Safety Improvement of a Tritium Removal System through a Gas Expansion Turbine

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Abstract: Tritium is a radioactive isotope of hydrogen, produced in heavy water, during CANDU reactor operations by neutron absorption. The tritium removal facility is used to extract tritium from the heavy water on a continuous basis and concentrates it in preparation for immobilization and storage. There are several internal and external hazards associated with the operation of a Tritium Removal Facility (TRF), such as fires, onsite transportation accidents, exposure to radioactive materials, and the release of radioactive substances. The Tritium Immobilization System (TIS) is designed to process batches of tritium gas within specialized process equipment. Due to the nature of these operations, internal surfaces are subject to potential tritium contamination. To mitigate risks, the system is contained within inert gas-filled gloveboxes, valveboxes, and airlocks. This containment strategy prevents the formation of flammable or explosive mixtures and ensures that radioactive tritium gas is not released into the environment. This paper conducts risk analyses for the TRF Cryogenic Refrigeration, Tritium Immobilization and Air Cleanup Systems, which include Event Tree Analysis (ETA) and Fault Tree Analysis (FTA), system reliability, human reliability analysis and risk estimation.

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1. INTRODUCTION

Demand for tritium is growing as it is a critical fuel for nuclear fusion – however; the operation of a tritium removal facility presents several hazards, including fire, exposure to radioactive materials, hydrogen-induced explosions, and the release of radioactive substances from the Tritium process and auxiliary Systems i.e. *Low and High Tritium Distillation columns (LTD and HTD)*, *Tritium Immobilization System* (TIS) and *Air Clean-Up System* (ACS). Tritium is a very small molecule and has the ability to absorb into process piping holding it presenting a surface contamination hazard. This tritium will slowly leak out of the metal, i.e., "outgas". Outgas will be in the gas and oxide forms of tritium. By mixing tritium with a chemical that emits light in the presence of radiation, a continuous light source is made. The extracted Tritium is sold for a variety of industrial applications (e.g., emergency exit signs, aircraft instrumentation panels, etc.) and upon decay; it is sold as Helium-3 for many other applications, including fusion reactors. This paper presents a description of the Tritium removal process; *Tritium Immobilization System* (TIS), ACS control system and containment bypass release due to rupture disk or process valve leakage to the environment. The rest of this paper is organized as follows: Section 2 describes the Cryogenics Refrigeration system (CRS) operation; Section 3 covers system Event Tree and Fault Trees modelling; Section 4 discusses CRS Operation Reliability Improvement model to estimate Operator Response affectivity; Section 5 discusses Risk Importance Measures for basic events; Section 6 recommendation for system reliability improvement; and Section 7 concludes the paper.

2. SYSTEM DESCRIPTION

2.1 TRF Cryogenics Refrigeration system (CRS)

After several years of operation of a CANDU reactor, tritium in the moderator reaches a level, which may result in potentially high occupational exposure from tritium during maintenance and servicing. Since tritium oxide is approximately 20,000 times more hazardous radiologically than elemental tritium; separation, concentration and subsequent storage of tritium is done in its elemental form. Tritium is extracted from tritiated heavy water vapour by way of isotope exchange in contact with depleted deuterium gas aided by a catalyst. The tritiated gas is subjected to low temperature distillation to separate the hydrogen isotopes - deuterium, tritium and traces of protium. The simplified flow diagram of Darlington TRF is shown in Figure 1. A Vapour Phase Catalytic Exchange (VPCE) process is used to remove tritium from heavy water [2, 3]. The VPCE utilizes steam generated from any running reactor units to super-heat the tritiated heavy water to 200°C. Tritium from heavy water is exchanged with deuterium from a deuterium gas stream in the VPCE system, which turns tritiated heavy water (DTO) into vapour. Following de-tritiation, the heavy water is kept in product tanks. The tritium is then concentrated to high percent purity by cryogenic distillation; the low tritium cold box (LTD) contains a single column which enriches the less volatile tritium in the bottom part of the column. The bottom product from this column is transferred continuously to the high tritium cold box. The tritium depleted deuterium stream leaving the upper section of the low tritium distillation column is recycled to the VPCE cascade. The high tritium cold box (HTD) is equipped with three columns, in series, in which the tritium concentration increases progressively. These columns are of successively smaller diameters to minimize the inventory of tritium in the system.

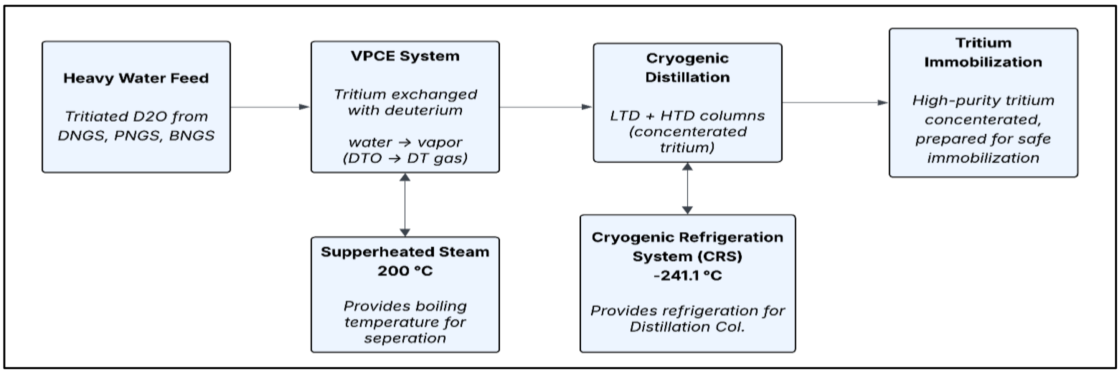

Figure 1: Simplified Flow Diagram of DTRF and CRS with the H_2 Compressors Operation

2.2 Tritium Immobilization System (TIS)

Tritium with an atomic purity of 99.9% is withdrawn from the bottom of the last column and transferred to the Tritium Immobilization System. Tritium is then immobilized by way of a chemical reaction with titanium metal creating a metal tritide in the Tritium Immobilization System (TIS). Figure 2 provides an overview of the TIS used at the Tritium Removal Facility. The Tritium Immobilization System is designed to handle batches of tritium gas, the tritium gas is contained in process equipment, as a result of tritium gas being present there is the possibility of tritium surface contamination on the internal surfaces of process equipment. The Tritium Immobilization System is confined to inert (argon) gas filled gloveboxes and other enclosures such as valveboxes and airlocks. This design limits the possibility of formation of flammable or explosive mixtures of tritium in air and limits the possibility of releasing radioactive tritium gas.

