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Waste Evaporator Accident Simulation Using RELAP5 Computer Code

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Abstract

An evaporator is used on liquid waste from processing facilities to reduce the volume of the waste through heating the waste and allowing some of the water to be separated from the waste through boiling. This separation process allows for more efficient processing and storage of liquid waste. Commonly, the liquid waste consists of an aqueous solution of chemicals that over time could induce corrosion, and in turn weaken the tubes in the steam tube bundle of the waste evaporator that are used to heat the waste. This chemically induced corrosion could escalate into a possible tube leakage and/or the severance of a tube(s) in the tube bundle. In this paper, analyses of a waste evaporator system for the processing of liquid waste containing corrosive chemicals are presented to assess the system response to this accident scenario.

This accident scenario is evaluated since its consequences can propagate to a release of hazardous material to the outside environment. It is therefore important to ensure that the evaporator system component structural integrity is not compromised, i.e. the design pressure and temperature of the system is not exceeded during the accident transient.

The computer code used for the accident simulation is RELAP5-MOD3[1]. The accident scenario analyzed includes a double-ended guillotine break of a tube in the tube bundle of the evaporator. A mitigated scenario is presented to evaluate the excursion of the peak pressure and temperature in the various components of the evaporator system to assess whether the protective actions and controls available are adequate to ensure that the structural integrity of the evaporator system is maintained and that no atmospheric release occurs.

Introduction

A waste evaporator is simple hardware generally designed to operate at low pressure. The evaporator pot collects the liquid waste to be processed via a feed system. The source of heat used for the evaporation process is a steam supply system feeding a heat exchanger tube bundle in the lower portion of the evaporator vessel. The steam used to evaporate the liquid waste can be cycled or once through. The evaporator vapor space is connected to a system of pipes to exhaust the vapors after being condensed through a condensing heat exchanger. In the lower plenum of the condenser piping is included to vent non-condensable gases.

The liquid waste processed in the evaporator could in time induce corrosion in the tube bundle. The chemically-induced corrosion could in turn result in leakage of steam into the evaporator vessel. In accident analysis space a double-ended guillotine break with a full diameter displacement is postulated to occur. This abstraction makes the problem more severe and is used because of the difficulty in defining a less-severe break that can be characterized as reasonably bounding.

Overview of RELAP Code

The RELAP5/MOD3 computer code is chosen because of its well-known capabilities in handling two-phase flow. The code is enriched with a robust method of solution for the governing six-equation set for steam and water and the constitutive relations. The various code models have been the subject of numerous validations by the developers at the Idaho National Engineering Laboratory, and by the commercial nuclear industry in the US and abroad. The code is mainly designed for high pressure ranges, and it works well in the lower pressure range of the subject accident. Some of the various code components (Pipe, Single Volume, Single Junctions, and Valve) used in this accident simulation offer a simple as well as a complete simulation of the evaporator system analyzed here.

Problem Description and Process Conditions

The evaporation process is at low pressure and at the saturation temperature of the aqueous solution. The supply of steam for the evaporation process is simulated by a reservoir supplying saturated steam at a constant pressure of 1.27 MPa (170 psig). The steam is a once-through system discharging at the end into a system of vented tanks. The steam discharge piping controlling flow area is a 1-1/2 in Sch. 40 pipe. From the compressed air supply system there is a connection downstream of the evaporator tube bundle to assure that upon steam low pressure signals (e.g. tube break in the tube bundle) the flow of steam is isolated and high pressure air is injected into the steam piping. This action also prevents liquid waste from entering the broken ends of the broken tube(s). The high pressure air supply system is available to continuously flush the broken ends of the tube(s). The stagnation pressure used for the air supply system is set at 1.14 MPa (150 psig). The broken tube in the tube bundle assembly has a small flow area, 0.00017 m^2. The vapors produced in the evaporation process normally flow to the evaporator dome equipped with a filtering system, and then to a condenser. The condensate is collected at the bottom of the condenser for processing in a system of holding tanks. A non-condensable vent line is also provided to vent out these gases. The design pressure and temperature of the evaporator vessel are arbitrarily set at 0.32 MPa (32 psig) and 409 K (277 ºF) respectively. Figure 1 shows a simple sketch of the evaporator system used of the analysis preformed for this accident problem.

