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Steam Generator Tube Rupture Accident at a NPP and Exploration of Mitigation Strategies for Its Consequence

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1. Introduction

Steam tube rupture accident (SGTR) is one of the bypass accident sequences that could result in a direct release of radioactivity to the environment through secondary system safety relief valves. At least 14 cases of SGTR have been reported since the first at Point Beach in 1975.[1] All these accidents had single ruptured tube and were successfully mitigated without any damage to the reactor without any significant release of radioactive material to the environment. However, multiple tube ruptures may lead to severe accident conditions if the operator response in respect of mitigating the break flow is inadequate or it combines with other accident sequences such as Station Blackout (SBO). The frequency of this occurrence is extremely low, but the nature of the accident i.e. provision of bypass pathway, provides one of the fastest routes for unfiltered release of radioactive material to the environment. Studies suggest that for some accident sequences (e.g. TI-SGTR), the start of atmospheric release could be as early as 3-4 hours [2]. Early release of radioactive material to the environment could have serious repercussions on severe accident management activities as well as the safety of plant workers and the people residing in the vicinity of the plant. Firstly, the available time might not be enough for effective and complete evacuation of public before environmental releases. Secondly, available time window in such an accident sequence might not be enough for correct and timely assessment of the plant conditions, which could delay the notification of evacuation orders, further aggravating the impact of the accident. Under such circumstances, it will be reasonable to assume that people residing in plume path are likely to be exposed to radiation in violation of the fundamental safety principle [3], and therefore, efforts should be made to either eliminate the potential of this kind of accident or develop measures for mitigation of its radiological consequences.

Progress has been made in reducing the probability of this kind of accident for advanced power plants, through improvements in SG tube material as well as through relevant modifications in plant design and procedures. However, the issue is still relevant for most of the existing NPPs, and efforts in mitigating the radiological consequences of an accident-induced SGTR are still lacking. In this work, we propose a potential solution for mitigating the consequences of this kind of accident, and explore several strategies based on this proposal. The proposal uses fixed suction nozzles to capture and divert the radioactivity to controlled environment where it could be treated or dumped temporarily.

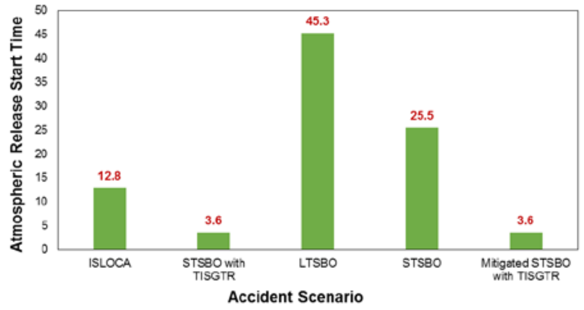

Fig. 1: Comparison of atmospheric release start time between SBO, ISLOCA and SGTR. [2]

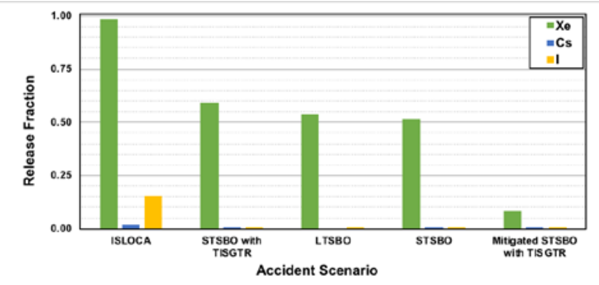

Fig. 2: Comparison of release fractions of Xe, Cs, and I for SBO, ISLOCA and SGTR. [2]

2. Methodology

2.1 Types of steam tube rupture accident

Steam generators (SGs) are part of the Nuclear Steam Supply System (NSSS) at pressurized water reactors and are there to transfer heat from the primary system to the secondary system. A steam generator consists of many tubes carrying primary coolant at high pressure. The secondary water runs on shell side of the SG kept at relatively lower pressure. The two sides exchange heat through tube walls without mixing and produces steam, which is then used to run turbines to produce electricity. Steam generator tube is one of the many barriers between radioactive coolant and the environment. A damage to this barrier (i.e. rupturing of SG tubes) may allow release of radioactivity directly to the environment, posing a serious safety concern.

Steam generator tube ruptures are usually grouped into two main categories;

a) ***Spontaneous***: This type of steam generator tube ruptures is caused by tube degradation mechanisms such as stress corrosion cracking, fretting and pitting, and is expected to occur during normal operation of the plant with a potential to develop into a severe accident.

b) ***Induced:*** This type of tube ruptures is the consequence of other events. These events could be maintenance related (e.g. an incorrect installation of anti-vibration devices, inappropriate water chemistry, or foreign debris) or accident related.
Under accidental conditions, the steam generator tube ruptures can result from an excessive pressure or temperature gradient across the tubes, called as pressure transient induced SGTR, and temperature induced SGTR respectively. The pressure transient-induced SGTR can occur as a result of a Design Basis Transient or Accident (DBA) that depressurizes either the secondary (such as Main Steam Line Break, MSLB) side or the primary side (such as Anticipated Transient Without Scram, ATWS) and creates an excessive pressure differential across primary-secondary system boundary, close to normal operating temperature. The temperature induced tube rupture can result from a core damage during a severe accident progression that elevates tubes temperature at differential pressure.

