identified hazards were still anticipated to be bounded by those that had previously been analyzed as part of the CSTF safety analysis. As discussed in Table I, it was expected that these hazards would either not require controls or would be adequately addressed by existing administrative controls or safety structures, systems, and components (SSCs) of the same design or function as others throughout the CSTF. Although some unique hazards were also identified, they were also not anticipated to require unique controls.

The primary unique hazard identified for the TCCR process was the IX media (CST). Processing the Tank 10 salt solution results in the concentration of the Tank 10 radionuclides in the TCCR IX columns. Although IX media is used at other locations in the CSTF (e.g., waste tank cooling systems), the TCCR IX media is designed to be loaded with an amount of Cs-137 more than three orders of magnitude greater than has previously been analyzed for IX hazards. Furthermore, the loaded IX columns will be stored at the ISS location without the protection of a secondary containment structure. The increased loading and storage configuration of the IX media were anticipated to increase the risk of direct exposure to the facility worker; but more significantly, they were also anticipated to increase the risk that a release would impact other onsite personnel and the offsite public. Conservative scoping analysis of this hazard resulted in consequences that exceeded the onsite Evaluation Guidelines (EGs) but did not challenge the offsite EGs. Hence, safety controls functionally classified as Safety Significant (SS) were expected to be necessary to protect onsite personnel from new IX hazards. These hazards would not, however, require Safety Class (SC) controls for public protection. Additionally, like those hazards enumerated in Table I, it was expected that IX hazards would be adequately addressed by existing administrative controls or by SSCs of the same function as others throughout the CSTF.

Another unique element of the TCCR safety analysis was the methodology by which chemical hazards were analyzed. The methodology, described in DOE-STD-1189-2008 Appendix B, stipulates that concurrent releases of different hazardous chemical substances and their combined effects should be analyzed if a plausible release scenario exists. Currently, the CSTF safety basis only analyzes the effects of a single bounding chemical species in a release. For the vast majority of potential accidents, the safety basis is therefore able to demonstrate that chemical releases either (1) are not significant enough to challenge or exceed chemical EGs or (2) coincide with radiological releases that are bounding and would otherwise inform the selection of safety controls. This validity of this argument is also partly supported by the conservative radiological concentrations in the waste streams utilized in hazard and accident analyses. Radiological consequences are hence conservative and can bound other hazards. Given the relatively low radiological concentrations in the Tank 10 salt solution (when compared to bounding streams in the CSTF) and the conservative nature of the new chemical analysis methodology detailed in DOE-STD-1189-2008, it was anticipated that chemical hazards would play a greater role in TCCR safety basis development than had previously been observed for the CSTF. Once again though, it was not anticipated that the controls for chemical hazards would vary significantly from those that were already in place throughout the CSTF.

## Hazard and Accident Analyses

Initial hazard evaluations and scoping calculations were completed to inform the final design of the TCCR system. Formal hazard and accident analyses could not be completed at that time due to uncertainty in the behavior of the IX media and consequently in the final flowsheet and process streams. To be able to adjust to ongoing developments and forthcoming information, the final hazard analysis [4] and accident analysis [5] were performed concurrently, with new iterations of each analysis process informing the other.

Hazards were identified and analyzed in the following locations/processes in the TCCR system (see Figures 1 and 2 for reference):

1. Transfer lines from Tank 10 to the TCCR enclosure and from the TCCR enclosure to Tank 11
2. Process piping, pre-filters, and resin trap within the TCCR enclosure
3. TCCR enclosure ventilation system
4. IX columns while connected to the process within the TCCR enclosure
5. Transportation of IX columns to ISS
6. Storage of IX columns at ISS

Events which might affect multiple components within and around the TCCR enclosure (e.g., transfer lines, process piping, IX columns) were also analyzed.