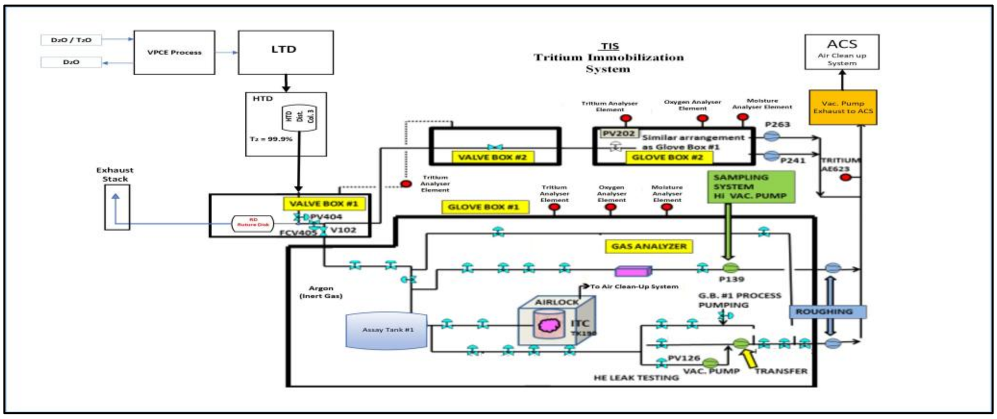

Figure 2: Simplified Flow Diagram of Tritium Immobilization System

Finally, this T2 gas is stored using the Tritium Immobilization System (TIS) inside an Immobilized Tritium Container (ITC). This will lower the radiation doses given to operating staff and lower the radioactive content of any heavy water leaks into the environment.

2.3 Air Clean-up System

The Air Cleanup System (ACS) is provided to capture and clean up any tritium which may leak into the rooms of the TRF Building and thus prevent its escape to the environment. The ACS includes provision to provide the motive force for re-circulating the air between itself and the individual room to which it is connected at a given time. It recombines the elemental hydrogen isotopes with oxygen and subsequently condenses and dries the moisture from the air. This moisture is collected and stored for periodic return to the downgraded D20 Transfer System. Figure 3 provides an overview of the ACS used at the Tritium Removal Facility. It highlights key subsystems such as the blower, charcoal filter, re-combiner, condenser, chilled water cooler, molecular sieve dryers, and the regeneration control components. This system is designed to isolate and decontaminate tritiated air through a sequence of thermal and catalytic processes, ultimately preventing environmental discharge and ensuring safe reintegration of cleansed air into the facility environment.

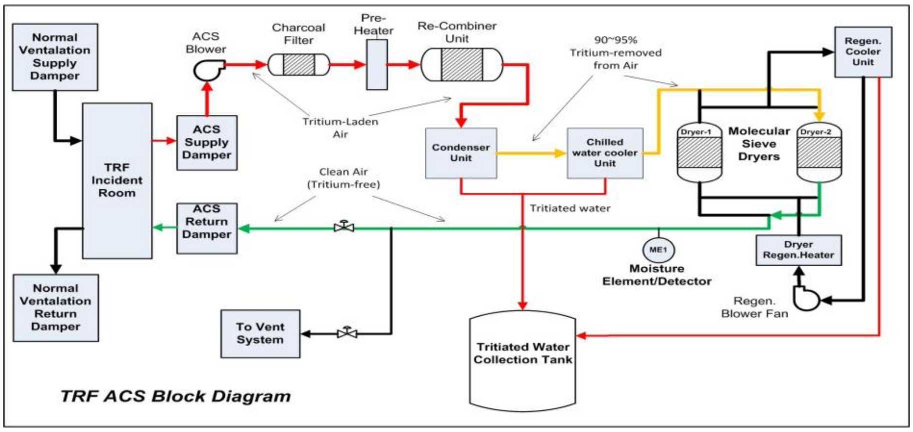

Figure 3: Simplified Flow Diagram of Air Cleanup System

3. SYSTEM EVENT TREE / FAULT TREES MODELING

Event Tree Analysis (ETA) is a forward-looking risk assessment method that visually maps how an initial accidental event escalates (or fails to escalate) based on the success or failure of safety barriers. It helps organizations identify accident scenarios, evaluate potential consequences, and calculate risk probabilities. The ETA related to initial HTD columns loss of cooling event is depicted in Figure 4.

