



# International Agreement Report

## Assessment of the Capability of the TRACE Code to Calculate Hydraulic Piping Loads During Fluid Transients

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## ABSTRACT

This document assesses TRACE v.5 Patch 9 code for its ability to calculate hydraulic piping loads during fluid transients (i.e., water hammer). Current software for water hammer analysis assumes liquid flow at low Mach numbers and rather limited cavitation. However, nuclear power plants must also be designed for fluid transients that fall beyond the capabilities of programs commonly used for water hammer analysis because of the appearance of two-phase flow at high speed (in other words, with a Mach number close to or greater than 1). Examples of these special fluid transients are pipe break, safety relief valve discharge and steam pocket collapse. So far, RELAP5 has been the tool commonly used for analyzing these types of fluid transients, but RELAP5 is now being phased out, so a replacement is needed. TRACE is designed to replace RELAP5 for analyzing the transient thermal-hydraulics in nuclear reactors. The aim of this study, then, is to determine if TRACE may be used to calculate the hydraulic loads during fast fluid transients.

In this study, the TRACE code was used to calculate three representative cases in which significant pipe loads may arise due to the formation and propagation of shock waves:

- 1) Shock tube with nitrogen gas
- 2) Discharge line of a safety relief valve with steam
- 3) Discharge line of a safety relief valve with hot water

The results for Case 1, 2 and 3 are compared with the analytical solutions. The accuracy of the results relevant to the predicting of hydrodynamic loads are assessed.



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## EXECUTIVE SUMMARY

This study aims to assess if the TRACE code [1] can be used to estimate the unsteady pipe forces that occur in the discharge piping of a Safety Relief Valve (SRV), thereby providing useful data for piping stress analysis and support design. Achieving this goal requires a suitable simulation of very fast fluid phenomena that occur in a shorter time scale than what the code was originally intended to use.

The three cases listed here were selected for the assessment of the capability of the TRACE code to evaluate fluid transient forces in the discharge lines of SRVs:

1. Shock tube with nitrogen gas
2. Discharge line of an SRV with upstream steam
3. Discharge line of an SRV with upstream hot water

The particular details of the calculation cases were selected to be close to those found in practical applications and to have an analytical solution that can be used for comparison purposes.

The cases were simulated with TRACE, calculating the behavior of the relevant variables for the pipe load estimation. The pipe loads created by the simulated events were calculated from the rate of change of the fluid momentum.

The assessment compares the results of simulations performed with the TRACE code for Case 1 with the exact analytical solution. For Cases 2 and 3, the TRACE results are compared with the theoretical analytical solution described in [2].

The code is able to represent all the relevant phenomena in the shock tube experiment. All the variables were calculated with reasonable accuracy, especially the compression shock wave, which is the major phenomenon inducing a transient force in the pipes.

For all the cases where a shock wave appears (not only the shock tube case), the code is able to calculate accurately the loads resulting from the passage of the shock wave. However, the loads caused by moving density discontinuities are not calculated to the same degree of accuracy, although it should be noted that the loads due to density discontinuity are usually lower than the loads due to shock wave. Additional issues arise in the case of hot water discharge through an SRV; flashing is so slow that a shock wave does not appear in the discharge line as would be expected. This abnormal behavior can be corrected by increasing the interfacial heat transfer coefficient to a rather large value.

While the calculations may not always be suitable for the estimation of forces, the code was able to reproduce all the relevant phenomena, including the formation and propagation of a shock wave and the flow of the compressing and expanding fluids and mixture, so they can be spotted during the analysis.



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The work presented in this paper has been performed with the use of the TRACE code and the SNAP graphical user interface provided under the CAMP agreement.



## **ABBREVIATIONS**

NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
RELAP	Reactor Excursion and Leak Analysis Program
SNAP	Symbolic Nuclear Analysis Package
SRV	Safety Relief Valve
TRAC	Transient Reactor Analysis Code
TRACE	TRAC/RELAP Advanced Computational Engine
US NRC	United States Nuclear Regulatory Commission
PWR	Pressure Water Reactor
BWR	Boiling Water Reactor



# 1 BACKGROUND AND INTRODUCTION

Both Pressure Water Reactors (PWR) and Boiling Water Reactors (BWR) are susceptible to the effects of water hammer with two-phase flow in SRV discharge lines. Although a number of different computer programs exist that are suitable for calculating loads during fluid transients in piping systems with a single-phase flow, there is a decided lack of programs for analyzing transients with two-phase flows.

In PWR plants, the discharge lines from the pressurizer SRV may experience two-phase flows due to the discharge of water seals located on the line upstream or due to the discharge of hot (flashing) liquid if the pressurizer is flooded. After the accident at Three Mile Island, one of whose causes was a malfunction of the pressurizer safety valve, the nuclear industry made a considerable effort to measure the fluid-dynamic loads on SRV discharge lines and to develop a methodology that would predict such loads. Because of the fact that complex phenomena (e.g. the appearance of shock waves, the movement of water slugs, flashing) take place during these types of discharges, the load calculation methodology made use of the RELAP5/MOD1 software program, which, although it had been designed for slower transients, was found to be able to predict loads to an adequate degree of accuracy [3]. Later on, new versions of the software appeared, such as RELAP5/MOD3, that made it necessary to re-evaluate the code to check that the new changes had not affected the code's ability to predict hydrodynamic loads in SRV discharge lines [4].

Today, RELAP5 is being phased out in terms of maintenance and updates and is being replaced by TRACE. This makes it advisable to develop a new methodology for calculating hydrodynamic loads on SRV discharge lines based on a code that is still being maintained. TRACE may be such a code; accordingly, this study offers an initial evaluation on TRACE's ability to predict phenomena that take place in the discharge line of an SRV.

The present assessment focuses on two capabilities of the TRACE code. The first is TRACE's ability to simulate the basic phenomena that occur in the discharge line during an SRV opening event: shock waves, density discontinuities (such as the passage of a water slug). The second is the ability to predict the hydrodynamic forces due to shock waves and discontinuity waves to a degree of accuracy that is suitable for engineering purposes.

Discharge lines located downstream of an SRV are subject to a very fast fluid acceleration, pressure rise and density changes. The simulation of such an event and quantification of the induced loads are the two main purposes of this study.

The analysis of the simulation results focuses on the calculation of the fluid forces, trying to determine whether any accurate and useful results can be derived from them. In each case, the known load-inducing phenomena are identified in the simulation results. Finally, the results are used to determine the loads induced in the piping.

Three benchmark cases are used for this assessment. Case 1 is representative of a shock tube with ideal gas. The shock tube with ideal gas is a classical problem that was previously used to test other one-dimensional thermo-hydraulic codes [5], [6]. Case 2 is representative of the discharge line of an SRV with steam discharge. Case 3 is representative of the discharge line of an SRV with saturated water discharge.

Results for Case 1 were subsequently compared with the exact analytical solution. Results for Cases 2 and 3 were compared with the results of an idealized analytical model described in reference [2], which assumes instantaneous valve opening, frictionless pipe and homogeneous equilibrium flow.

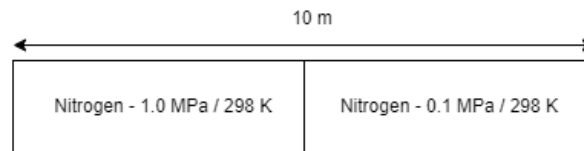
The shock tube was calculated first and it was used to set a suitable volume size and time step, as well as the numerical method for an accurate description of the pressure waves. The SRV discharge cases were investigated later, identifying other phenomena that might be relevant for the calculation and assessing the accuracy in conditions closer to those found in actual nuclear power plant systems.

## 2 ANALYSIS CASES

### 2.1 Case 1: Shock Tube Problem with Ideal Gas

#### 2.1.1 Case 1 - Description

The shock tube problem is a classical problem involving a sharp pressure change in a compressible fluid. This problem consists of a tube filled with gas, separated into two regions by a diaphragm located at the center of the tube length, where the pressure in one region is higher than in the other, see Figure 1.



**Figure 1 Case 1 Shock Tube with Gas**

The filler gas is initially stagnant and keeps a homogeneous temperature until the diaphragm bursts, sending a shock wave into the low-pressure region. The gas in this region is heated and pressurized by the gas from the high-pressure region, which is cooled by expansion. The gas expansion in the high-pressure region also propagates with a wave as the perturbation reaches the previously unaffected gas. During the time it takes for the shock wave and the rarefaction wave to reach the end of the tube, the velocity and fluid properties along the tube can be determined with an exact solution to this problem and they can also be calculated using the TRACE code in order to assess the application of the code.

The simulated tube is a 10-meter-long pipe with an inner diameter of 5 cm and a diaphragm located in the middle of the tube. The high-pressure region is filled with nitrogen at 298 K (25 °C) and 1 MPa. The low-pressure region is filled with nitrogen at 0.1 MPa and the same temperature.

An exact analytical solution (Riemann problem) can be calculated for this case. The exact solution neglects the friction losses, and it is valid until the moment when the pressure waves caused by the diaphragm rupture reach the dead ends of the tube. The exact solution is shown for comparison purposes in the results.

#### 2.1.2 Case 1 - Model

The analysis of the shock tube involves phenomena propagating at supersonic speeds and extremely rapid transient changes. Therefore, the time limits that are commonly used in other hydraulic calculations may not be suitable here.

The exact analytical solution of the shock tube problem indicates that the shock wave velocity reaches 564.84 m/s. The Courant time-step limit was calculated for three cell lengths—0.05 m, 0.10 m, and 0.20 m—as shown in Table 1 using the shock wave velocity. Based on recommendations from previous studies [7], the time step should be set to one tenth of the acoustic Courant limit; this value is also presented in Table 1 (third column) as a reference for the choice of the time step to use.

The time step used for TRACE shock tube simulations in Case 1 is  $10^{-5}$  s. The impact of the time step choice on the results will be reviewed with the calculation of the reaction forces on the pipe.

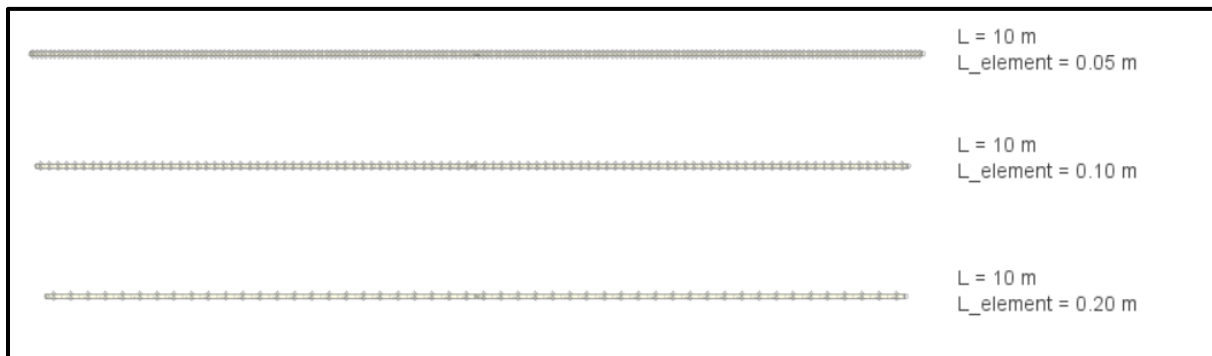
In all cases, the transient begins at the moment when the boundary separating the different pressure regions disappears.

The time step data, the required PIPE component geometry and initial conditions, and the friction settings—disabled to enable comparison with the exact solution—are entered into the TRACE input as previously described. All other input parameters and default calculation options within the hydraulic components and the namelist remain unchanged.

Moreover, this model was tested using both the SET numerical method (the default numerical method in TRACE) and the semi-implicit numerical method. The results of the simulations remain unchanged when either method is used. Therefore, the SET numerical method was used for all simulations.