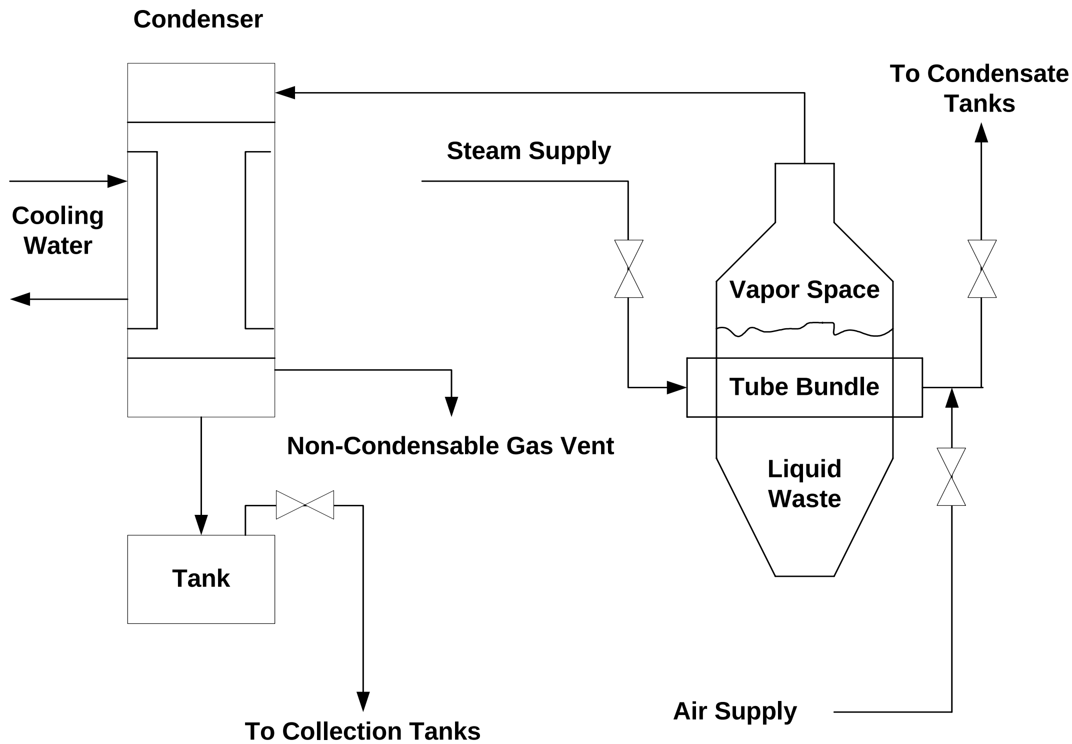

Figure 1 – Evaporator Arrangement.

The main assumptions made to simplify the analysis as well as to maintain a good degree of conservatism are:

1. The heat exchanger tube break is instantaneous with a full tube diameter displacement and leads to steam flow from both ends of the tube break into the evaporator pot,
2. The discharge of steam and subsequent air from both ends of the tube break occurs in the vessel vapor space and not in the region of the evaporator filled with liquid waste where the tube bundle is located,
3. The condensation of steam in the heat exchanger (tube bundle) inside the evaporator vessel is neglected,
4. The steam flow isolation due to a low pressure signal and the subsequent injection of high pressure air into the steam piping is not modeled on pressure signals, but is modeled on preset long timings (e.g. 10, 20, and 30 s after the tube break occurs),
5. The heat exchanger in the evaporator discharge used to condense the vapors generated in the evaporation process is not modeled thus neglecting the condensation process,
6. The piping connected to the condenser to discharge the condensed vapors is not available because of closed valves,
7. The only flow path out of the system for the vapors out of the evaporator pot and the condenser is the non-condensable vent line out of the condenser and it is assumed being a small bore piping (1-1/2 in Sch. 40), and
8. The only portion of the evaporator modeled is the vapor space.

A RELAP model of the evaporator, steam, and air system is constructed to assess the postulated accident progression, study the influence of the various parameters that could affect the results, and ultimately to ensure that the system design pressure and temperature are not exceeded so that no release of liquid waste would take place because of the evaporator vessel structural failure. Figure 2 shows a block diagram and the RELAP model constructed to simulate the subject accident.