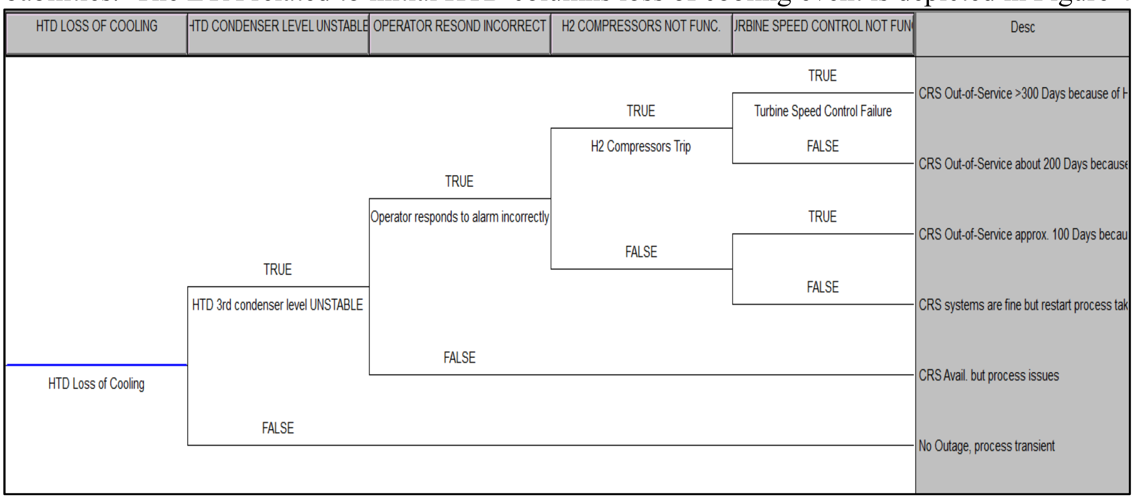

Figure 4: Event Tree Analysis (ETA) for HTD columns loss of cooling event

3.1. Probability Model Development and Risk Calculations

The CRS *Coldbox, heat exchangers and expansion Turbine* process and instrumentation diagram (P&ID) are shown in Figure 5. The function of this portion of the CRS process is to control the refrigeration temperature by expanding hydrogen stream in Turbine and controlling the turbine cooling power output using turbine speed control to adjust the cooling (35 to 25 Kelvin) required for operation of the LTD and HTD columns.

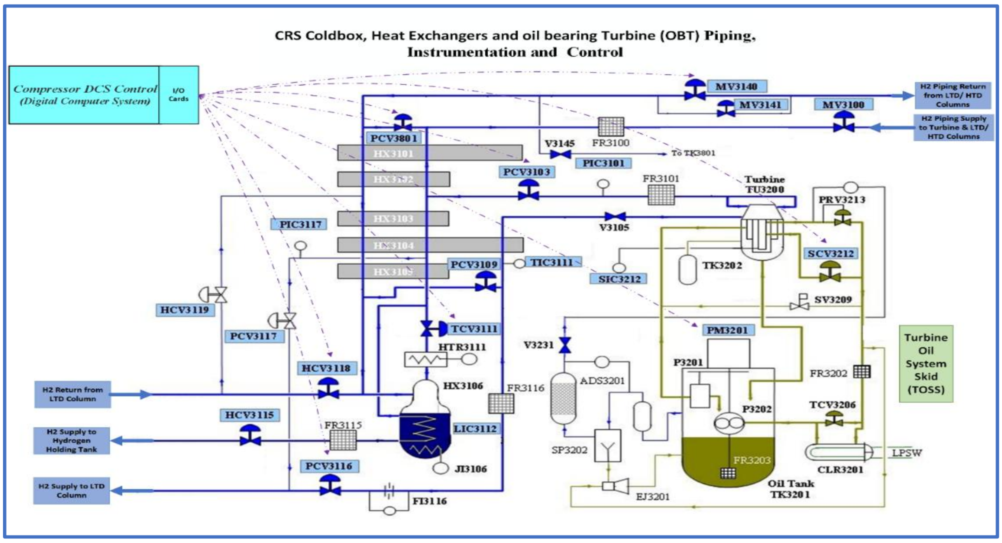

Figure 5: Simplified Flow Diagram of CRS process and instrumentation

The FTA (Fault Tree Analysis) method [5, 6] was used to calculate the probability of Basic Events as shown in Figure 6 and Table 1.

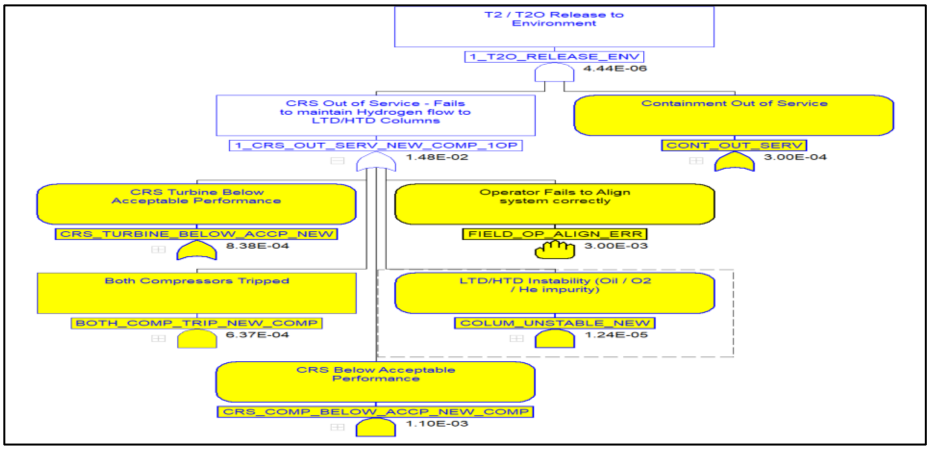

Figure 6: CRS Out-of-Service Fault Tree Analysis

Table 1: Cryogenic Refrigeration System Out-of-Service Main Basic Events

No.	Basic Event Description	Prob. Value (1)	Reference
B1	CRS Compressor Below Acceptable Performance (One H2 Compressor Trip)	1.10E-03	[8], [9], [11], [12]
B2	Operator Error / Operator Delay Response	3.00E-03	[7]
B3	CRS H2 Compressors Tripped (Both H2 Compressors Tripped)	6.37E-04	[8], [9], [11], [12]
B4	Turbine Speed Control NOT Function	8.38E-04	[8], [9], [11], [12]
B5	High Tritium Distillation (HTD) Column Unstable	1.24E-05	[8], [9], [11], [12]

(1) Probability vales are failure probability per year based on industry data from Darlington NGS risk assessment when applicable

The Computer Assisted FTA (CAFTA) software was used to develop two scenarios; the first one is based on 2 x 50% H_2 Compressors and oil-bearing expansion turbine (OBT) as part of the cryogenic refrigeration system, with one operator monitoring the CRS process in the control room, depicted in Figure 7.