**Table 1 Case 1 Time Step for Courant Number C=1 and C=0.1**

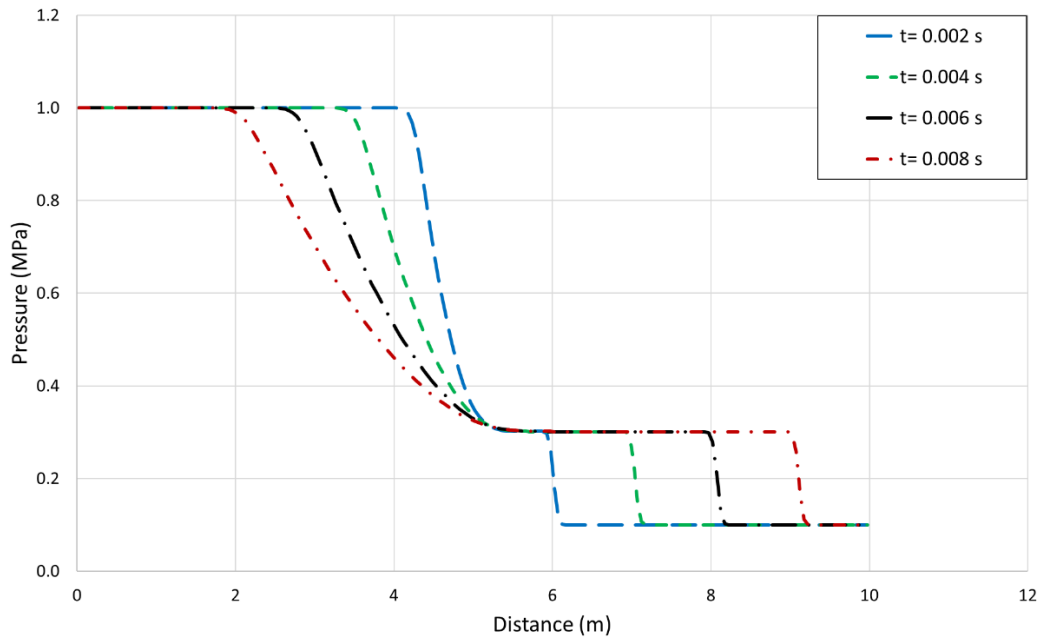
Cell Length (m)	Time Step (s)	Time Step (s)
	Courant =1	Courant =0.1
$\Delta x = 0.05$	$8.85 \cdot 10^{-5}$	$8.85 \cdot 10^{-6}$
$\Delta x = 0.1$	$1.77 \cdot 10^{-4}$	$1.77 \cdot 10^{-5}$
$\Delta x = 0.2$	$3.54 \cdot 10^{-4}$	$3.54 \cdot 10^{-5}$



**Figure 2 Case 1 (Shock Tube) TRACE Model**

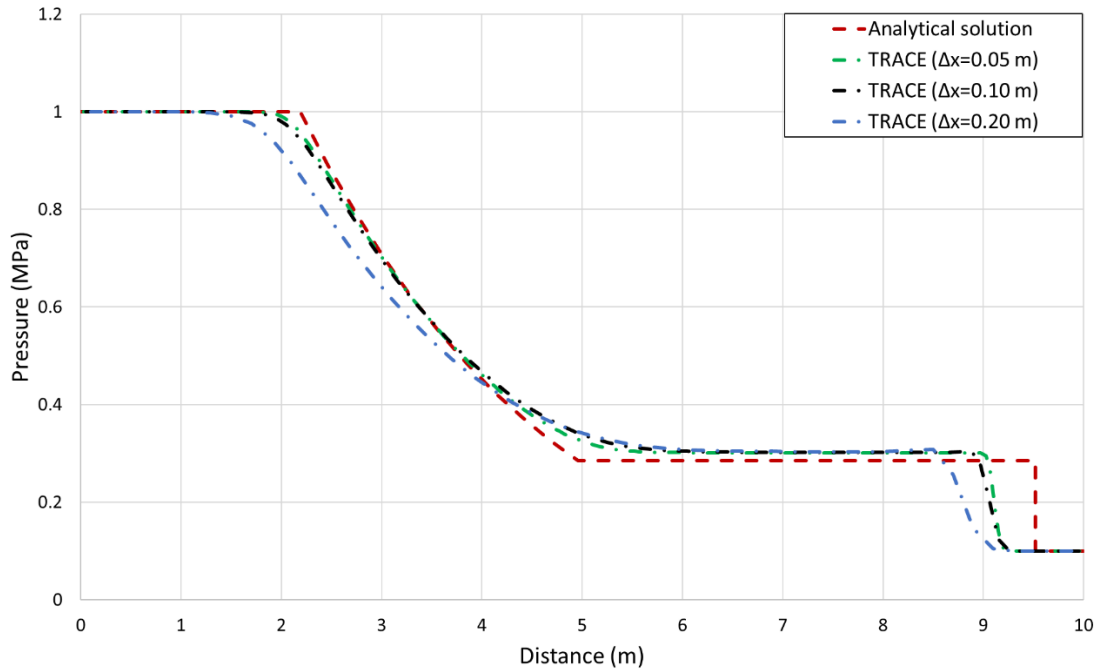
### 2.1.3 Case 1 - Results

Figure 3 shows the pressure profile at four different times: 2 ms, 4 ms, 6 ms and 8 ms with a volume size of 0.05m. Figure 4 to Figure 7 then provide a comparison of the TRACE simulation and the analytical solution for the pressure, density, temperature and velocity gas profiles at 8 ms. The shock wave phenomenon is clearly represented in both the numerical solution and the TRACE simulation, including the pressure wave travelling into the low-pressure area and the depressurization wave in the high-pressure region. The behavior of the gas tube is reasonably well represented in this simulation.

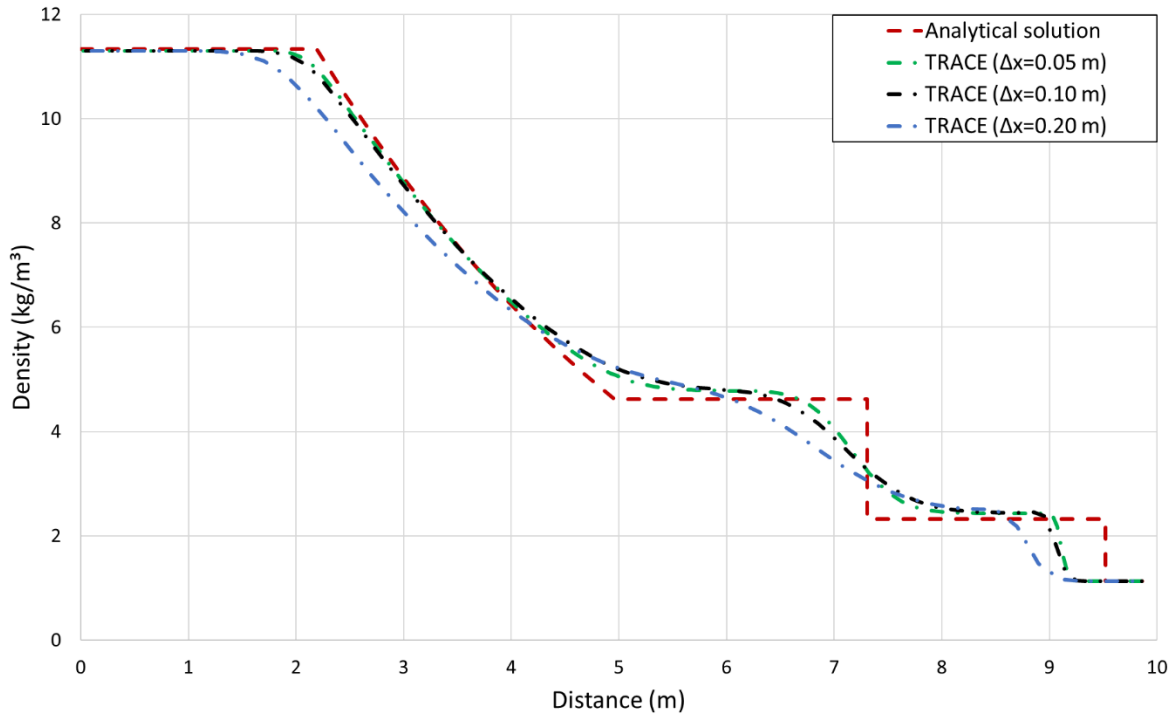


**Figure 3 Case 1 (Shock Tube): Pressure Profile at 2, 4, 6 and 8 ms**

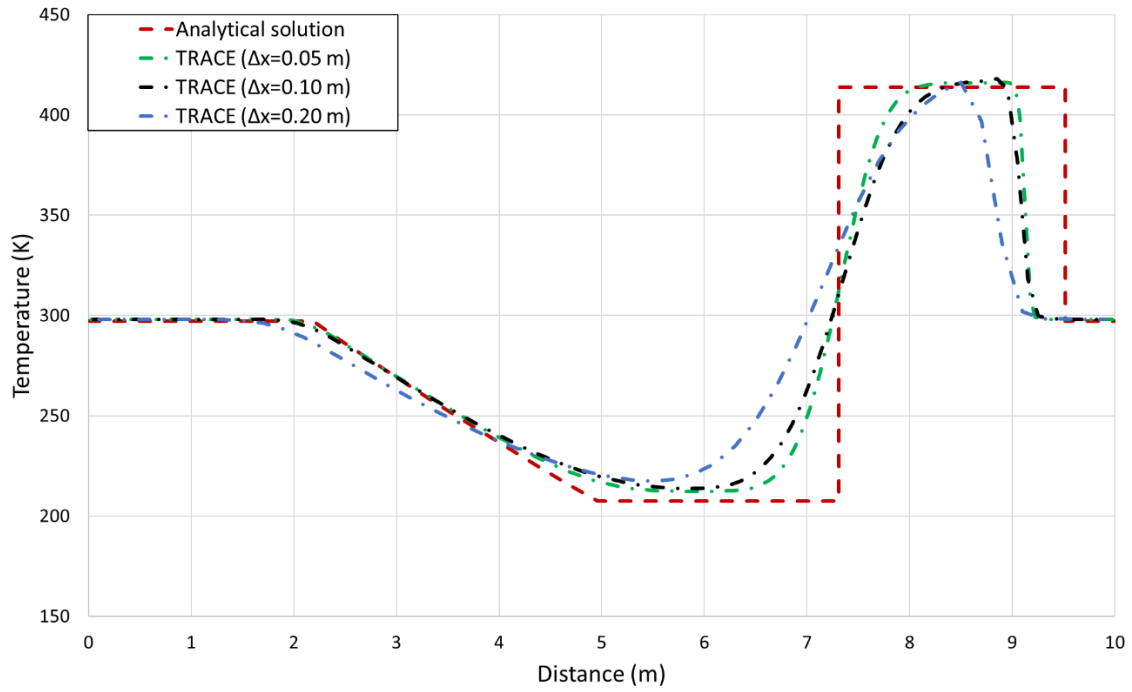
When compared with the analytical solution, the TRACE results show some minor inaccuracies, especially in the shock wave propagation. The numerical results tend to overestimate the shock wave pressure and underestimate the propagation speed slightly. Regarding the depressurization wave occurring in the high-pressure region, there is a close match between the exact and numerical solutions.