Spontaneous and pressure transient-induced SGTRs are included in the plant design and are expected to be mitigated without any core damage, provided that corrective operator actions are taken as per existing regulatory requirements. In fact, all SGTRs to occur to date were of these types and were managed successfully without the release of radioactive substances to the environment.[4]

However, the thermally induced-SGTR (TI-SGTR) has long been considered as a safety concern due to its potential for releasing radioactive material directly to the environment. Studies suggested that this accident sequence is one of the main contributor to bypass release frequency and could cause early radioactivity release to the environment regardless of the fact that SBO conditions are mitigated successfully or not. Therefore, engineered solutions should be explored to mitigate the radiological consequences of this accident sequence.

2.2 Exploring mitigation strategies for thermally induced-SGTR

The short-term station blackout (STSBO) with thermally induced SGTR (TI-SGTR) is the accident sequence leading to early release of radioactivity to the environment. This kind of SBO could be initiated by a seismic event that leads to complete loss of all onsite and offsite power. The loss of total power combined with physical damage results in ECCS system failure alongside turbine driven auxiliary feedwater (TDAFW) pumps failure. Secondary side safety relief valve (SRV) sticks open due to excessive cycling. The stuck open SRV leads to thermally induced SGTR opening up a bypass pathway for transport of fission products such as Cesium and Iodine from reactor core to the environment. This accident sequence is expected to cause a core damage within 3 hours and atmospheric releases within 4 hours.[5][4]

Some of the important attributes of this accident sequence are summarized in Table-I.

Table I: Typical timings of key events during TI-SGTR.[2]

Event Description	Unmitigated STSBO with TI-SGTR	Mitigated STSBO with TI-SGTR
	Timing (hrs.)	
FP gap release	~3.0	~3.0
Stuck open SRV	~3.0	~3.0
TI-SGTR	~3.5	~3.5
Env. releases start	~3.5	~3.5
Hot-leg creep failure	~4.0	~4.0
Containment failure	~30	~75

For designing an engineered system for radiological consequence mitigation, the location, damage size, magnitude, and release rates are some of the important parameters. This information is hard to predict for most accident sequences due to the uncertain nature of underlying phenomena. Therefore, it is particularly difficult to design an engineering system for this purpose. However, the TI-SGTR release scenario is quite different. The release of radionuclides is through secondary side stuck-open SRV. The location of SRVs is certainly known along with the leakage size. The flow characteristics of SRV under given conditions could fairly be estimated using appropriate codes and tools. Due to the nature of this accident, the operation of the mitigation system is required for short period of time (max: 30min). Availability of this information makes TI-SGTR an ideal case for designing an engineered response to the released of radioactivity with a certain degree of confidence.

A solution to TI-SGTR radioactivity threat can be to collect and divert the leaking radioactivity for appropriate treatment. With all the known information, an appropriate fixed nozzle structure or diversion piping could be installed at the SRVs to capture and divert contaminated steam. Combined with an appropriate radioactivity treatment option, this kind of arrangement could practically eliminate the potential safety concerns of this accident as well as reduce overall threat of bypass sequences. In the following section, we discuss how the fixed nozzles could be effectively combined with available resources as a complete mitigation solution.

2.3 Design considerations

The important design consideration to use as guidelines for TI-SGTR mitigation are given below;

a) The mitigation strategies do not impact the normal functionality of safety relief valve in any way.

b) The nozzles structure is able to withstand the seismic events as well as the thermal and pressure loads of discharged steam.

c) The system should preferably be passive; however, power supply should be guaranteed through portable means in case it is required.

d) A dedicated system is available for the treatment of diverted radioactive steam.

2.4 Diversion to the containment

The first strategy could be to redirect SRV vent to the containment. As we know that, reactor containment holds a tremendous free volume, and the pressure rise inside containment is gradual and is lower than that of SRV vent line for initial period of the accident. This can allow passive injection of SRV vent into the containment. The injection of SRV vent to the containment building may result in pressure rise at higher rate than usual and may result in containment failure a bit earlier than no injection. However, a number of arguments can be made in favor of this strategy.

1. Diversion of SRV vent steam is required for short period of time (~1 hrs.) i.e. for time between SGTR and the hot-leg creep rupture, as after hot-leg creep rupture, majority of radionuclides are released to the containment through ruptured hot-leg and the leakage of radioactivity through SRV will be negligible.

2. With diversion of SRV vent to containment, the immediate threat of early release is mitigated, and evacuation of the public can be completed in time.