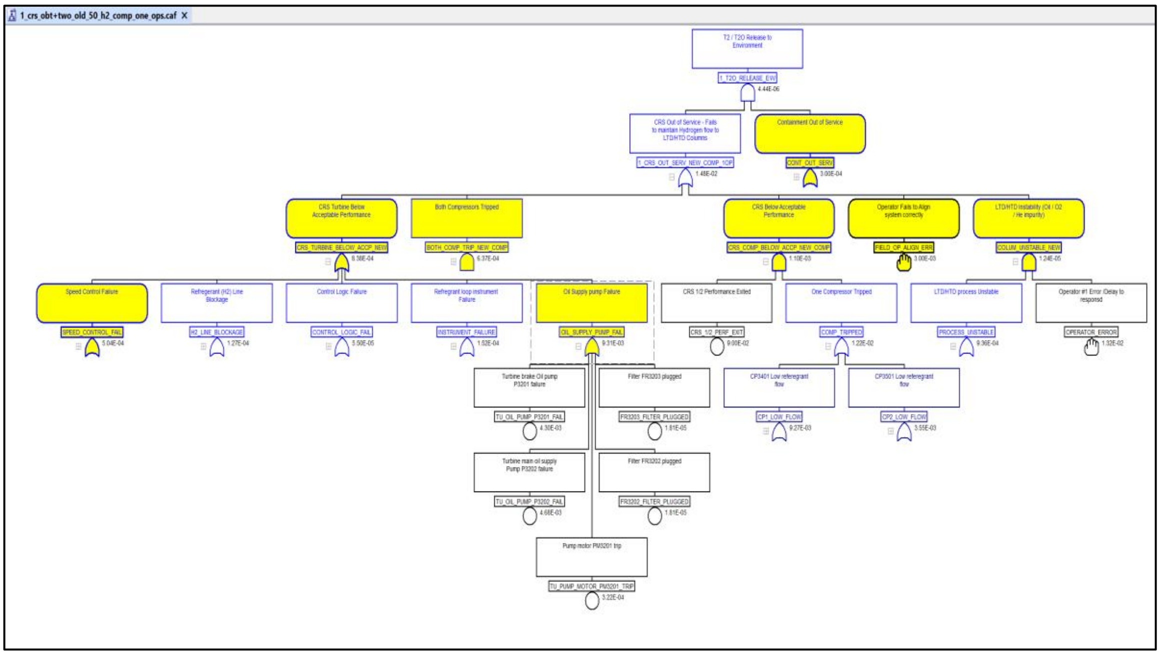

Figure 7: Overall FTA based on 2 x 50% H_2 Compressors and oil-bearing expansion turbine (OBT)

The top 3 dominant Cut sets are shown in Table 2.

Table 2: The Dominant Cut sets - Fault Tree Analysis-01

T2O_RELEASE_ENV = 4.46E-06 (Probability)				
#	Cut set Prob.	BE Prob	Inputs	Description
1	4.68E-07	1.00E-04	ACS_OUT_OF_SERVICE	Air Clean Up System (ACS) out of Service
		4.68E-03	TU_OIL_PUMP_P3202_FAIL	Turbine main oil supply Pump P3202 failure
2	4.68E-07	1.00E-04	GB_RUPTURE_DISK_FAIL	TIS Glove box Rupture Disk Failure
		4.68E-03	TU_OIL_PUMP_P3202_FAIL	Turbine main oil supply Pump P3202 failure
3	4.68E-07	1.00E-04	RE_COMBINER_RUPTURE_DISK_FAIL	Re-combiner Rupture Disk Failure
		4.68E-03	TU_OIL_PUMP_P3202_FAIL	Turbine main oil supply Pump P3202 failure

The top 3 dominate contributors sorted by Fussell-Vesely's measure of importance are shown in Table 3. Fussell-Vesely's measure of importance, is the probability that at least one minimal cut set that contains component (i) is failed at time t, given that the system is failed at time t. Fussell–Vesely measures how much of current risk includes the event.

Table 3: Fussell-Vesely's measure of importance - FV01

No.	Probability	Fus-Ves	Event Description
1	1.00E-04	0.33333	TIS Glove box Rupture Disk Failure
2	1.00E-04	0.33333	Re-combiner Rupture Disk Failure
3	1.00E-04	0.33333	Air Clean Up System (ACS) out of Service

The top 3 Risk Achievement Worth values are shown in Table 4. The Risk Achievement Worth (RAW) measures the relative increase in the system's unreliability when it is known that component (i) is in a failed state. RAW measures how much risk increases if the event is unavailable

Table 4: Risk Achievement Worth Results - RAW01

No.	Probability	Ach W	Event Description
1	1.00E-04	3314.906	TIS Glove box Rupture Disk Failure
2	1.00E-04	3314.906	Re-combiner Rupture Disk Failure
3	1.00E-04	3314.906	Air Clean Up System (ACS) out of Service

The fault propagation is simulated by tripping one compressor motor. The CRS continues to operate since operation with only compressor is possible using the CRS at ½ Performance for a short duration (1 – 4 weeks). But if the compressor motor trip is due to major motor failure, then the CRS ½ Performance will be terminated and lead to a CRS-Out-of-service event. The Top Event "T2/T2O Environmental Release" can occur if Tritium Immobilization System (TIS) over pressure occurs that cause opening of rupture disk. This sequence of fault propagation is shown in Figure 8. The main contributor to CRS-Out-of-Service events is failure of expansion turbine main oil and brake pumps.

4. CRS OPERATION RELIABILITY IMPROVEMENT

The oil-bearing turbine on the CRS Coldbox will be replaced by a gas bearing turbo expander of type TED45. Self-activated gas bearing turbo-expanders are superior in their performance to oil bearing turbines. The elimination of the oil bearings also means elimination of a separate seal gas system, lube oil circuit with pump and instrumentation, heater etc. There is no possibility of bearing oil contaminating the hydrogen refrigeration cycle any more. Self-activating gas bearing turbines do not require a separate gas bearing system.