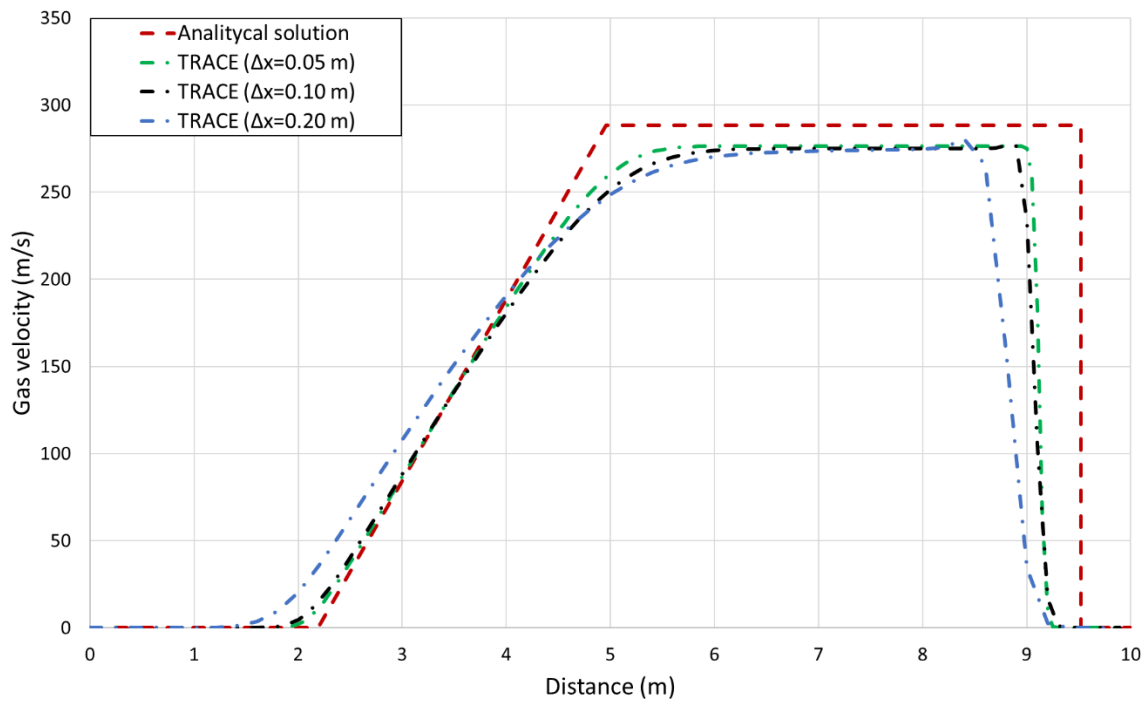
**Figure 4 Case 1 (Shock Tube): Pressure Profile at 8 ms**



**Figure 5 Case 1 (Shock Tube): Density Profile at 8 ms**

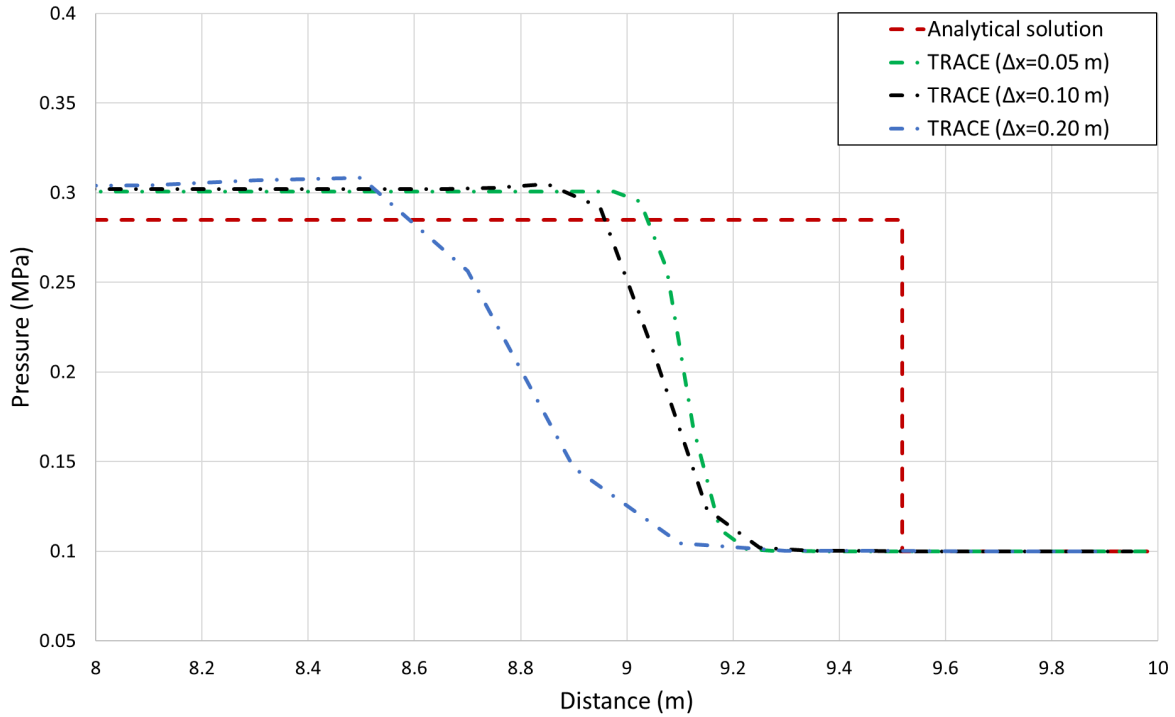


**Figure 6 Case 1 (Shock Tube): Temperature Profile at 8 ms**



**Figure 7 Case 1 (Shock Tube): Velocity Profile at 8 ms**

There is some apparent diffusion of the sharp pressure change on the edge of the shock wave. This phenomenon is linked to the node size because the abrupt pressure change requires several nodes to be properly represented and therefore the discontinuity is smeared along some length that is roughly proportional to the volume size. In all studied cases, the shock wave is diffused along five or six control volumes, see Figure 8. This provides a rule of thumb to estimate the calculated thickness of the shock wave (the analytical thickness of a shock wave is zero).



**Figure 8 Case 1 (Shock Tube): Pressure Profile From 8 to 10 m at 8 m**

This length can be very relevant for the calculation of the induced forces on a pipe segment during passage of a shock wave. Even when the total change of the fluid properties was properly calculated, the estimation of the instantaneous force would not be accurate if the number of fluid volumes in the pipe segments (where forces are calculated) is not enough to represent the shock wave front within the considered pipe length.

Any inaccuracy in the simulation of the fluid behavior, including both the calculation of the fluid characteristics and the numeric diffusion, affects the estimation of the mechanical loads that are induced on the piping.

The induced force on each pipe segment can be calculated from the change of momentum in the fluid. The results of a TRACE run provide the average properties on each cell, hence, the induced force can be calculated directly from the results.

$$F = \frac{d}{dt} \int \rho \cdot v \cdot dV \simeq \frac{1}{\Delta t} \cdot \sum_{i \in CV \text{ in segment}} V_i [\rho_i^t \cdot v_i^t - \rho_i^{t-\Delta t} \cdot v_i^{t-\Delta t}] \quad \text{Eq[1]}$$

where

$F$  is the transient fluid force

$\Delta t$  is the last step

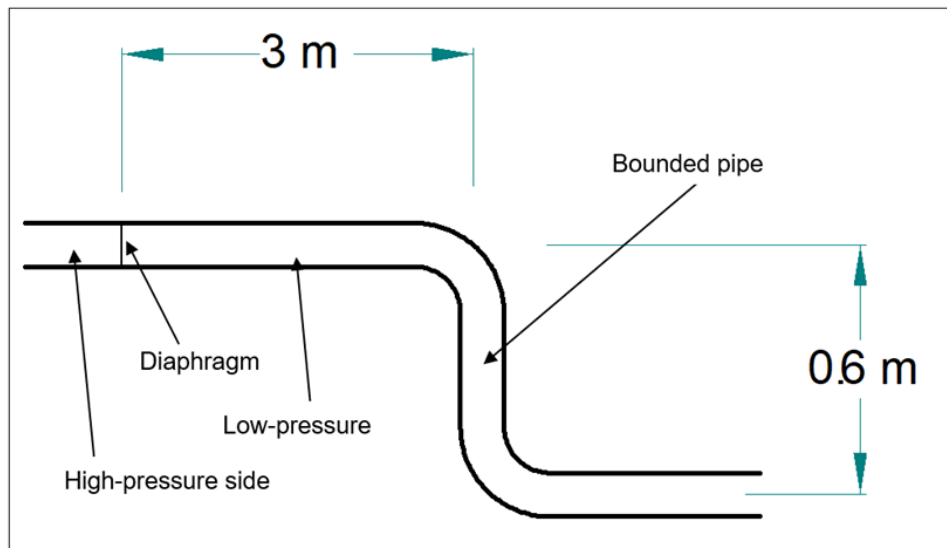
$V_i$  is the fluid volume of the  $i^{\text{th}}$  control volume

$\rho_{,i}^t$  is the fluid density in the  $i^{\text{th}}$  control volume at time  $t$

$v_{,i}^t$  is the fluid velocity in the  $i^{\text{th}}$  control volume at time  $t$

With this methodology, the force can be estimated using the results calculated with TRACE. For this purpose, a hypothetical pipe segment is postulated in the low-pressure region that is subject to the pressurization wave.

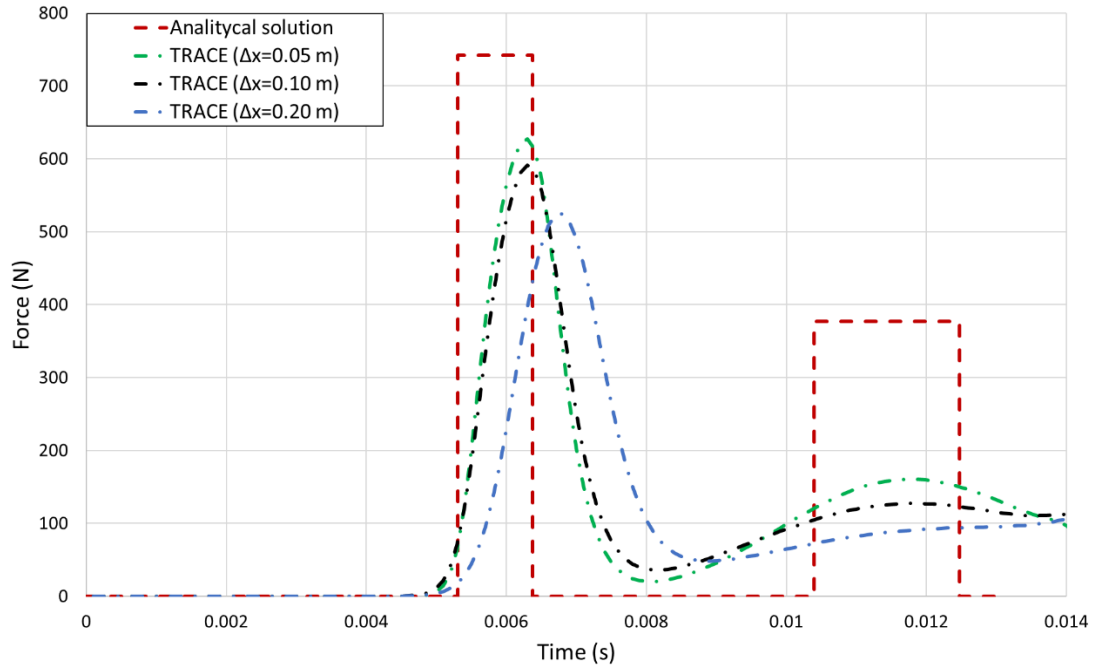
The hypothetical segment is placed 3 m away from the diaphragm and it is 0.6 m long, see Figure 9. This particular configuration shows the effect of excessively long cells (i.e. too few volumes in the pipe segment to be calculated) and is subject to the separate effect of the passage of the shock wave and the inrush of cold gas expanding in from the high-pressure region.



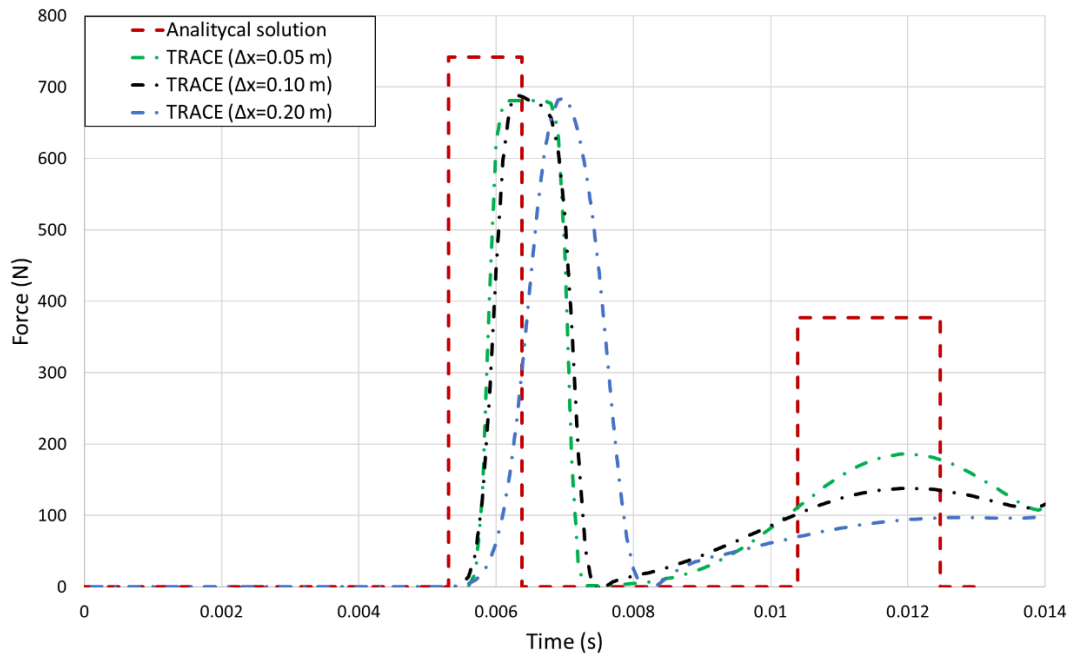
**Figure 9 Case 1 (Shock Tube): Hypothetical Pipe Segment for Fluid Force Calculation**

The induced forces created after the diaphragm burst are calculated with the same nodalization as in the previous section: 0.05 m, 0.1 m and 0.2 m. This means that the reference pipe segment is represented by 12 elements, 6 elements and 3 elements, respectively.