3. The time so gained may allow mitigation of station blackout conditions prior to ultimate containment failure.

4. For plants equipped with FCVS, all the radionuclides will be filtered (including SRV vent which otherwise was unfiltered and direct) before venting to the environment, reducing overall source term.

5. Even if the containment ultimately fails, the overall source term release will be reduced due to the in-containment removal mechanisms such as gravitational settling, surface deposition etc.

However, this possibility should be analyzed in detail for assessing feasibility of passive diversion to the containment and its impact on containment performance and integrity.

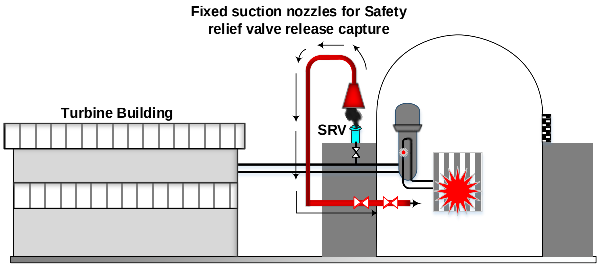

Fig. 3: A potential one-step strategy and corresponding system layout for mitigating steam generator tube rupture (SGTR) accident release source for nuclear power plants.

2.5 Diversion to filtered containment venting system

A majority of NPPs worldwide are expected to be equipped with million-dollar filter venting systems (FCVS). However, the usability of this system in mitigating the consequences of a bypass accident sequences is questionable. However, if the SRV vent could be directed to the filtered venting system, it could potentially handle this situation also. Some of the advantages of this approach are similar to the “diversion to the containment strategy”, with the addition that there is no added threat to containment integrity due to SRV vent diversion.

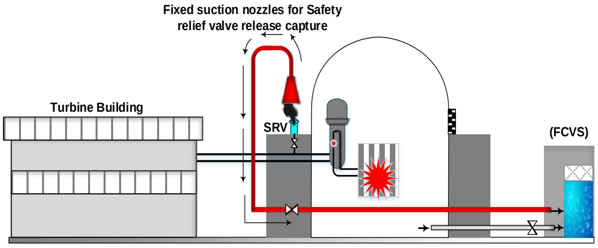

Fig. 4: A potential strategy and corresponding system layout for mitigating steam generator tube rupture (SGTR) accident SRV release source using existing filtered containment venting system (FCVS).

2.6 Diversion to portable treatment system for real-time treatment.

With the fixed capturing nozzles built at the SRVs vents, a portable treatment system could be used for real-time treatment of the captured vent steam. This kind of strategy is appropriate for plants without FCVS and where diversion to the containment isn't an option. This will require designing an appropriate portable treatment system. In this case, the temperature and flow rate of vented steam will be required to provide reasonable condition for cleaning of radioactive substances from steam. An added advantage of this approach could be that the portable equipment can carry its own power resources in case it is required. Since, this approach requires portable equipment, which though could be used for multiple plants; it will still be a comparatively expansive option.

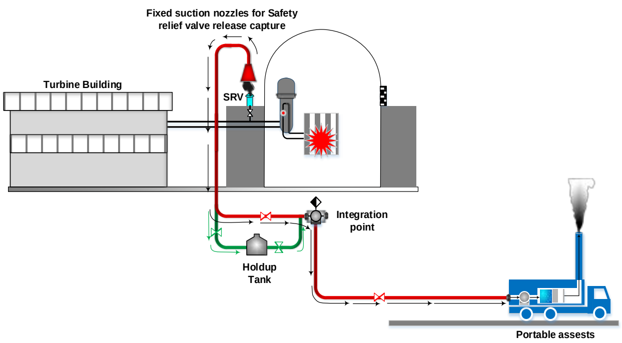

Fig. 5: A potential strategy and corresponding system layout for mitigating steam generator tube rupture (SGTR) accident release source using portable safety equipment

2.7 Combined approaches

In addition to the individual strategies discussed above, these strategies could be combined to cover a broader spectrum of accident conditions depending on plant design, accident progression and performance requirements. For example, "diversion to the containment strategy" may be combined with "portable equipment option" to handle only the initial phase of the accident and then using portable equipment once it has arrived and configured. This kind of combined approach can reduce any added threat to containment integrity while improving the reliability of mitigating the radiological consequences.

3. Conclusions

Thermally induced SGTR (TI-SGTR) during a severe accident progression, is one of the main contributor to plant risk profile because of its potential for early release of radioactive material to the environment. The radionuclides will be released through secondary side safety relief valve which is stuck open due to excessive cycling. Several options are provided in this work to mitigate the consequences of this kind of accident by diverting SRV vent for dumping or treatment using fixed capturing nozzle structures. In general, the options discussed in this work should be applicable to all events involving radioactivity release through SRV regardless of the accident type or the plant state. However, for SRV operation during normal operation or DBA, when no release of radioactivity is expected, the system based on the proposed strategies, should allow release of SRV vent directly to the environment.

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