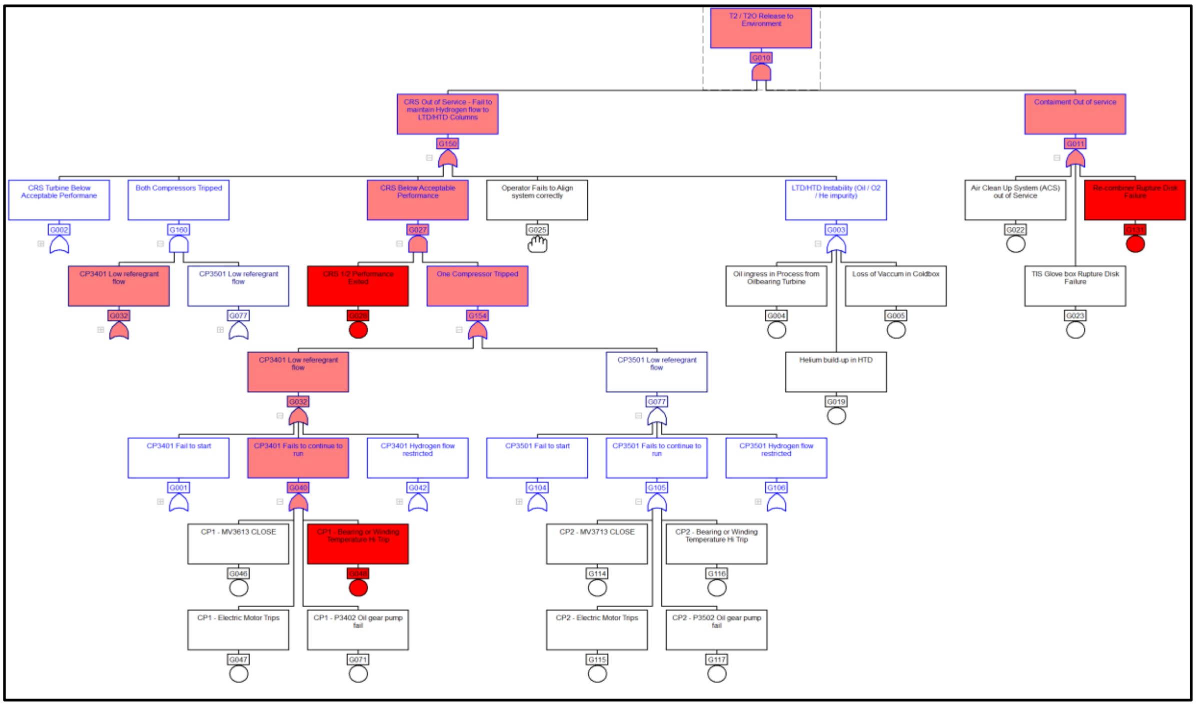

Figure 8: The sequence of fault propagation due to one H_2 Compressor motor failure

The compressor circuit supplies bearing gas automatically. The CRS flow diagram of the gas bearing turbine (TED45) system is shown in Figure 9.

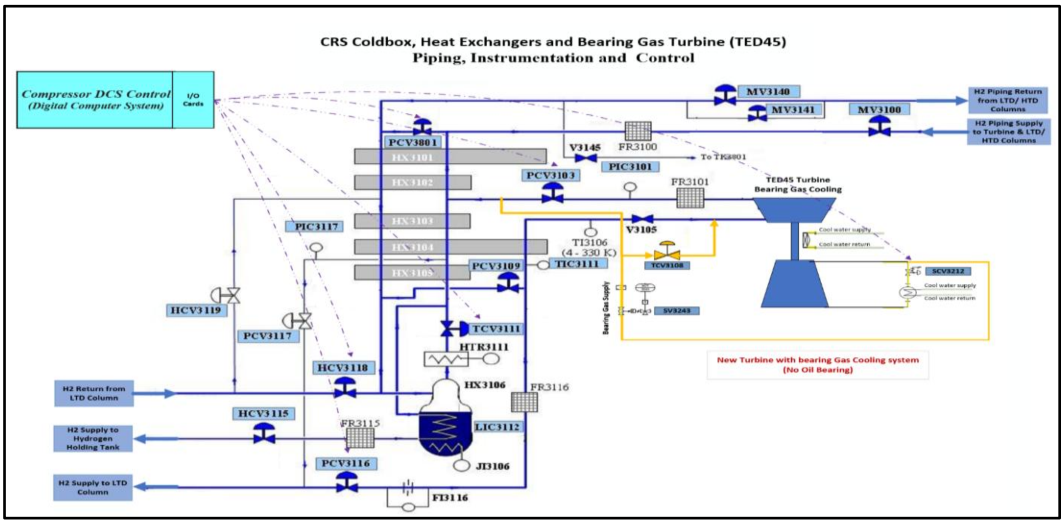

Figure 9: CRS flow diagram with new Bearing Gas Cooling (TED45)

The new FTA scenario is based on 2 x 50% H_2 Compressors with new bearing gas cooling turbine (TED45), as part of the cryogenic refrigeration system, as depicted in Figure 10.