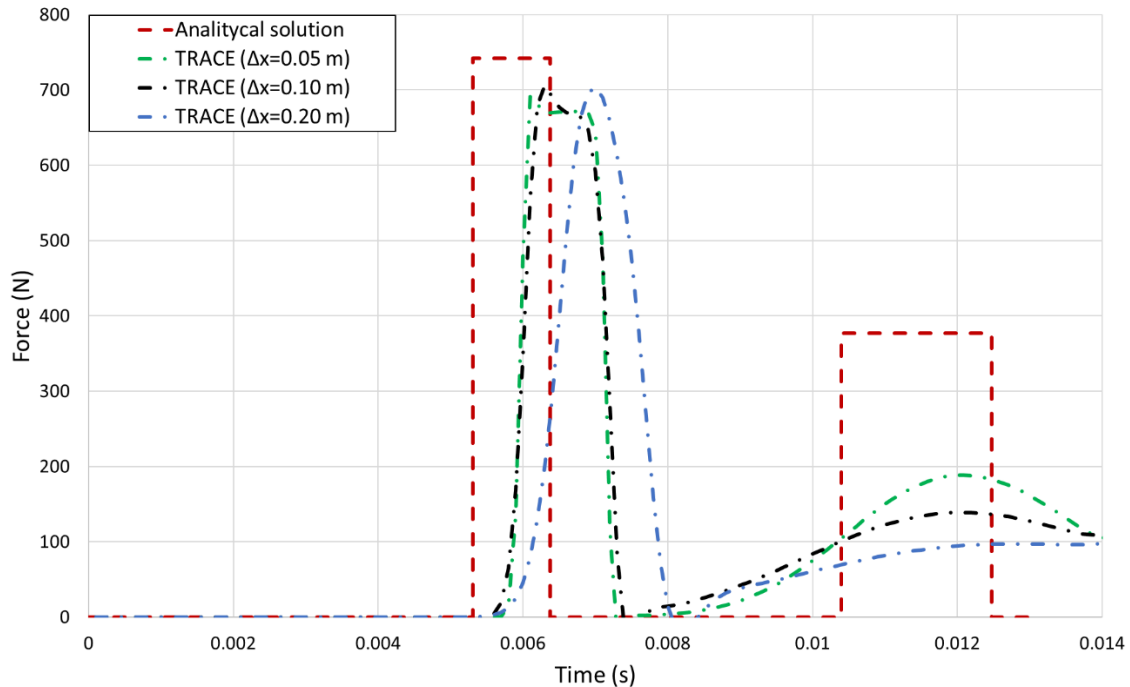
Additionally, the axial forces were obtained from TRACE simulations using the previously calculated time step,  $10^{-5}$  s, as well as two alternative time steps: one an order of magnitude larger,  $10^{-4}$  s, and the other an order of magnitude smaller,  $10^{-6}$  s, see Figure 10, Figure 11 and Figure 12.



**Figure 10 Case 1 Shock Tube Problem: Wave Force on Pipe Segment with a Time Step of 100  $\mu$ s ( $\Delta t = 10^{-4}$  Seconds)**



**Figure 11 Case 1 Shock Tube Problem: Wave Force on Pipe Segment with a Time Step of 10  $\mu$ s ( $\Delta t = 10^{-5}$  Seconds)**



**Figure 12 Case 1 Shock Tube Problem: Wave Force on Pipe Segment with a Time Step of  $1 \mu\text{s}$  ( $\Delta t = 10^{-6}$  Seconds)**

These results include two separate forces, the first of them caused by the shock wave is fairly close to the expected theoretical results. The second force is caused by the passage of the gas cooled by the expansion from the high-pressure region.

There is a moderate difference in the shock wave force between the cases with  $L=0.05$  m and  $L=0.1$  m while the case with  $L=0.2$  m is clearly smeared. In all cases, the total mechanical impulse is very similar despite the difference in the instantaneous load. Regarding the time step, similarly to the assessment of the fluid characteristics, there is a noticeable difference with the largest time step, while the results for  $10^{-5}$  s and  $10^{-6}$  s (Courant number close to 0.1 and 0.01) remain quite similar.

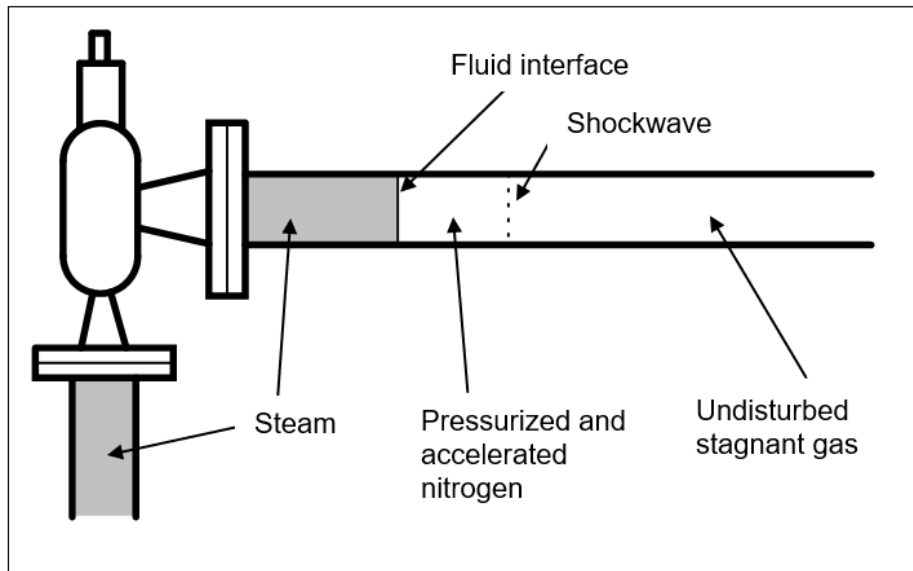
The load created by the density difference shows considerable diffusion, with major differences affecting all the simulated cases. This is an effect of the numerical diffusion that can also be observed in Figure 5 and Figure 6 (density and temperature profiles) where a theoretical sharp change in temperature and density between the compressed gas from the low-pressure region and the cold gas from the high-pressure region is instead calculated by TRACE as a relatively smooth change.

It should be noted that theoretical calculation neglects the diffusion of the discontinuity wave that will happen in a real system because of the gas turbulence. Nevertheless, the observed result of the TRACE calculation is actually a consequence of the numerical diffusion (as can be seen in the dependence on the particular nodalization).

## 2.2 Case 2: Safety Valve Steam Discharge

### 2.2.1 Case 2 - Description

During the opening of an SRV, the phenomena present in the discharge pipe are similar to the ones that take place in the low-pressure region of the shock tube. When the valve opens, fluid from a pressurized component is relieved into a discharge pipe, see Figure 13. This pipe is typically filled with stagnant air or an inert gas at atmospheric pressure. The relieved fluid enters the discharge line, where it expands, thereby propelling the gas which was previously undisturbed. The expanding fluid creates a compression wave propagating through the air or gas filling the discharge line.



**Figure 13 Schematic of the Effects of an SRV Steam Discharge**

The characteristics of the flow during this event can be calculated with the methodology described in [2] neglecting the wall friction and the mixing of the involved fluids.

In case of the shock tube, a discontinuity in the gas phase is created when the diaphragm bursts. This event is assumed to be instantaneous. Nevertheless, when a valve opens, the flowrate across the SRV rises from zero to the discharge rate during a certain amount of time. Typical opening times of SRVs are in the range of tens of milliseconds. This means that the shock wave will not occur immediately after the SRV opening, and it may appear sometime after that event at some distance downstream the valve. This report explores two cases. The first case will be an idealized assumption where a constant discharge rate is achieved instantaneously after the valve opening. This case will be compared with the analytical solution derived from the equations in [2]. The second case will consider an opening time of 10 ms. It will be used to test if the shock wave formation can be reproduced with the TRACE code.

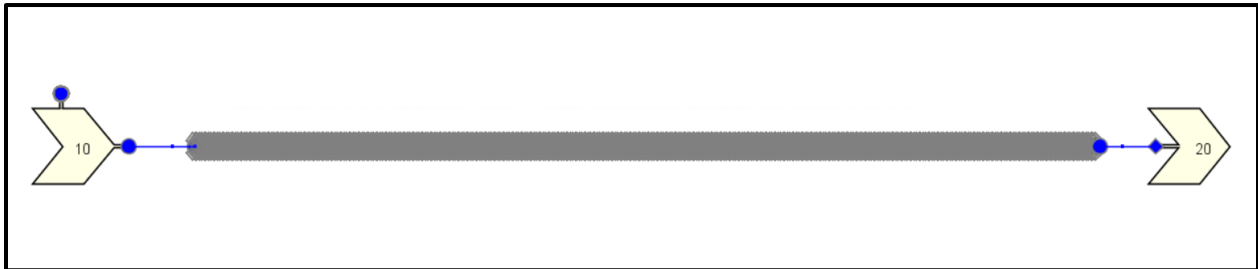
In the described scenario of an SRV discharge, the relieved fluid can be any gas or liquid which was not defined in the previous paragraph. The most common case in a nuclear power plant is the discharge of water or steam, as there are multiple valves protecting both the primary circuit,

other water systems and the water/steam power cycle components. In this section, the released fluid is assumed to be saturated steam.

### 2.2.2 Case 2 - Model

The SRV is represented using a FILL hydraulic component instead of the VALVE hydraulic component. This representation allows including the discharge flow rate into the hypotheses of the model (instantaneous opening and flow ramp) so that the analytical calculation can be used as a benchmark. The discharge rate in each instant is set using a flowrate-time table.

The opening and release of saturated steam at 9 MPa by an SRV into a DN500x12.5 mm pipe with a total length of 20 m is considered. The discharge pipe contains stagnant nitrogen under ambient conditions (298 K and 0.1013 MPa).



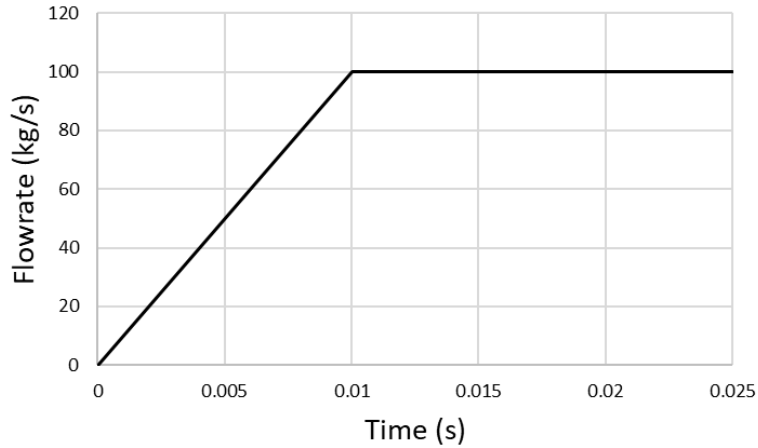
**Figure 14 Case 2 (SRV Steam Discharge) TRACE Model**

In this part of the evaluation, several calculation cases have been set. The test cases are listed below.

Run No. 1: The valve opening is assumed to be instantaneous, and the relieving rate is achieved immediately upon opening. This assumption is included in order to achieve results that are comparable with the analytical solution [2]. The discharge flowrate is 100 kg/s.

This calculation is performed with a cell length of 0.05 m, see Figure 14. An additional test is performed with an element length of 0.025 m in order to determine if there is a significant gain in refining the nodalization. The time step was set to  $10^{-5}$  s, as in Case 1.

Run No. 2: This case is almost identical to Run No.1 ( $\Delta t = 10^{-5}$  s and a cell length of 0.05 m). The only difference is that the instant opening assumption is removed. The valve is now assumed to open in a period of time. The discharge flowrate increases linearly until it reaches 100 kg/s during 10 ms, see Figure 15. This change aims to determine if a shock wave is formed during the acceleration of the fluid as predicted by the analytical model.