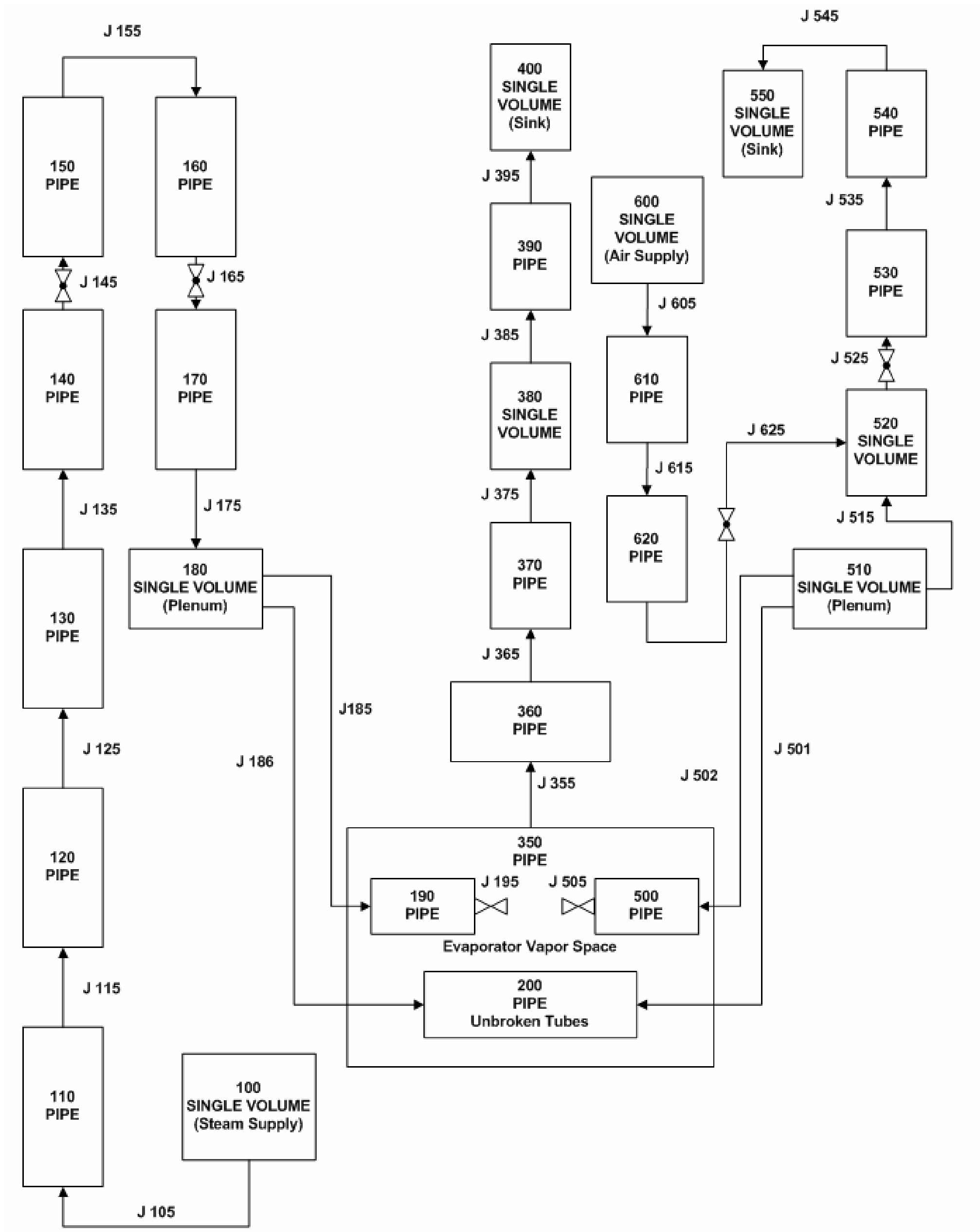

Figure 2 – RELAP Model Block Diagram.

Analyses

The key to success in analyzing an accident as described in this paper is to construct a robust model. That is, the analyst must assure the basic RELAP model simulates the operation of the system (evaporator under normal operating conditions). The analyst must benchmark the model with operational data (e.g., flow, pressure at predetermined locations, etc.) to make the appropriate fine-tuning to the model. Once the analyst has a good model at-hand, then the various accident conditions can be analyzed using conservative accident analysis values for the various parameters input into the analyses. It would be ill-advised not to simulate the system operation prior to accident conditions because, as it will be shown for this case as an example, a poor evaluation of the system hydraulic resistances would yield erroneous predictions.

The analysis presented is composed of a base-case accident simulation for the process condition given earlier, followed by various assessment on the influence of other parameters affecting the results. For the base-case analysis an evaporator vapor space of 6.5 m^3 is used, and the air injection into the system is conservatively assumed to start 30 s after the severance of the tube in the evaporator pot and not on a low pressure signal that would give a faster timing for the air injection. Figure 3 shows the pressure time-history in the evaporator vapor space for three air injection timings.

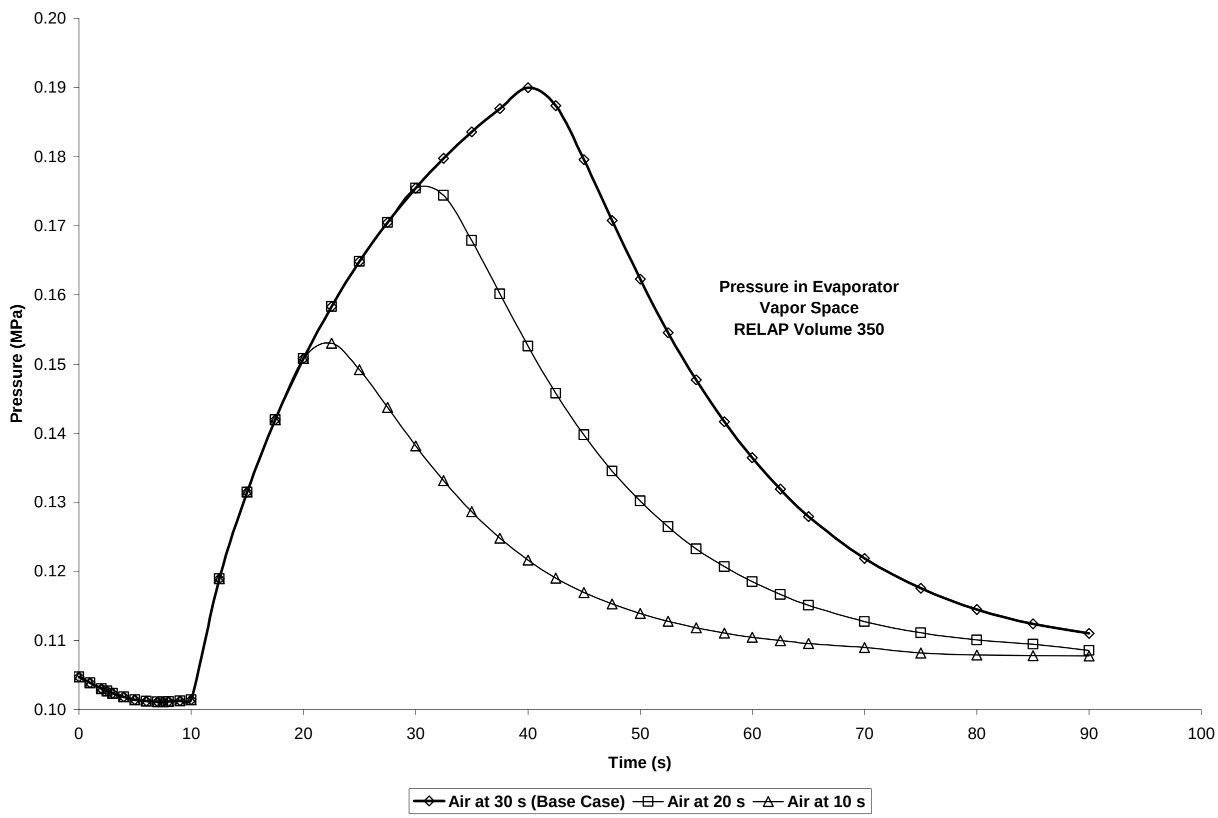

Figure 3 – Evaporator Vapor Space Pressure for Various Air Injection Times.