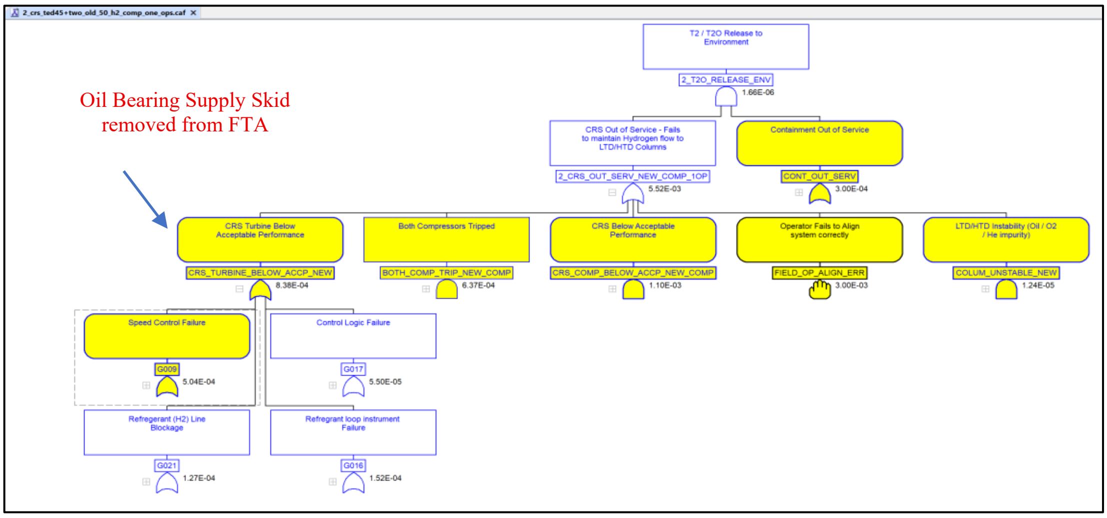

Figure 10: New FTA - 2 x 50% H_2 Compressors with TED45 Turbine

Table 5, "Cut set Report", lists top 10 probability calculated values in the Fault Tree diagram associated with CRS operation with 2x50% H_2 Compressors and TED45 Turbine operation. The probability of a Top Event, "T2 Stack Release", due to failure of the CRS operation, is estimated to be 1.66 $x10^{-6}$, as shown in Table 5 and the probability of CRS Out of Service event is $5.52x10^{-3}$ as shown in Figure 10. The main contributor to "CRS-Out-of-Service" events is due to H2 Compressor Stator Winding Temp RTD faulty. The new top 3 dominant Cut sets are shown in Table 5.

Table 5: The Dominant Cut sets - Fault Tree Analysis-02

T2O_RELEASE_ENV = 1.66E-06				
#	**Cutset Prob.**	**BE Prob**	**Inputs**	**Event Description**
1	3.00E-07	1.00E-04	ACS_OUT_OF_SERVICE	Air Clean Up System (ACS) out of Service
		3.00E-03	FIELD_OP_ALIGN_ERR	Operator Fails to Align system correctly
2	3.00E-07	3.00E-03	FIELD_OP_ALIGN_ERR	Operator Fails to Align system correctly
		1.00E-04	GLOVEBOX_RUPTURE_DISK_FAILURE	TIS Glove box Rupture Disk Failure
3	3.00E-07	3.00E-03	FIELD_OP_ALIGN_ERR	Operator Fails to Align system correctly
		1.00E-04	RUPTURE_DISK_FAILURE	TIS Glove box Rupture Disk Failure

The new top 3 contributors sorted by Fussell-Vesely's measure of importance are shown in Table 6.

Table 6: Fussell-Vesely's measure of importance – FV02

No	Probability	Fus Ves	Description
1	3.00E-03	0.54331	Operator Fails to Align system correctly
2	1.00E-04	0.33333	TIS Glove box Rupture Disk Failure
3	1.00E-04	0.33333	TIS Glove box Rupture Disk Failure

The new top 3 Risk Achievement Worth values are shown in Table 7.

Table 7: Risk Achievement Worth (RAW) Results-02

No.	Probability	Ach W	Event Description
1	1.00E-04	3327.772	TIS Glove box Rupture Disk Failure
2	1.00E-04	3327.772	Air Clean Up System (ACS) out of Service
3	1.00E-04	3327.772	TIS Glove box Rupture Disk Failure

4.1. Human Reliability Risk

Operator monitoring and controlling the process values in the TRF control room is paramount to proper operation of the cryogenic process thus, it is important to estimate the human reliability risk. To reduce the single operator (Human) Reliability Risk, it is suggested to add 2nd Operator in the control room to monitor the CRS process alarms. The fault tree was revised to include another operator (Operator #2) in the control room to monitor the alarms and annunciations as depicted in Figure 11.

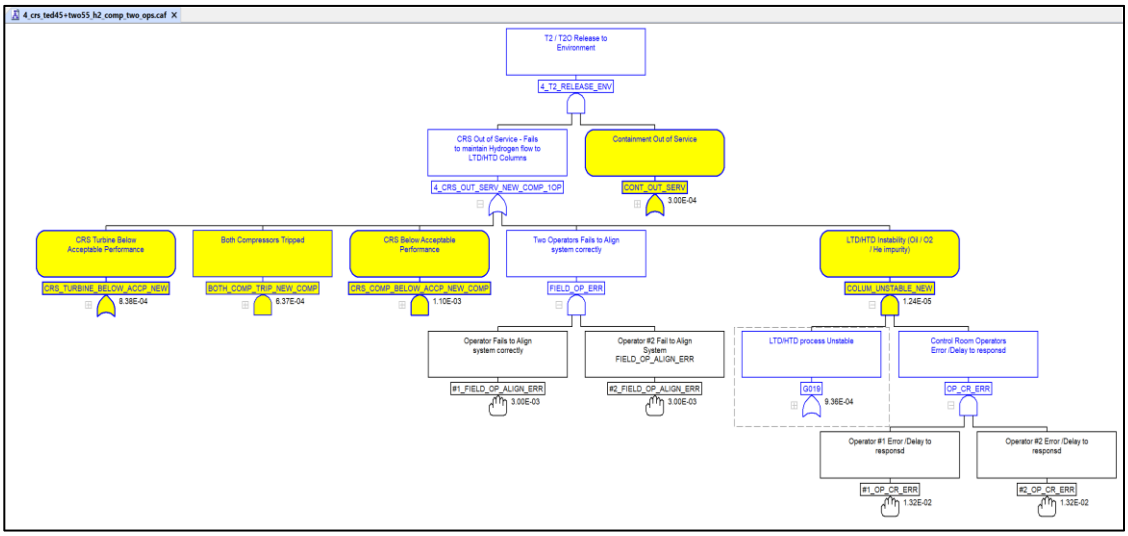

Figure 11: New FTA – Two operator in the control room to monitor the alarms and annunciations

The top 3 dominant Cut sets are shown in Table 8.