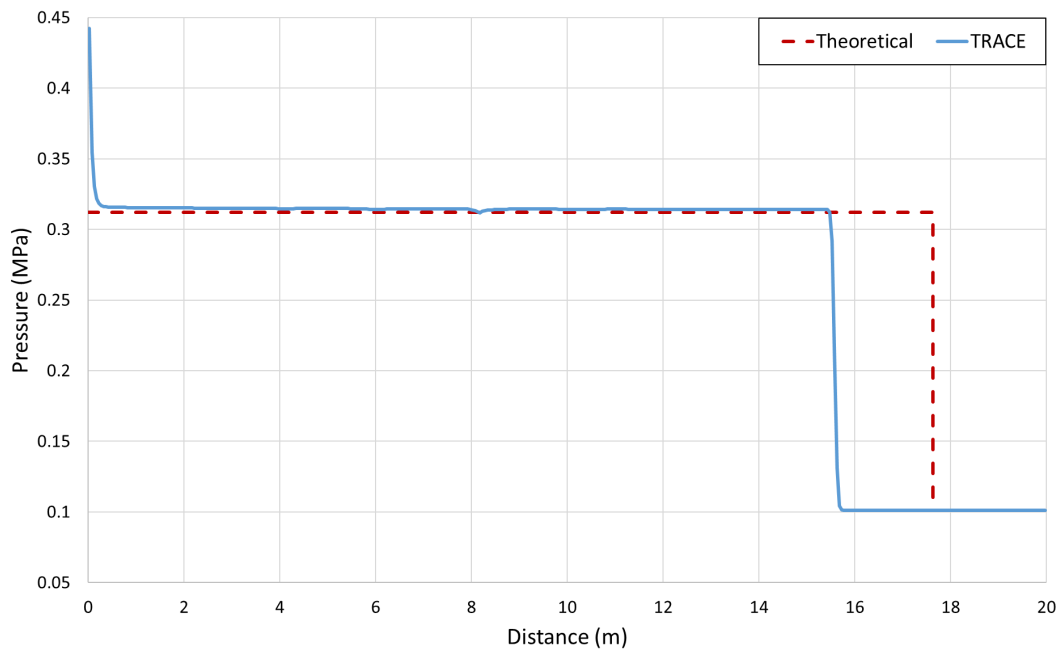


**Figure 15 Case 2 (SRV Steam Discharge): Flowrate Ramp Through SRV for Run No. 2**

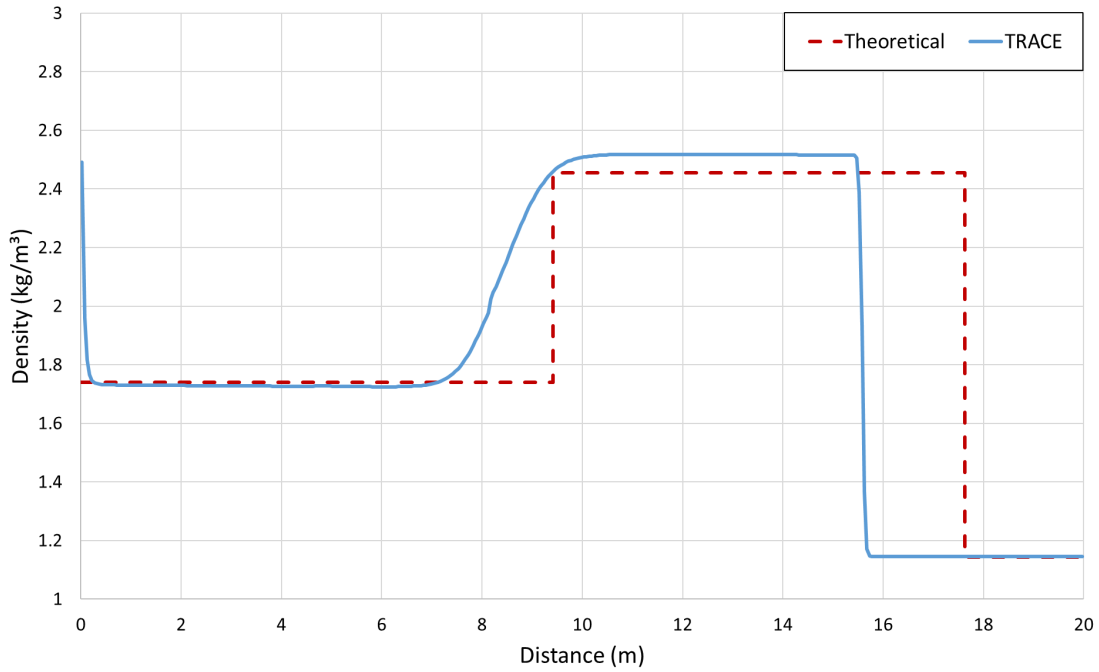
### 2.2.3 Case 2 – Results

#### Run No. 1: Saturated steam discharge: Instantaneous opening

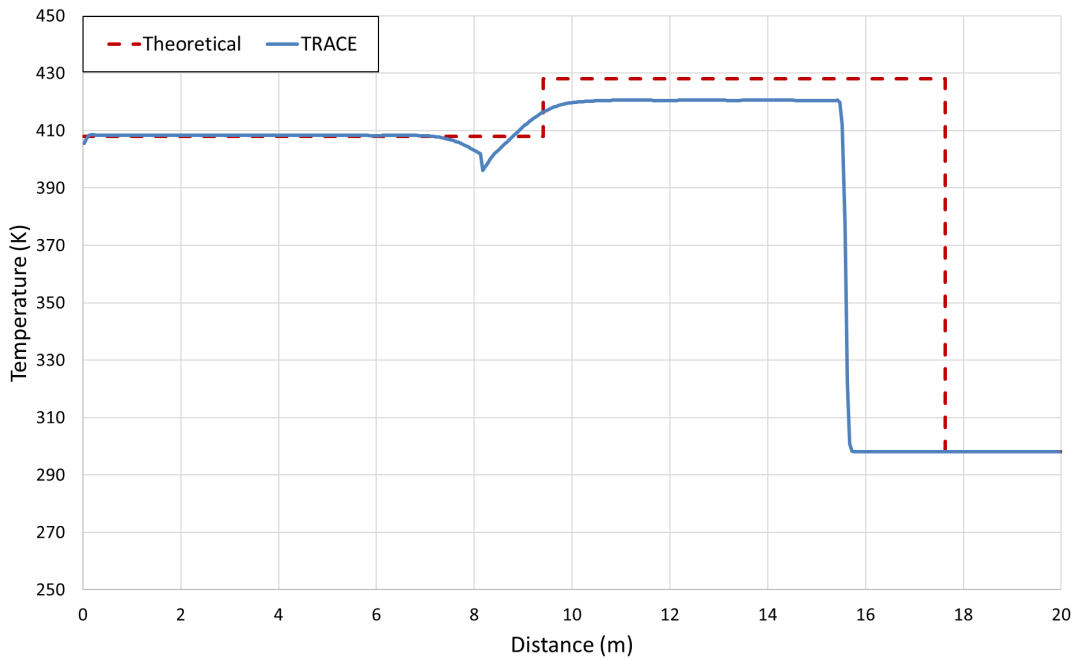
The first case, representing the discharge of saturated steam, is represented in Figure 16 to Figure 19. The figures include the main variables describing the phenomena occurring in the discharge line: temperature, pressure, density and gas velocity. Magnitudes are represented along the pipe length 0.03 s after the SRV opening.



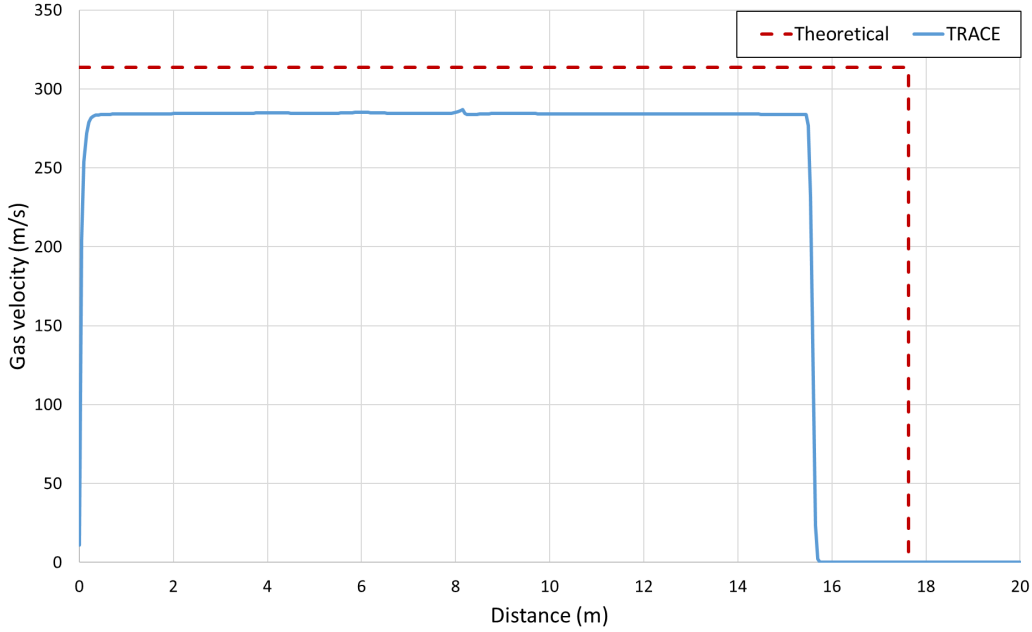
**Figure 16 Case 2 (SRV Steam Discharge) Run No. 1 (Instantaneous Opening): Pressure Profile at 30 ms**



**Figure 17 Case 2 (SRV Steam Discharge) Run No. 1 (Instantaneous Opening): Density Profile at 30 ms**



**Figure 18 Case 2 (SRV Steam Discharge) Run No. 1 (Instantaneous Opening): Temperature Profile at 30 ms**



**Figure 19 Case 2 (SRV Steam Discharge) Run No. 1 (Instantaneous Opening): Gas Velocity Profile at 30 ms**

The results in this case are analogous to the ones found in the low-pressure region of the shock tube. The gas velocity is underestimated in the shock wave propagation and the shock wave is slightly delayed compared with the theoretical values. In addition, the numerical diffusion mostly affects the mixing of the discharged fluid (steam) with the gas present in the pipe. Those inaccuracies affect the calculated load in a similar way to the effects that were found in Section 2.1.3.