As shown in Figure 3, the transient starts 10 s after the beginning of the simulation. During the 10 s prior to the severance of the tube in the evaporator heat exchanger, the code adjusts its initial conditions to proper physical values. In this case a 10 s time-span seems to be adequate.

It is of interest to evaluate the system steam flow rates during the accident and also the flow rate predicted at the tube break in the evaporator heat exchanger. Figure 4 shows the predicted flow rates for the system before and after the break occurrence. Before the break, the steam follows a simple path from the steam supply through the unbroken tubes of the evaporator tube bundle and then exits the system through downstream piping. In Figure 4, the mass flow rates match at the monitoring locations upstream (junction 115 in the RELAP model) and downstream (junction 535 in the RELAP model) of the evaporator system as expected.

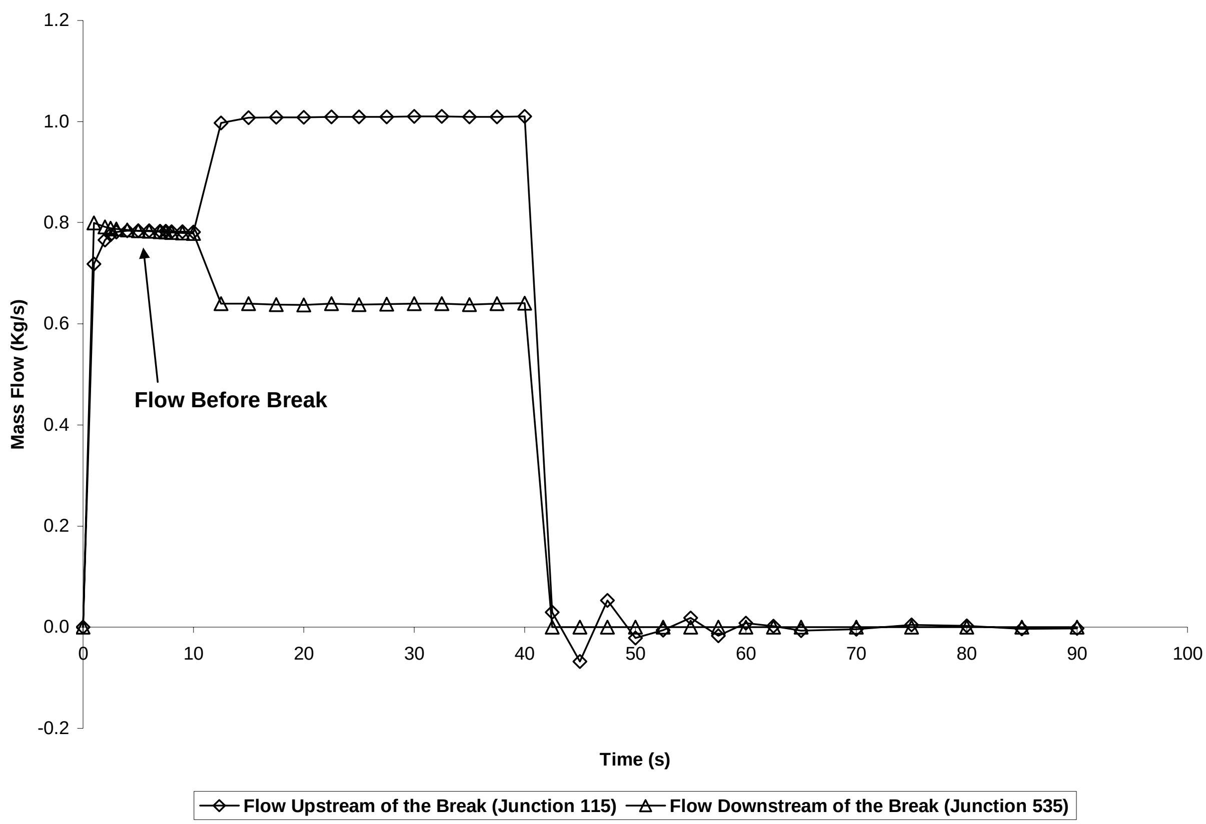

Figure 4 – System Steam Flow Upstream and Downstream of the Break Location.

The steam upstream flow increases immediately after the break occurrence because of the sudden downstream change in flow conditions. After the break, an additional flow path is created for the steam to exit the system. Part of the steam now flows through the broken tube (from both ends) into the evaporator vapor space and exits the system through the evaporator overhead piping. Figure 4 shows that this represents about 35% of the steam flow as approximately 65% of the steam continues to flow through the unbroken tubes and past the monitoring location in the downstream piping. Once the steam flow is isolated, air flow is initiated from the downstream-side piping into the evaporator system through the broken tube.

Figure 5 shows the predicted flow rates (steam followed by air flow) into the evaporator vapor space from both sides of the broken tube.