Table 8: The Dominant Cut sets - FTA 03

T2_RELEASE_ENV = 4.32E-07				
#	**Cutset Prob.**	**BE Prob**	**Inputs**	**Event Decription**
1	4.68E-08	1.00E-04	ACS_OUT_OF_SERVICE	Air Clean Up System (ACS) out of Service
		4.68E-04	TU_BLADE_DAMAGED	Turbine blade damaged
2	4.68E-08	1.00E-04	GLOVEBOX_RUPTURE_DISK_FAIL.	TIS Glove box Rupture Disk Failure
		4.68E-04	TU_BLADE_DAMAGED	Turbine blade damaged
3	4.68E-08	1.00E-04	RUPTURE_DISK_FAILURE	TIS Glove box Rupture Disk Failure
		4.68E-04	TU_BLADE_DAMAGED	Turbine blade damaged

The new top 3 contributors sorted by Fussell-Vesely's measure of importance are shown in Table 9.

Table 9: Fussell-Vesely's measure of importance – FTA 03

No.	Probability	Fus Ves	Description
1	9.00E-02	0.39286	CRS 1/2 Performance Exited
2	1.00E-04	0.33333	Air Clean Up System (ACS) out of Service
3	1.00E-04	0.33333	TIS Glove box Rupture Disk Failure

The new top 3 Risk Achievement Worth (RAW) values are shown in Table 10.

Table 10: Risk Achievement Worth (RAW) Results - FTA 03

No.	Probability	Ach W	Event Description
1	1.00E-04	3331.892	Air Clean Up System (ACS) out of Service
2	1.00E-04	3331.892	TIS Glove box Rupture Disk Failure
3	1.00E-04	3331.892	TIS Glove box Rupture Disk Failure

5. ESTIMATE THE LIKELIHOOD OF CRS-OUT-OF-SERVICE & RISK CALCULATIONS

The ETA related to initial HTD columns loss of cooling event is depicted in Figure 12 as well as the likelihood estimation of CRS being Out-of-Service.

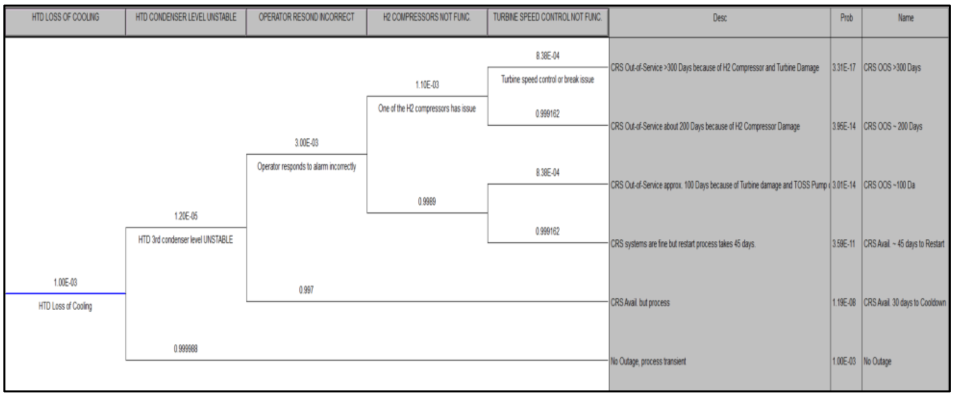

Figure 12: ETA for likelihood estimation of CRS being Out-of-Service

5.1. Risk Calculation with 2 x 50% Hydrogen Compressors as Part of the CRS

The Consequence Factor (CF) ratings will be used to identify the highest priority failure modes which should be considered for corrective action to mitigate risk. Mitigating risk can be achieved by designing out failure modes, reducing the likelihood of failure (Occurrence) through the addition of redundancy or high reliability parts and testing, and/or improving the ability to detect failures (Detection).

Cf is calculated as follows and results in a rating between 1 and 1000:

$$Cf = SEV * DET * P_{Cost} \tag{1}$$

Where:

- SEV = Severity Rating - the maximum value between the two Severity Classifications (**Pr**oduction or **E**nvironmental T_2 Release)
- DET = Detectability Rating
- P_{Cost} = Production Cost factor (Value between 1 and 10)

Severity Rating

The severity rating (SEV) is a qualitative measure of severity which is assigned to each failure mode to represent the worst potential consequences from that failure at the system level. The classification ranking definitions can be found in Table 11. A ranking of 1 indicated that the failure mode will have no effect on the system, while a ranking of 10 indicates that the failure mode will enact a catastrophic effect onto the system. There are two primary severity classifications:

- Production Impact (Pr): The impact of a failure with respect to tritium removal/extraction system operation and lost production.
- Environmental Impact (E): The effect of failures with respect to Tritium elemental or oxide (T_2 / T_2O) release risk to the environment.

Table 11: Severity Criteria

Effect	Production Impact (Pr)	Environmental Impact (E)	Rating
Significant	Major equipment replacement; Extended outage greater than 52 week.	Total release of Tritium Inventory from L HTD column greater than 10 x 10^5 Ci	10
Critical	Critical subsystem unavailable; production recovery 26 weeks.	Rupture Disk failure release of Tritium Inventory from TIS approx. 5 x 10^5 Ci	9
	Critical subsystem unavailable; production halted for 12 weeks.	Rupture Disk failure release of Tritium Inventory from TIS 1 x 10^5 Ci	8
High	Production halted; production recovery within eight (8) weeks.	Rupture Disk failure release of Tritium Inventory from TIS approx. 45 x 10^3 Ci	7
	Production halted; production recovery within four (4) weeks.	Valve failure release of Tritium Inventory from TIS approx. 1 x 10^3 Ci	6
Medium	Partial production halted (> 50%) ; production recovery within two (2) weeks.	Medium valve leaks in process lines approx. 1 x 10^2 Ci	5
	Minor production delays (20 - 50%); production recovery within one (1) week.	Medium valve leaks in process lines approx. 0.5 x 10 Ci	4
Low	Small reduction in efficiency; issue resolved within one (1) day.	Small leaks in two gloveboxes	3
	Nuisance production impact; issue resolved within eight (8) hrs.	Small leaks within one glovebox	2
None	No measurable production impact.	No environmental release	1

Detectability Rating

A numerical rating is assigned to each failure that indicates the likelihood that the available controls will detect the cause of the failure mode or the failure mode itself, thus eliminating or mitigating the effects of the failure. As shown in Table 3, a DET value of 10 represents "undetectable" (or "uncertain"), and a value of 1 indicates "always detectable" (or "certain automated detection").