The pipe load calculation is assessed with the same methodology as with the shock tube, calculating the forces from the momentum of the fluid in a hypothetical pipe segment. The forces are calculated from the rate of change of the fluid momentum. Since a two-phase flow exists in this case, the volume fraction, the density and the velocity of each phase are considered.

$$F \simeq \frac{1}{\Delta t} \cdot \sum_{i \in CV \text{ in segment}} V_i [ (\alpha_{g,i}^t \cdot \rho_{g,i}^t \cdot v_{g,i}^t - \alpha_{g,i}^{t-\Delta t} \cdot \rho_{g,i}^{t-\Delta t} \cdot v_{g,i}^{t-\Delta t}) + (\alpha_{f,i}^t \cdot \rho_{f,i}^t \cdot v_{f,i}^t - \alpha_{f,i}^{t-\Delta t} \cdot \rho_{f,i}^{t-\Delta t} \cdot v_{f,i}^{t-\Delta t}) ] \quad \text{Eq[2]}$$

where

$F$  is the transient fluid force

$\Delta t$  is the last step

$V_i$  is the fluid volume of the  $i^{\text{th}}$  control volume

$\alpha_{g,i}^t$  is the gas volume fraction in the  $i^{\text{th}}$  control volume at time  $t$

$\rho_{g,i}^t$  is the gas density in the  $i^{\text{th}}$  control volume at time  $t$

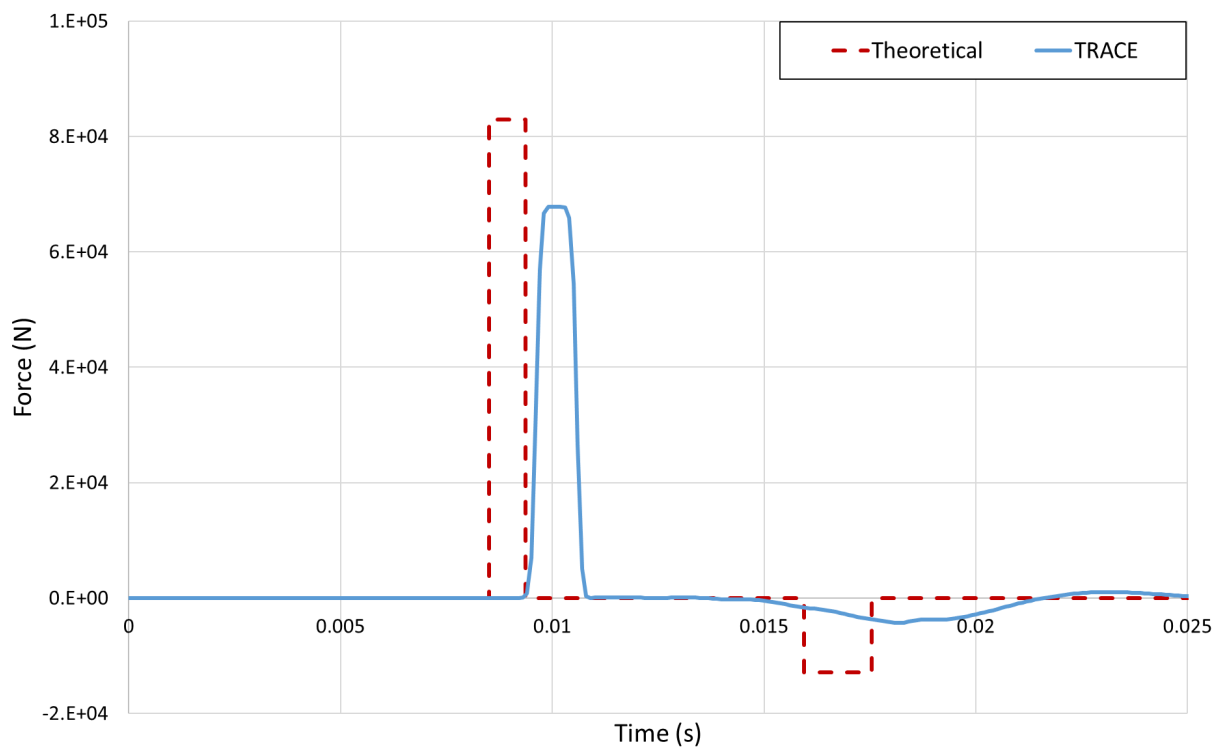
$v_{g,i}^t$  is the gas velocity in the  $i^{\text{th}}$  control volume at time  $t$

$\alpha_{f,i}^t$  is the liquid volume fraction in the  $i^{\text{th}}$  control volume at time  $t$

$\rho_{f,i}^t$  is the liquid density in the  $i^{\text{th}}$  control volume at time  $t$

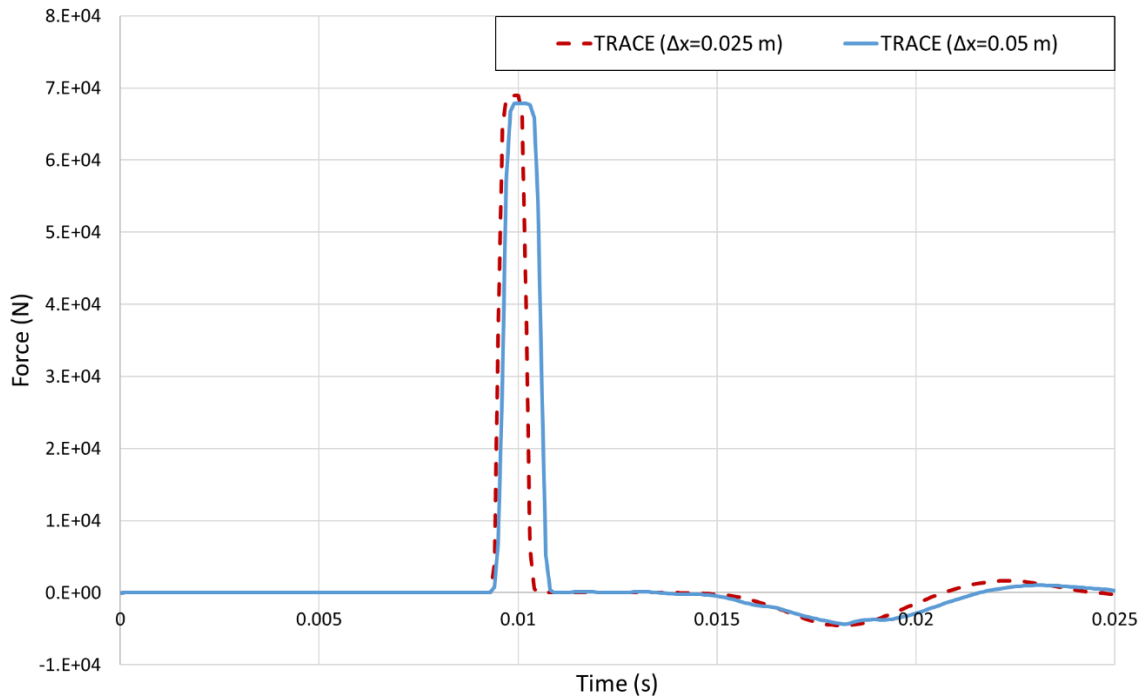
$v_{f,i}^t$  is the liquid velocity in the  $i^{\text{th}}$  control volume at time  $t$

The postulated pipe segment is located 5 m downstream of the SRV and has a length of 0.5 m. These values are arbitrary and have been selected in order to have a separate effect of the pressure wave and the arrival of the discharged steam instead of having an overlapping load. This separation makes the evaluation of the results easier.



**Figure 20 Case 2 (SRV Steam Discharge) Run No. 1 (Instantaneous Valve Opening): Pipe Loads (TRACE Versus Exact Solution)**

Figure 20 shows the pipe loads in the short segment located downstream of the SRV, including both the sharp effect of the shock wave passage and the load caused by the density difference between the steam and the nitrogen.



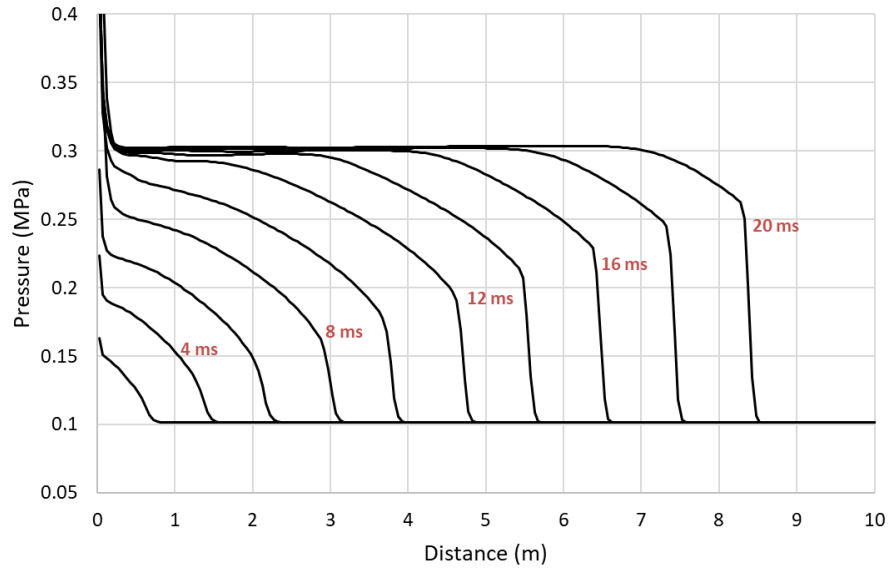
**Figure 21 Case 2 (SRV Steam Discharge) Run No. 1 (Instantaneous Valve Opening): Pipe Loads with Two Different Nodalizations**

The effect of the nodalization are checked by further reducing the volume size. The effect of the change in the nodalization is shown in Figure 21, which shows a rather small improvement with the lower nodal length. The simulation still shows an underestimation of the maximum forces and a large numerical diffusion in the load created by the arrival of the released steam.

Run No. 2: Saturated steam discharge: Opening time = 10ms

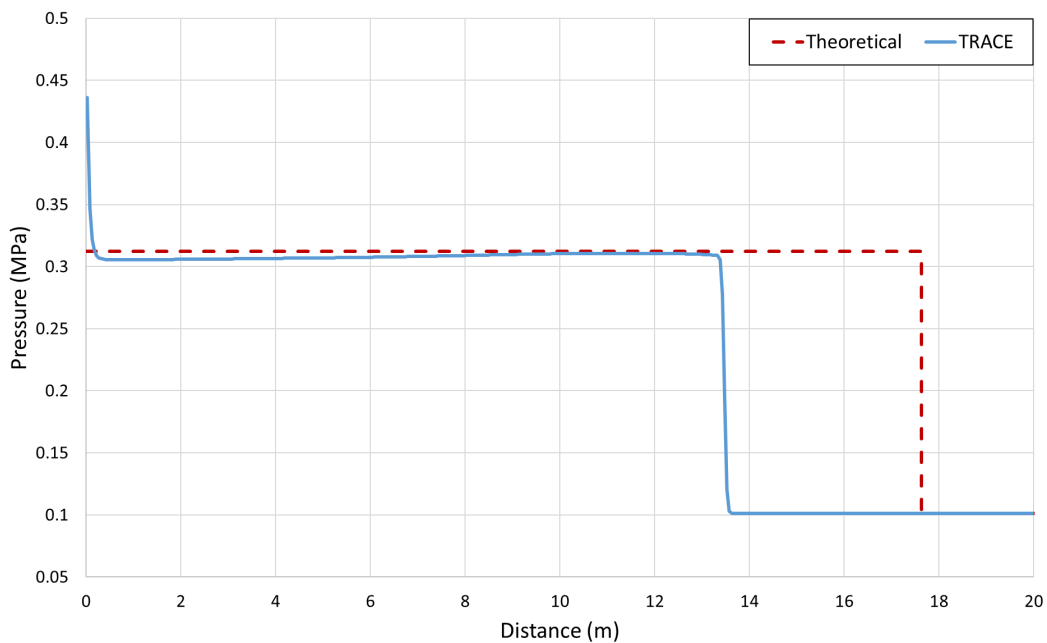
The previous run described an idealized SRV opening where the relieving rate is attained immediately. However, the assumption of a progressively increasing flow rate is closer to the actual behavior of the SRV release.

The Run 2 case, considering the discharge of saturated steam with a progressively increasing flow rate, is represented in Figure 23 to Figure 26. In this run, the flow rate increases linearly up to the maximum value. When the SRV starts opening, a compression wave is generated and propagates through the gas. At the same time, the flowrate rises, increasing the pressure downstream of the valve. While the pressure wave propagates, the gradient increases, turning the pressure wave into a shock wave. This phenomenon is adequately simulated by TRACE. Figure 22 shows the pressure evolution during the first 20 ms.