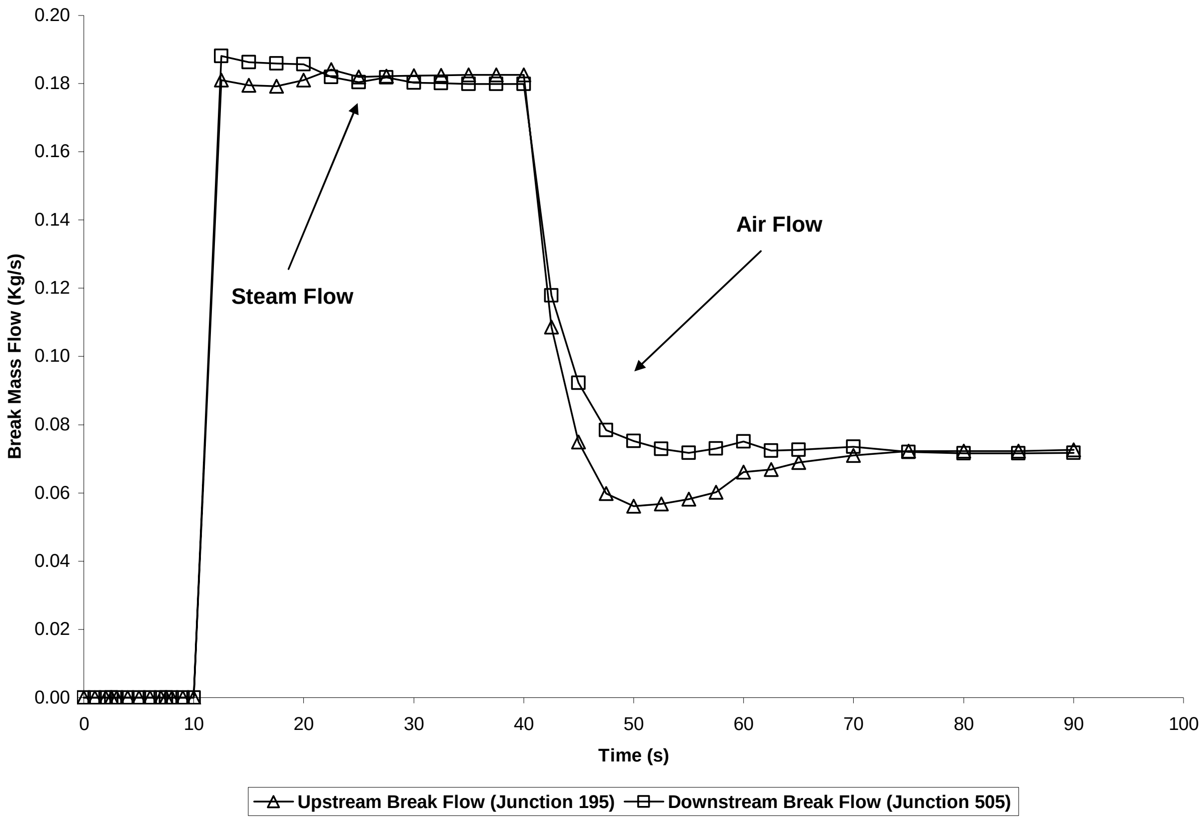

Figure 5 –Steam and Air Flow at Break Location.

As expected, the flow rates at the tube break location are about the same for the upstream and downstream ends of the break and a critical flow condition exists. The air flow follows after the 30 s time span used to isolate the flow of steam. The initial air mass flow out of the downstream end of the break is higher than the mass flow out of the upstream end of the break. That is obviously due to the fact that the air flow injection into the steam piping takes place in the downstream end of the evaporator condensate discharge piping and consequently the high pressure air must flow back through the unbroken tubes of the tube bundle to finally find its way out of the upstream end of the break. The air flow becomes then well established as shown in Figure 5.

A case of interest is to assess how the controlling flow area of the steam discharge piping affects the evaporator vapor space pressure. A controlling flow area equivalent to a 1 in Sch. 40 pipe is set into the RELAP model in the steam discharge piping (e. g., this could represent the inclusion of a flow orifice or pipe size change) and the new pressure transient given in Figure 6 shows a sensible increase in the peak pressure in the evaporator vapor space.