Table 12: Likelihood of Detection by Control Rating

Category	Likelihood of Detection by Control	Rating
Failure undetectable	No procedures or checks in place to detect. Cannot detect failure.	10
Only detectable by personnel	Failure is likely detected through general observation and monitoring of equipment.	9
	Not detectable by the Control Monitoring System.	8
	Failure is almost always detected and is more obvious to the operator.	7
Failure detected after it occurs	Failure is likely detected after it occurs.	6
	Failure is almost always detected after it occurs.	5
Failure detected as it occurs	Failure is likely detected as it occurs.	4
	Failure is almost always detected as it occurs.	3
System diagnostic detects adverse conditions that would lead to failure (certain automated detection)	Sensors/ process controls will likely detect the condition, allowing for intervention to prevent failure.	2
	Sensors/ process controls will almost always detect the condition, allowing for intervention to prevent failure.	1

A 90-day outage would result in the loss of TRF production in the amount of 525 Mg (2100 Mg/yr x 0.25 yr). The compressors are considered high risk components, due to the impact of their failure on plant operation, and the probability of failure. The costs related to consequences # 2 and # 4 are estimated based on equation (1), which includes loss of production, outage, maintenance and operational costs 90- and 200-day shutdown due to CRS major issues. The Darlington TRF uses the Tritium Immobilization System (TIS) to remove and immobilize pure tritium in 45 kCi batches, for long term storage on titanium filled stainless steel containers. Overpressure protection and system leak tightness is assured, using a rupture disc and relief valve that vents to the contaminated exhaust stack for the TRF. An overpressure event during a non-standard operation such as CRS-Out-of-Service could result in the failure of the rupture disc, and release of elemental tritium to the relief valve discharge line of the TIS. The $Cf_{(critical)}$ and $Cf_{(significant)}$ are calculated for two cases:

Case 1: SEV=5, DET = 10 and P_{Cost} = 9 $\quad$ $Cf_{(critical)} = (5 * 9 * 10) = 450$

Case 2: SEV=10, DET = 10 and P_{Cost} = 10 $\quad$ $Cf_{(significant)} = (10 * 10 * 10) = 1000$

The risk estimation with 2 x 50% compressor and Oil-Bearing Turbine (OBT) operation is calculated using the formula (2) below:

$$Risk = L\ (Probability) * Cf\ (Consequence\ factor) \tag{2}$$

The TRF plant configuration with 2 x 50% CRS compressor risk estimate needs to be assessed. The reasons for this are:

1) Maintenance activities are very costly and time consuming.
2) A major failure in any process system components would result in an outage extending more than 6 months. The lengthy outage duration is due to the need to burn down the hydrogen isotope inventory and replace it with helium, before opening the system to perform work.
3) Once maintenance is completed, the air must be purged of helium and the deuterium inventory then replaced, before start-up can begin. These activities can take several weeks to complete.

The top event risk calculation results are shown in Table 13 with 2 x 50% H_2 Compressor and Oil-Bearing Turbine (OBT) operation at TRF.

Table 13: Risk estimate calculation 2 x 50% H2 Compressor & Oil-Bearing Turbine operation

Risk	Probability	*Cf*	Risk Score	Risk Score
Critical shutdown due to Turbine, H_2 Compressor Flow control Valve, Instrumentation, etc. failures	1.37E-2	450	6.165	Medium
Significant shutdown due to Turbine, H_2 Compressors mechanical failure, electric motors.	1.37E-2	1000	13.70	High

To reduce the duration of TRF outages, a replacement of Oil-Bearing Turbine with a Gas-Bearing Turbo expander of type TED45 is considered; it would provide a safe environment for maintenance activities, without having to burn down the entire hydrogen isotope inventory.

The new probability calculations for CRS operation with 2 x 50% Compressors and Gas-Bearing-Turbine was performed. The TOP event risk calculation results are shown in Table 14.

Table 14: Risk estimate calculation 2 x 50% H_2 Compressor with TED45 Turbine operation

Risk	Probability	*Cf*	Risk Score	Risk Score
Critical shutdown due to Turbine, H_2 Compressor Flow control Valve, Instrumentation, etc. failures	4.40E-03	450	1.98	Low
Significant shutdown due to Turbine, H_2 Compressors mechanical failure, electric motors.	4.40E-03	1000	4.4	Low

6. RECOMMENDATIONS FOR FURTHER RELIABILITY IMPROVEMENT

To further improve the CRS system reliability, it is necessary to conduct additional feasibility study, estimate the cost of installing a new compressor and related auxiliary systems, and design a structural building to house the new compressor. To properly assess the return on investment, additional study needs to be done (ROI). Given the TRF's longer lifespan and the projected 30-year sales revenue from tritium (T_2) and helium-3 (He3), the capital cost investment may be justified.

7. CONCLUSION

The risk analysis for the TRF cryogenics identified main hazards associated with CRS failure for Low Tritium Distillation (LTD) and High Tritium Distillation (HTD) cold boxes. The implementation of Computer Assisted Fault Tree Analysis (CAFTA) provides a Probability Risk Assessment (PRA) for TRF that is more enhanced, in comparison with previous risk assessments related to similar hazard scenarios. The risk estimate, without protection and mitigation barriers, was performed and indicated that the risk score is high, due to the probability of a long unplanned outage and the high cost of maintenance activities. The study shows that the addition of protection barriers, such as the replacement of existing turbine with a gas-bearing turbine-expander, would reduce the consequence of failure from a high risk (13.70) to a low-risk value (4.4). The operation risk was also investigated, with both one and two operators monitoring the CRS process alarms in the control room, which was included in the Fault Tree (FT) analysis. This study contributes to a better understanding of the risks associated with the TRF operation in conjunction with Darlington Nuclear Power Plant (DNPP). PRA used in this study attempts to create an environment of safe nuclear power plants and tritium removal facilities therein. This paper did not consider risk due to external hazards such as seismic, high wind and flooding.

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