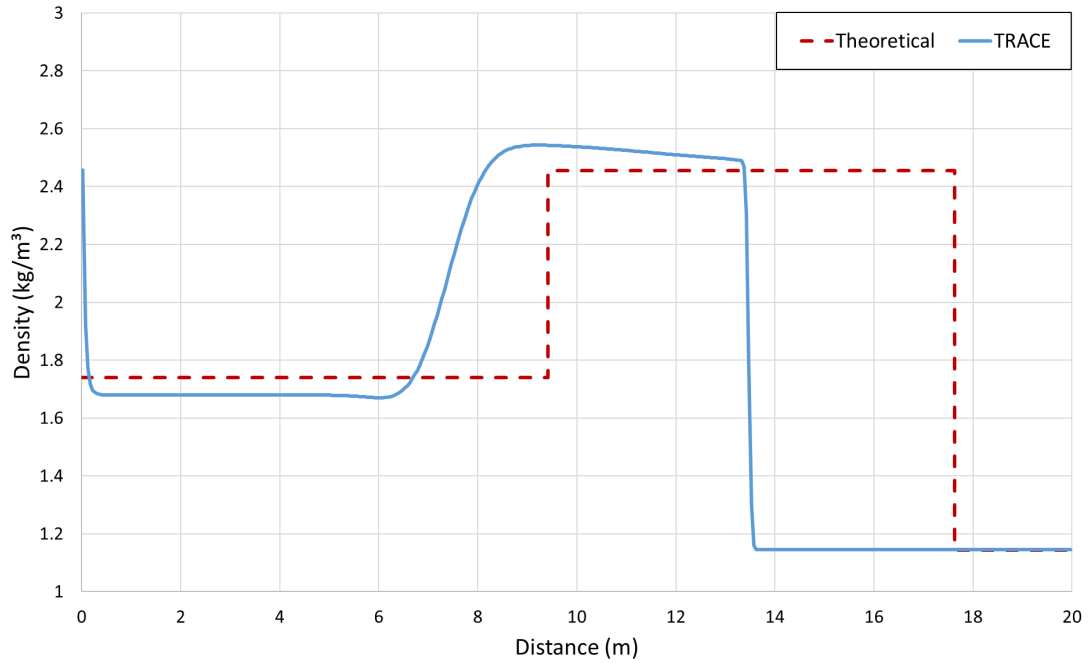


**Figure 22 Case 2 (SRV Steam Discharge) Run No. 2 (Non-instantaneous Valve Opening): Shock Wave Development**

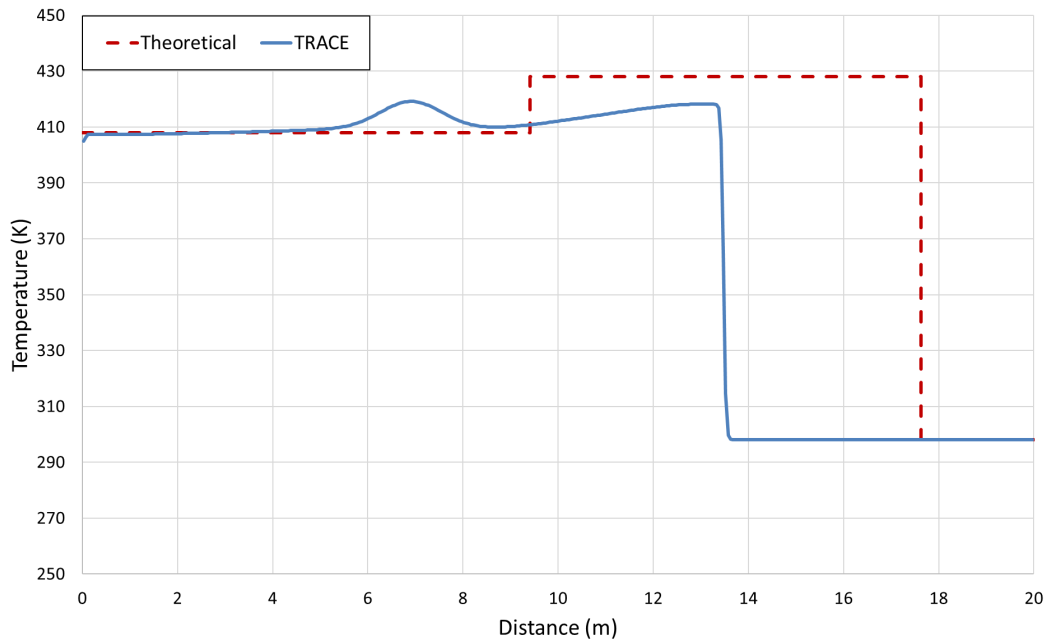
In the rest of the variables, there is an additional delay as well as some changes in the temperature and property profiles. However, this is a realistic consequence of the lower flowrate in the first milliseconds of this transient event.



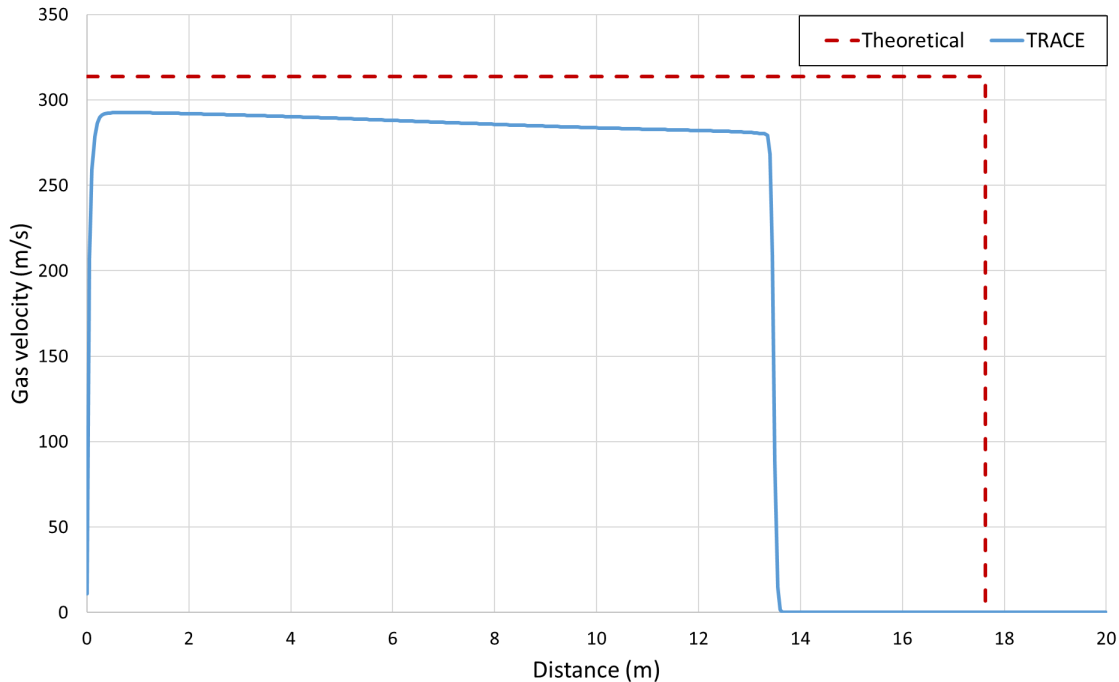
**Figure 23 Case 2 (SRV Steam Discharge) Run No. 2 (Non-instantaneous Opening): Pressure Profile at 30 ms**



**Figure 24 Case 2 (SRV Steam Discharge) Run No. 2 (Non-Instantaneous Opening): Density Profile at 30 ms**



**Figure 25 Case 2 (SRV Steam Discharge) Run No. 2 (Non-Instantaneous Opening): Temperature Profile at 30 ms**



**Figure 26 Case 2 (SRV Steam Discharge) Run No. 2 (Non-Instantaneous Opening): Gas Velocity Profile at 30 ms**

## **2.3 Case 3: Safety Valve Discharge with Saturated Liquid**

### **2.3.1 Case 3 – Description**

In the previous section, the fluid discharged was steam. When the relieved fluid is hot water, an additional complication arises due to flashing. The pressurized hot water is discharged as a steam/water mixture. In this case, with a two-phase flow, evaporation plays an important role in this event.

### **2.3.2 Case 3 – Model**

The TRACE model for evaluating a discharge event that includes a flashing liquid is almost identical to the model used in the previous section ( $\Delta t = 10^{-5}$  s and a cell length of 0.05 m), see Figure 14. The only difference was the conditions of the released fluid.

In this part of the evaluation, several calculation cases have been set. The test cases are listed below.

**Run No. 1:** This run represents the discharge of flashing water through an SRV. The discharged fluid is saturated water at 9 MPa, which will evaporate as it enters a low-pressure pipe. This case differs significantly from the former ones because evaporation and the two-phase flow play an important role in the simulated event.

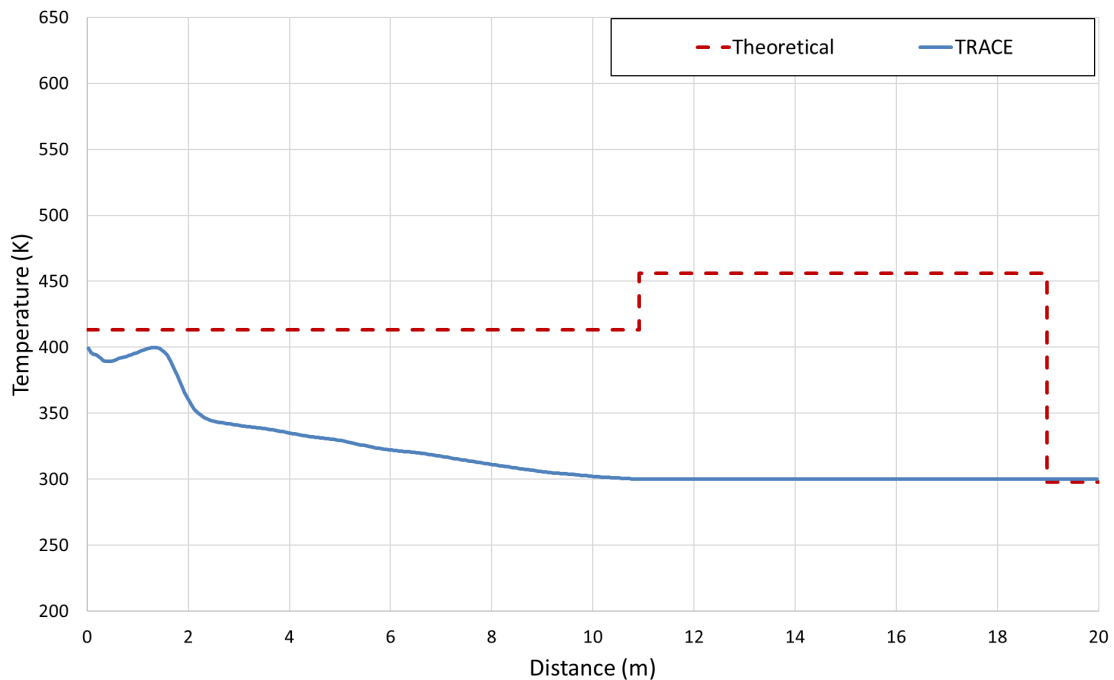
The simulated pipe remains unchanged; it is a DN500x12.5 mm pipe. The discharge pipe is initially full of stagnant nitrogen at ambient conditions (298 K and 0.1013 MPa). The valve opening is assumed to be instantaneous, and the relieving rate is achieved immediately upon opening. The discharge flowrate is 400 kg/s.

Run No 2: This run explores the effect of the interfacial heat transfer coefficient in the two-phase SRV discharge. This case is identical to the former one but it is performed by increasing the value of HTC ( $h_i = 10^7$  W/m<sup>2</sup>K).

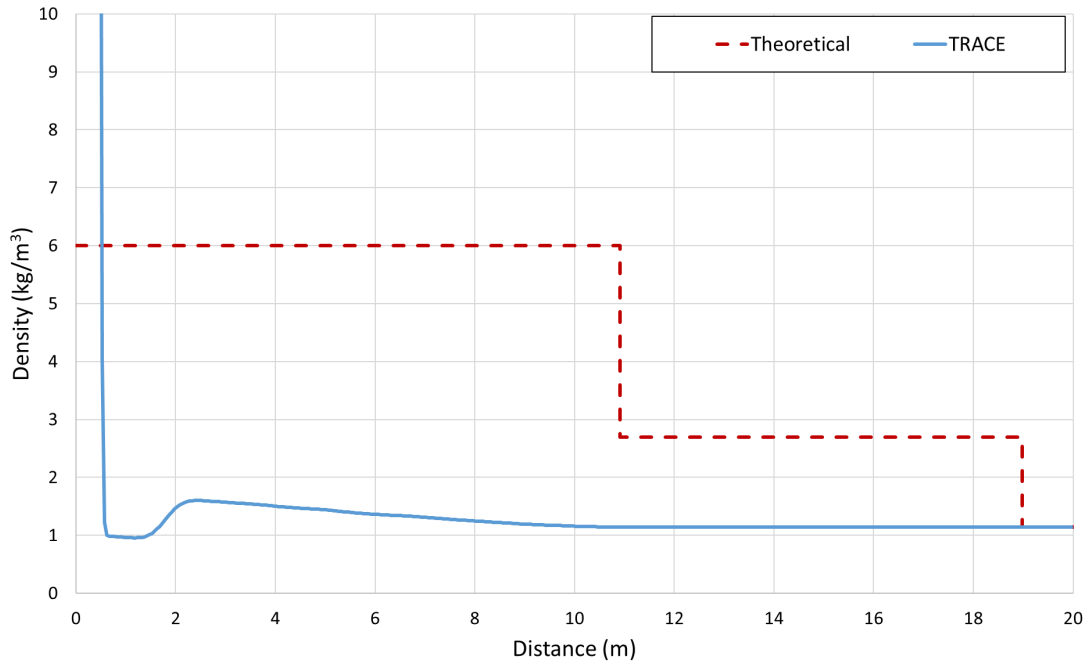
### 2.3.3 Case 3 - Results

#### Case 3 Run No.1: Saturated liquid discharge

In this case, the simulation with TRACE default calculation options was not satisfactory for estimating the phenomena involved in this fast transient, see Figure 27 and Figure 28.