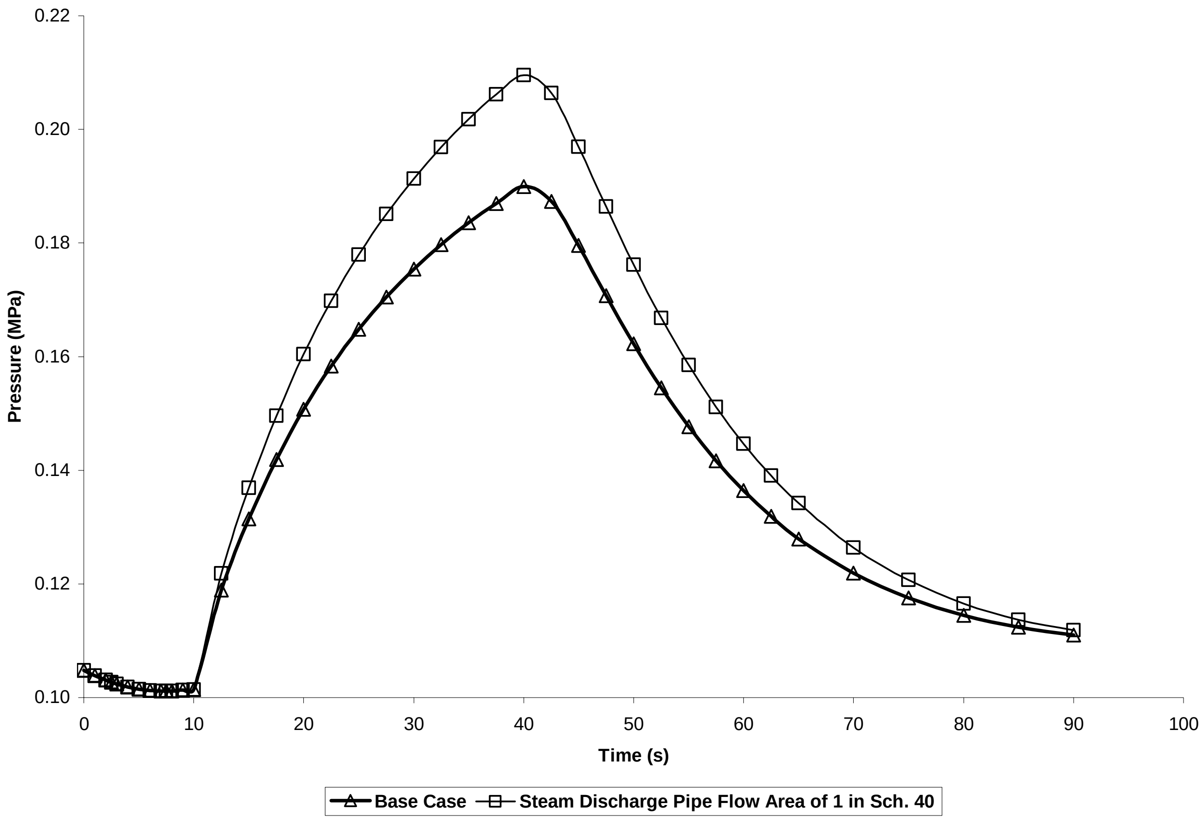

Figure 6 – Effect of Steam Discharge Piping Flow Area on Evaporator Vapor Space Pressure.

As mentioned earlier the evaluation of the system hydraulic resistances is quite critical. That is, the analyst must evaluate the hydraulic resistances with care. The equipment included in the piping system (heat exchangers, valves, orifices, fittings, etc.) must be carefully studied. In the case of valves and other equipment is important to use manufacturer's information whenever possible. For piping and fittings there are several sources of information available to evaluate the frictional and local losses. A successful ending for the task associated with the evaluation of the various hydraulic resistances is a successful simulation of the evaporator system normal and/or other operational mode(s) for which benchmark data is available. In this stage of the analysis the analyst can fine-tune the model structure and hydraulic resistance data to assure the results predicted by the simulation are in good agreement with the selected system operational data. This will enhance the model confidence and it will assure the results of the accident analyses are represented by robust solutions.

Figure 7 shows how variations of the hydraulic resistances in the steam discharge and supply piping, and the non-condensable gas vent line independently affect the peak pressure in the evaporator vapor space.