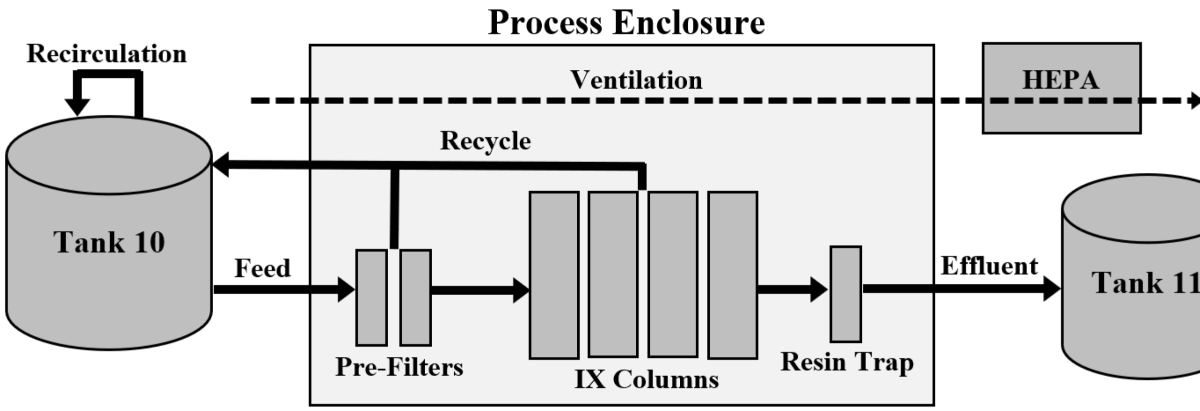


**Figure 2: TCCR Process Flow Diagram**

The general hazards and associated onsite consequences (radiological and chemical) for these locations/processes are summarized in Table II. No hazards were analyzed to exceed the offsite EGs, as predicted by preliminary scoping calculations. External hazard events and natural phenomena hazard (NPH) events were analyzed in addition to those listed in Table II; however, these events induced accidents that were commensurate with those in the table.

For both radiological and chemical hazards, those initiators linked to high temperatures were of greatest concern. For radiological releases from IX columns:

If an event were to occur at nominal temperatures (e.g., spill of loaded IX media and salt solution from a column), the concentrated radionuclides loaded on the columns would remain bound to the IX media and would not be made airborne in significant quantities. At high temperatures (i.e., above the boiling point of water), the behavior of the IX media is not well understood. In these conditions, it could not be assumed that the radiological material loaded onto the columns would remain bound to the IX media. To determine conservative radiological consequences for these accidents, the analysis instead assumed that all the radioactive material that could potentially be loaded onto the media could also be desorbed. Therefore, a much larger fraction of the loaded radionuclides could be made airborne for an equivalent release mechanism that is expected to occur at a higher temperature.

For all chemical releases:

At nominal temperatures, all the chemicals in each waste stream were analyzed in the same manner. The release fractions and respirable fractions of each chemical was consistent with the release mechanism (e.g., spill, explosion). At high temperatures, the contributions from the more volatile chemical species were expected to become more significant. To determine conservative radiological consequences for these accidents, 100% of each volatile chemical in the affected waste stream was assumed to become airborne and respirable (i.e., no reduction from airborne release fractions or respirable fractions).

These analysis methodologies resulted in much higher consequences for high temperature events.

**TABLE II: Hazard and Accident Analyses Summary**

| **Location/Process** | **Hazards** | **Onsite Consequences** | |
|---|---|---|---|
| | | **Radiological** | **Chemical** |
| Transfer Lines | Fire, Explosion, Loss of Containment, Direct Exposure | < EG | < EG |
| Process Piping and Equipment within Enclosure | Fire, Explosion, Loss of Containment, Direct Exposure | < EG | < EG |
| Enclosure Ventilation | Fire, Explosion, Loss of Containment | < EG | < EG |
| **IX Column within Enclosure** | Fire, Explosion | < EG | < EG |
| | **Loss of Containment** | **> EG** | < EG |
| **IX Column during Transport** | Explosion, Loss of Containment | < EG | < EG |
| | **Fire** | **> EG** | < EG |
| **IX Column at Interim Safe Storage** | Explosion, Loss of Containment | < EG | < EG |
| | **Fire** | **> EG** | < EG |
| **TCCR Processing System (Enclosure and Surrounding Equipment)** | Loss of Containment | < EG | < EG |
| | Explosion | Not Credible | |
| | **Fire** | **> EG** | **> EG** |

From the information in Table II, it is clear that the most significant hazards were associated with releases from the IX columns. The IX media stored in the columns was designed to separate and concentrate the radioactive material (specifically Cs-137) from thousands of liters of Tank 10 salt solution; hence, a total release from IX columns results in high radiological consequences. Furthermore, as the IX column are self-heating and can become pressurized, a vessel failure could result in a flashing spray release with a large airborne release fraction. The IX columns were assumed to fail from large external forces and from high internal pressures, despite their stainless-steel construction and the lead shielding cask in which they are encased.

Analyzed events which did not affect the IX media tended to produce much lower radiological consequences. The radiological compositions of the other waste streams (salt solution feed, filtered recycle, and decontaminated salt solution effluent) were more benign and did not result in significant radiological consequences when released.