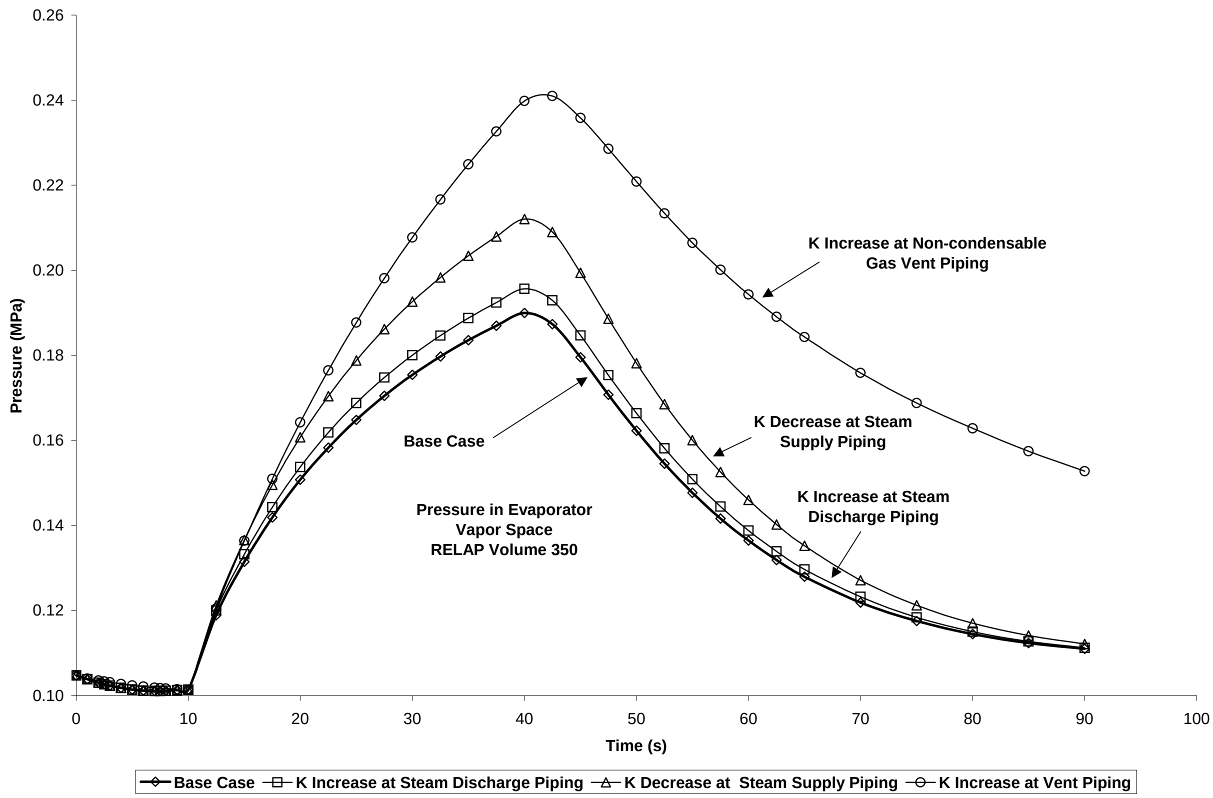

Figure 7 – Effect of Hydraulic Resistance Variation on Evaporator Vapor Space Pressure.

The base case values of the hydraulic resistance used for the various fittings and system components were evaluated using Idel'chik[2]; the overall variations imposed in the parametric studies were arbitrarily set. The non-condensable gas vent piping hydraulic resistance was increased by incrementing the number of fittings and using a higher value of the piping roughness. The steam discharge piping hydraulic resistance was increased by the same method above and by adding few local losses. The decrease of the hydraulic resistance in the steam supply piping was accomplished by a decreasing the number of fittings and type of valves.

Figure 7 clearly shows how the hydraulic resistance of the non-condensable gas vent piping affects the evaporator vapor space peak pressure, and it represents the most sensible component of the system under study. The pipe diameter of this vent piping is also responsible for the magnitude of the peak pressure in the evaporator vapor space. Ideally this vent piping should be big enough to minimize the pressure in the evaporator vapor space.

In an accident analysis space we can use all bounding values running toward the conservative direction. A bounding scenario can be found by including in the RELAP base case simulation model all the hydraulic resistance variations described above.

Figure 8 shows the new profile of pressure and temperature in the evaporator vapor space for this bounding case.

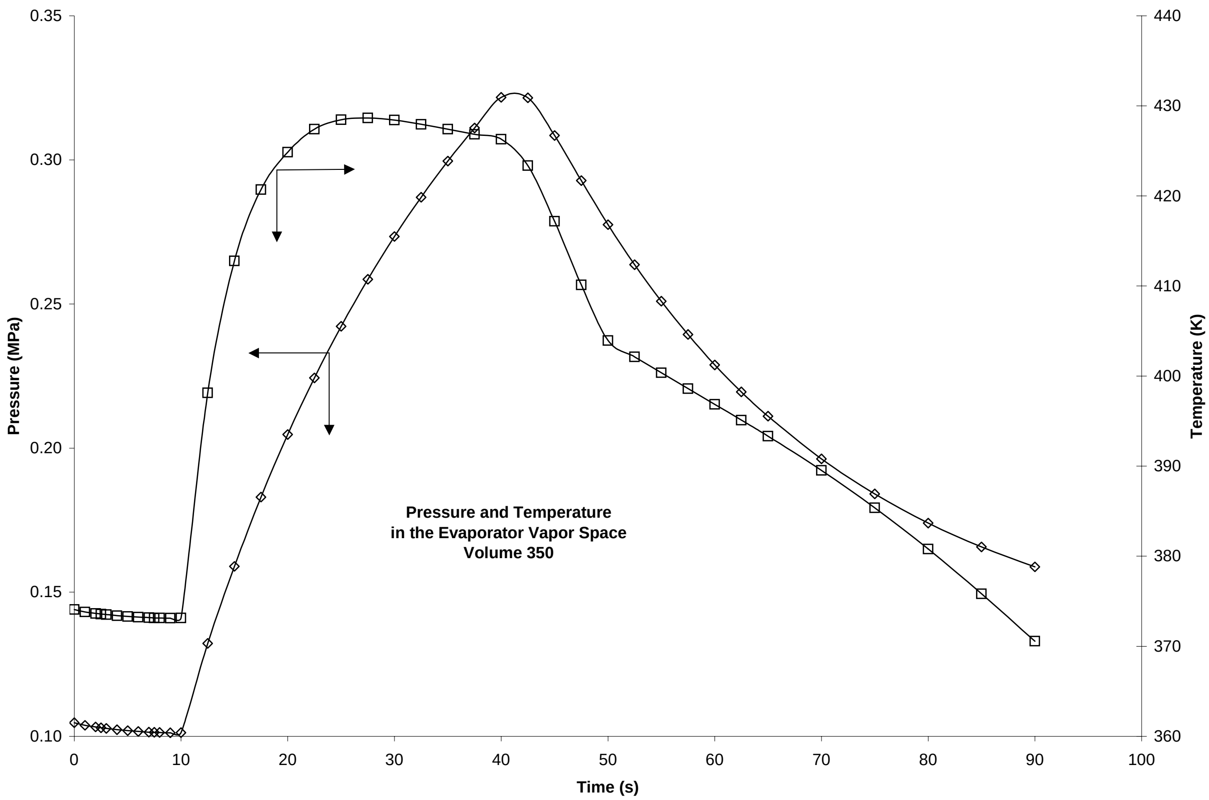

Figure 8 – Bounding Pressure and Temperature in the Evaporator Vapor Space.

Figure 8 shows that the peak pressure in the evaporator vapor space is at the assumed evaporator vessel design pressure and that the temperature already exceeds the assumed design temperature of 409 K. This example is of importance because it enables the analyst to make assessments on the various parameters affecting the analysis and in turn recommend, if required, the modification of process conditions and settings, or equipment changes and modifications.

One more event of importance would be to evaluate the pressure profile in the evaporator vapor space in case of failure of the air injection into the system. In this case the steam is flowing from both ends of the tube break into the evaporator vapor space without isolation, thus making it a totally unmitigated scenario.

Figure 9 shows the unmitigated pressure profiles for base case and bounding analyses.

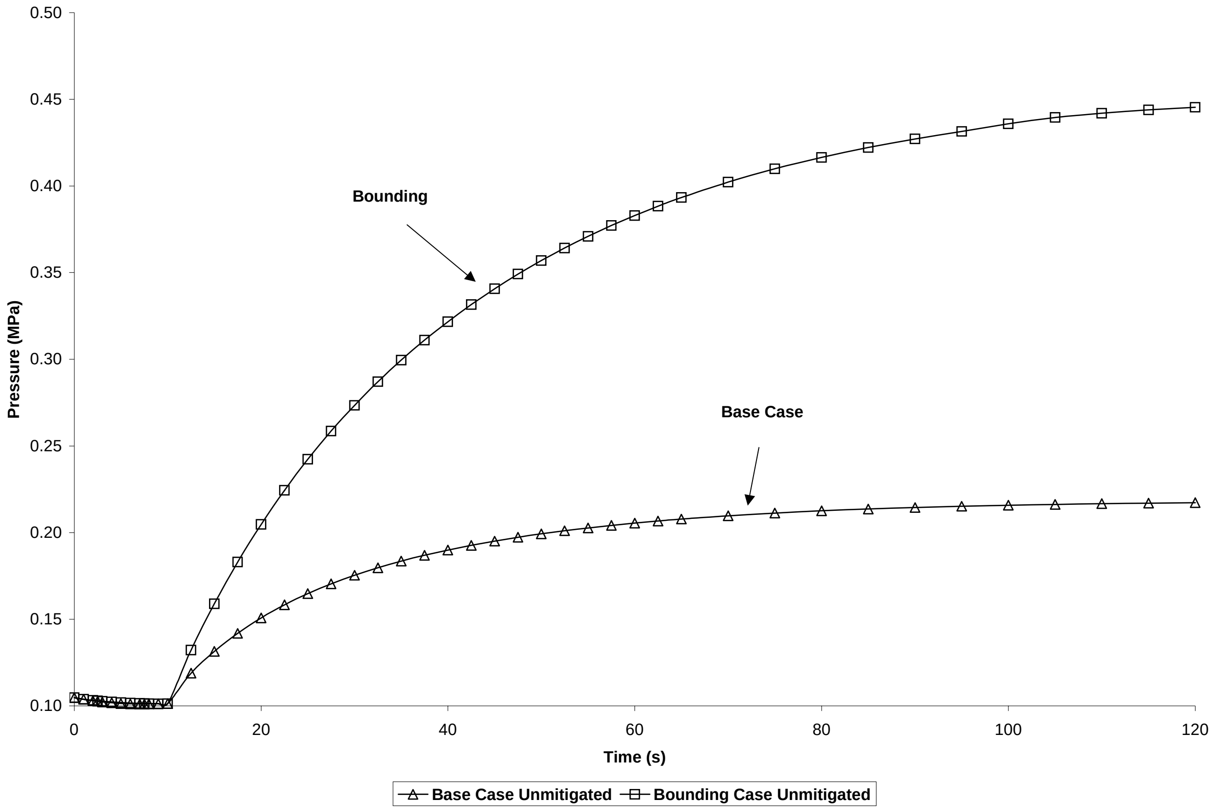

Figure 9 – Unmitigated Pressure Profiles in the Evaporator Vapor Space.

Figure 9 shows how the unmitigated bounding case is exceeding the design pressure of the vessel, while the base case is below the design pressure with sufficient margin.

Concluding Remarks

The analysis performed in this paper is an example of how an evaporator can be modeled in a conservative fashion to assess its operability during the accident scenario described above. The use of RELAP computer code is essential to properly evaluate the pressure and temperature transients taking place in the evaporator vessel as well as, if required, in other parts of the system.

The fundamental recommendation given is to simulate the process of the system prior to model accident situations to enhance the confidence of the results. Furthermore, it is recommended to carefully evaluate the hydraulic resistances of the system components because of their effects on the analysis results and possibly work with as-built piping drawings. It is clear that the simple methodology to study an evaporator accident as presented in this paper using RELAP, lends itself to two situations. 1) An existing evaporator, as analyzed here, needs an assessment to determine whether or not is capable to withstand accident conditions. In this way all possible scenarios are analyzed and process data are altered to yield conservative answers. This is a basic process of synthesis that lies at the base of engineering work. 2) A new evaporator will be designed. This situation will lend itself to a broader involvement where the analysts can use RELAP and can in turn span its imagination to many possible design/scenario configurations. This is a fundamental process of engineering analysis. In both cases, when these accidents are analyzed as described, by possibly varying all parameters influencing the results, the chief benefit is the achievement of a defensible work.

References

1. "RELAP5/MOD3 Code Manual," NEWREG/CR5535, INEL-95/0174, June 1995.

2. I. E. Idel'chik, "Handbook of Hydraulic Resistance – Coefficients of Local Resistance and Friction,"US Atomic Energy Commission, AEC-TR-6630, 1972.