Equivalent compositions of toxic chemicals were considered for all waste streams (inclusive of IX media streams). Chemical hazards generally did not result in bounding consequences or inform control selection for the analyzed events. The exception to this was a large fire affecting the whole TCCR processing system. In the absence of combustible loading controls, a fire with sufficient fuel was assumed to boil-off thousands of liters of salt solution within the TCCR enclosure. Given the large volume of low level waste affected and the contributions of the volatile chemicals in the TCCR waste streams, the chemical consequences bounded the radiological consequences during the large fire event. However, radiological consequences still exceeded onsite EGs for the event, and chemical hazards did not independently inform safety control selection.

**Administrative Controls**

The high-consequence hazards in Table II are most often predicated by either (1) a failure of batch qualification process and subsequent overloading of the IX columns or (2) the introduction and ignition of a large combustible load to the TCCR system. These initiators could both cause the IX columns to overheat and/or become pressurized, potentially resulting in a flashing spray release with high radiological and chemical consequences. Control of the identified accident initiators could not be performed independently by safety SSCs, and administrative controls were developed to ensure safe of operation of the TCCR system. Some hazard mitigation was provided by existing administrative controls in the CSTF, such as the Fire Protection Program, Radiological Protection Program, and Emergency Response Program. However, several new safety functions not already performed by CSTF controls were also deemed necessary.

TCCR Operations Program

To minimize the impact to the structure of the CSTF DSA, the various administrative control functions were consolidated to be performed by a single specific administrative control. This SS control, termed the TCCR Operations Program, governs the batch qualification process, liquid transfers within the TCCR system, transport and storage of combustible material, and preparation of loaded columns before transport to ISS. The program also ensures that supporting SSCs are functional throughout during the lifetime of the process (see next section).

Given the complexity of the batch qualification process, most of the controls in the TCCR Operations Program are associated with qualifying the feed material and preventing transfers and other activities that could invalidate the predicted loading on the columns. Before waste is fed to the process, batch qualification is performed by direct measurement of the performance of the IX media in the prepared salt solution of Tank 10. Loading on the media could be affected by the composition and temperature of the salt solution, both of which must be protected by the TCCR Operations Program. Attributes which perform these functions are summarized below. In concert with the SSCs in the next section, successful implementation of these requirements precludes many of the high-consequence hazards postulated within the TCCR enclosure.

1. Transfers of waste to Tank 10 are prohibited.
2. Recirculation of Tank 10 and transfers to the TCCR process are prohibited during the batch qualification test.
3. The Tank 10 temperature limits are established by the batch qualification test and verified every 7 days and immediately prior to transfers to the TCCR process.
4. Non-waste liquid additions (e.g., water) to Tank 10 are limited to less than approximately 11,000 liters following batch qualification.
5. A flush of the lead IX column is performed before operating IX columns in series (lead-lag) configuration.

Following processing, the TCCR Operations Program also stipulates that the liquid inventory of the IX columns is reduced as much as possible. This minimizes the continued activity of adsorption-desorption mechanisms and "locks" the radioactive material onto the IX media. In concert with the SSCs in the next section, this action precludes the release mechanisms postulated during storage of the IX columns at ISS.

**Safety Structures, Systems, and Components**

The TCCR system was procured to meet design requirements that conform to the standards mandated for SS SSCs. This level of procurement was selected based on the results of the initial hazard evaluation, which projected that some hazards may exceed the onsite EGs. However, the final hazard analysis was not complete at the time of procurement, the safety SSCs that were eventually selected had not been identified, and the functions of said SSCs had not been developed. As the TCCR system was procured via a fixed price contract, the qualification of the safety SSCs and the associated design changes were not included as part of the procured design. These activities were instead performed by SRR during the installation of the procured system.

The most pertinent safety SSCs and their functions are discussed below. Most of the SSCs act concurrently with TCCR Operations Program (see previous section) to prevent or mitigate the significant hazards in Table II. A non-safety SSCs is also discussed given its significant effect on the unmitigated analysis.

IX Column Water Jacket

The design of the procured IX column assemblies included an annular space between the column vessel and the surrounding lead shielding cask (see Figure 3 for reference). Initially, this annular space was intended to be left empty, with natural air convection within the annular space providing marginal cooling of the IX column. For the design loading of Cs-137 onto each column, air cooling would have maintained the temperature of the columns below approximately 100°C even when no liquid was flowing through the column. However, equilibrium testing of the IX media showed that the loading on the columns could far exceed the design value. With the procured air-cooling design, a loaded and isolated column could overheat, pressurize, and initiate a high-consequence event.

To address this vulnerability, the drain valve and other penetrations in the annular space were sealed and the annular space was filled with water. A fill pipe was also designed and installed to allow for additional water to be added intermittently to account for losses from evaporation. Analysis of this new design was performed in X-ESR-H-00924 [6]. The “water jacket” increases the thermal conductivity across the radius of IX column assembly, reducing the temperature in the column. Provided a qualified feed of Tank 10 salt solution, this maintains the temperature of each column below boiling, preventing high-temperature/high-pressure IX column releases.

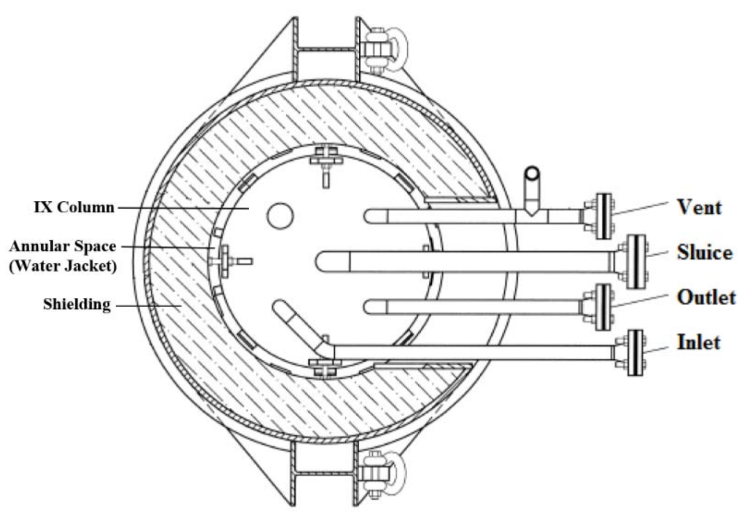


**Figure 3: IX Column Configuration**

The IX column water jacket and rigid fill pipe are both qualified SS SSCs. The water jacket is credited during normal operations as well as for both tornado/high wind events and seismic events. The jacket is designed to meet NPH Design Category 3 (NDC-3) criteria. The fill pipe is not credited during NPH events as its function is not continuous (i.e., water jacket is filled infrequently). The TCCR Operations Program requires that each water jacket is filled to overflow approximately once a year.

Three-Way Valve

Flow from the Tank 10 transfer pump is controlled by a three-way valve. Flow can be directed to the TCCR process or to the Tank 10 recirculation lines. Inadvertent transfers could either produce a release or invalidate the batch qualification and disrupt subsequent transfers. The valve is designated SS to isolate flow from the non-intended transfer path. The valve is credited during normal operations and seismic events. It is designed to meet NDC-3 criteria.

IX Column Flexible Hoses

Within the TCCR enclosure, the IX columns are connected to the process piping by non-metallic flexible hoses. These hoses are not safety but are a design requirement incorporated into the unmitigated hazard and accident analysis. Given their non-metallic material of construction (e.g., rubber), they are expected to fail if a large fire were to occur within the process enclosure. This failure would provide pressure relief of the IX columns if pressure were to accumulate in the high-heat environment. Without other releases occurring simultaneously, the resulting accident (spill or boil off of IX column waste) would not have high consequences.

IX Column Passive Vents

Within the TCCR enclosure, the IX columns are connected to the process via inlet and outlet piping as well as a third independent vent path (note that the sluice line has a blind flange installed throughout TCCR operation). Under normal operating conditions, these paths would provide relief of any pressure that may build within the column. Once the columns have been disconnected from the process, these vent paths must be sealed or filtered to prevent releases during transport and storage at ISS. Provided successful implementation of the TCCR Operations Program, there would be limited liquid in the columns and pressure accumulation due to water vapor would be limited. However, without sufficient pressure relief, internal radiolytic heat or external heat from a fire could cause the columns to become overpressurized and fail to produce a release.

To preclude this hazard, a single SS passive vent will be installed on each IX column immediately after it has been disconnected from the process. This filtered vent path will either provide adequate pressure relief such that no pressure accumulates in the column or it will blow-out and result in a low-consequence event. The SS passive vent is not credited during NPH events. Note also that the SS passive vent is in addition to a second non-safety vent path that was previously included in the design.

## CONCLUSIONS

The TCCR system has been installed in the CSTF at SRS to supplement the current salt waste processing facilities of the LWS. Safety analyses indicate that hazards associated with the operation of the TCCR process may impact personnel at SRS. Most notably, failures of the IX columns at high temperatures and high pressures will produce a flashing spray release of a concentrated radiological stream and result in high consequences. An integrated control set has therefore been developed and is being implemented to support the safe operation of the TCCR system. The TCCR Operations Program, in conjunction with limited safety equipment, will prevent significant radiological and chemical releases without limiting the processing capabilities of the system. This will enable the TCCR system to begin operating in 2019 and may lay the foundations for future utilization of similar systems at SRS and across the DOE complex.

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