**Figure 27 Case 3 (SRV Saturated Water Discharge) Run No. 1 (with Default HTC): Temperature Profile at 30 ms**

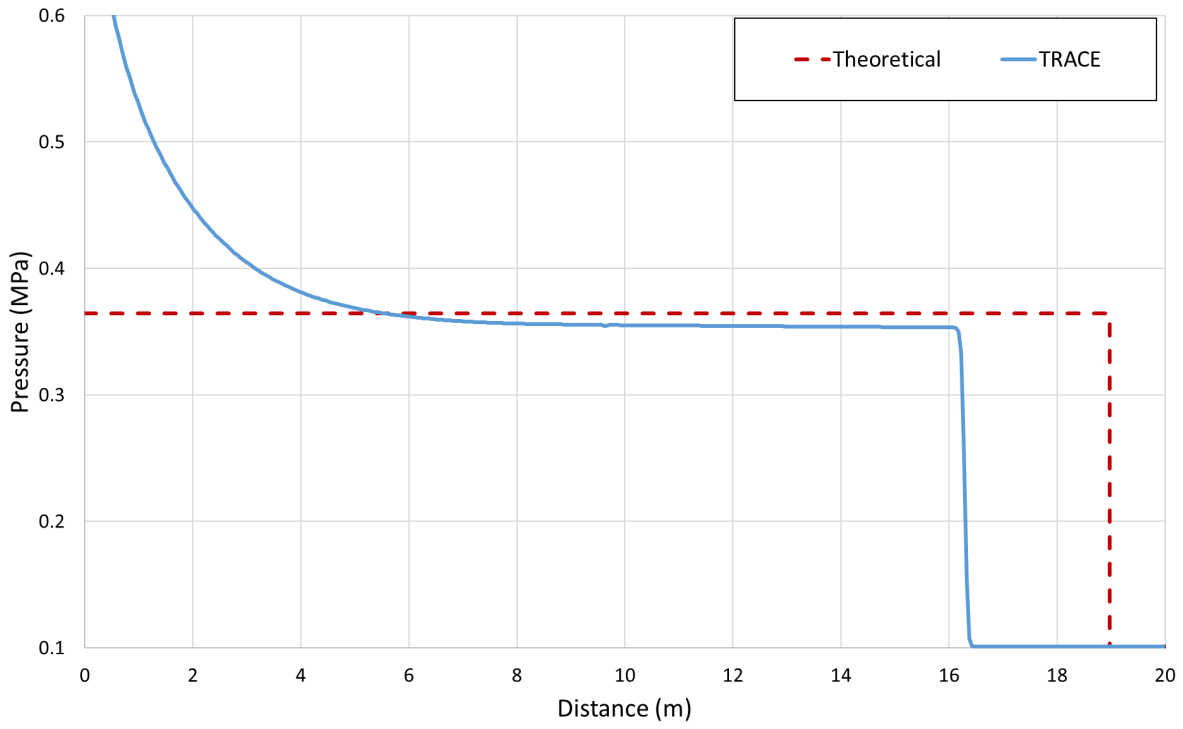


**Figure 28 Case 3 (SRV Saturated Water Discharge) Run No. 1 (with Default HTC): Density Profile at 30 ms**

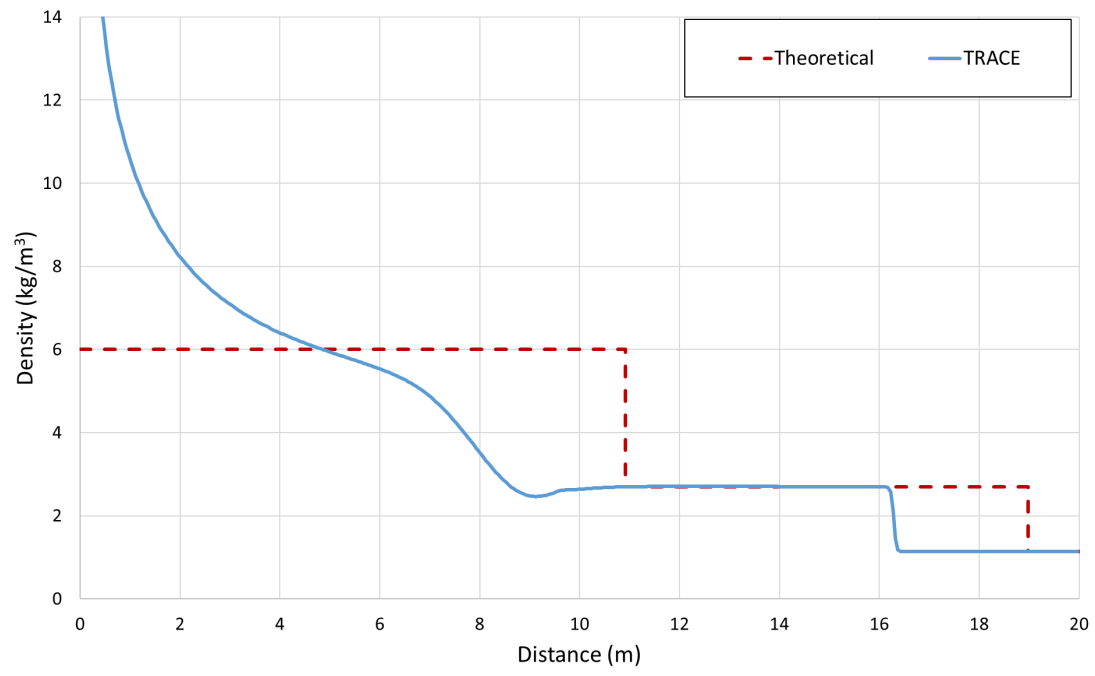
The previous case does not adequately represent the sudden boiling that will occur when the hot water is released in the low-pressure tube. This unrealistic simulation presents water that remains below its saturation temperature for too long, which delays the expansion that would actually occur in a sudden boiling event.

Case 3 Run No. 2: Saturated liquid discharge: Interfacial HTC= $10^7$ W/m<sup>2</sup>K

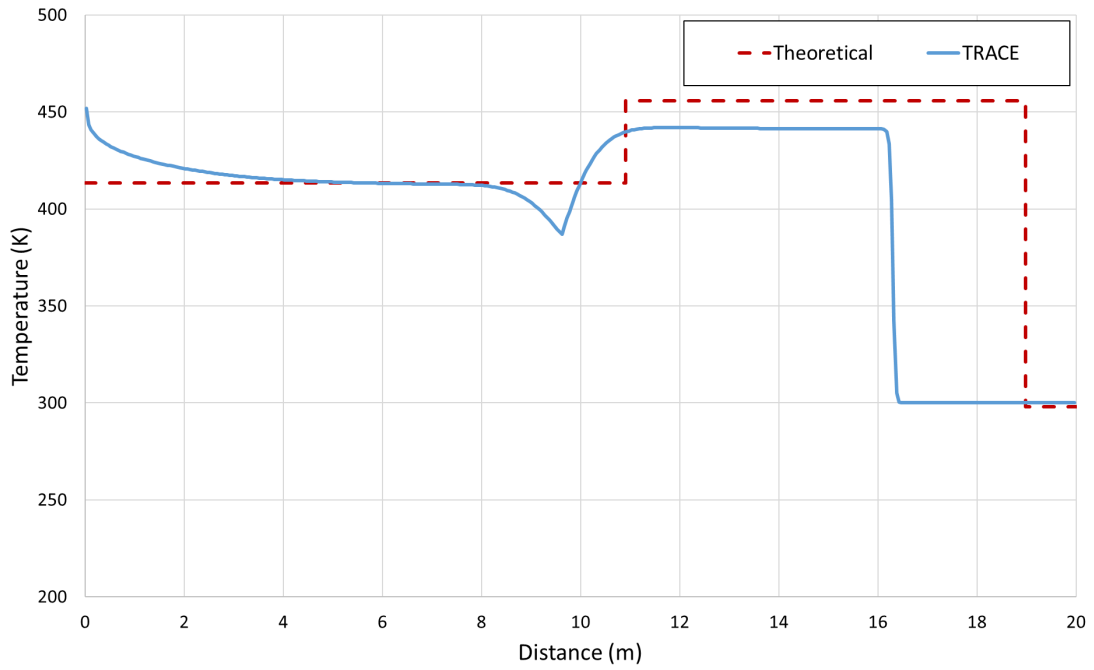
In Case 3 Run No. 2, see Figure 29 to Figure 32, the interfacial heat transfer coefficient was changed artificially in order to verify the factor limiting the evaporation of the hot water that should occur when it depressurizes. Forcing the code to use a very high heat transfer coefficient enabled a more realistic simulation of the flash boiling phenomenon. The interfacial heat transfer coefficient, which is used by TRACE to quantify the evaporation and condensation rate, was forced to an extremely high value ( $10^7$ W/m<sup>2</sup>K) in all flow regimes, thus creating an almost instantaneous evaporation once the liquid temperature was above its saturation temperature.



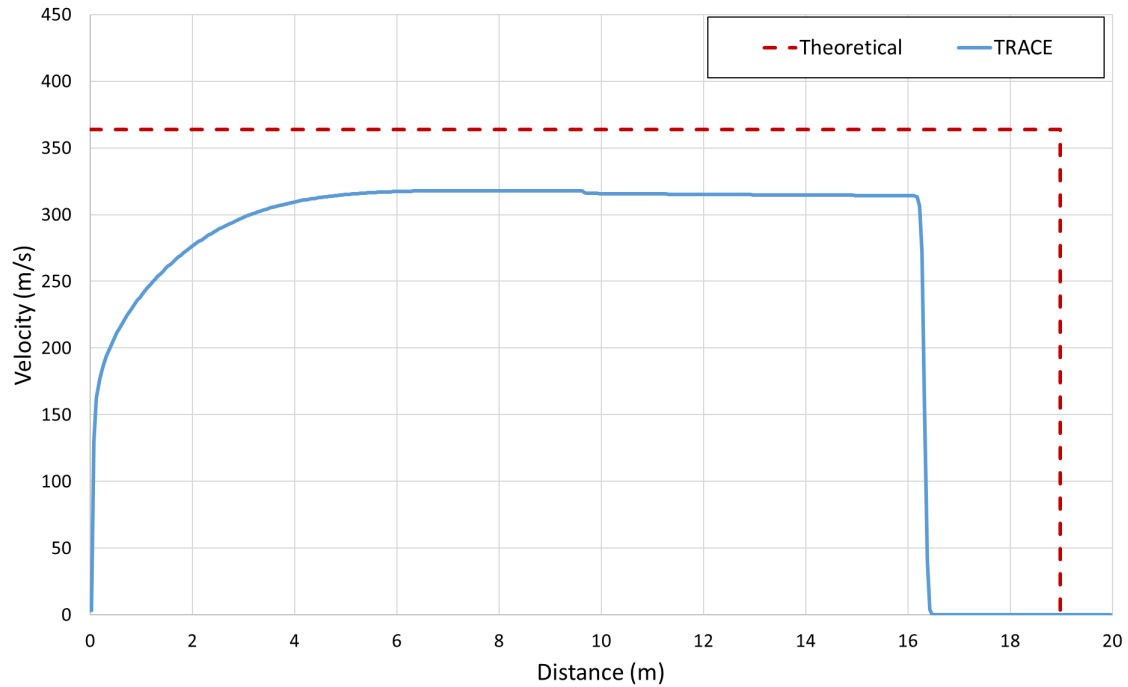
**Figure 29 Case 3 (SRV Saturated Water Discharge) Run No. 2 (with  $HTC=10^7 W/m^2K$ ): Pressure Profile at 30 ms**



**Figure 30 Case 3 (SRV Saturated Water Discharge) Run No. 2 (with  $HTC=10^7 W/m^2K$ ): Density Profile at Time 30 ms**



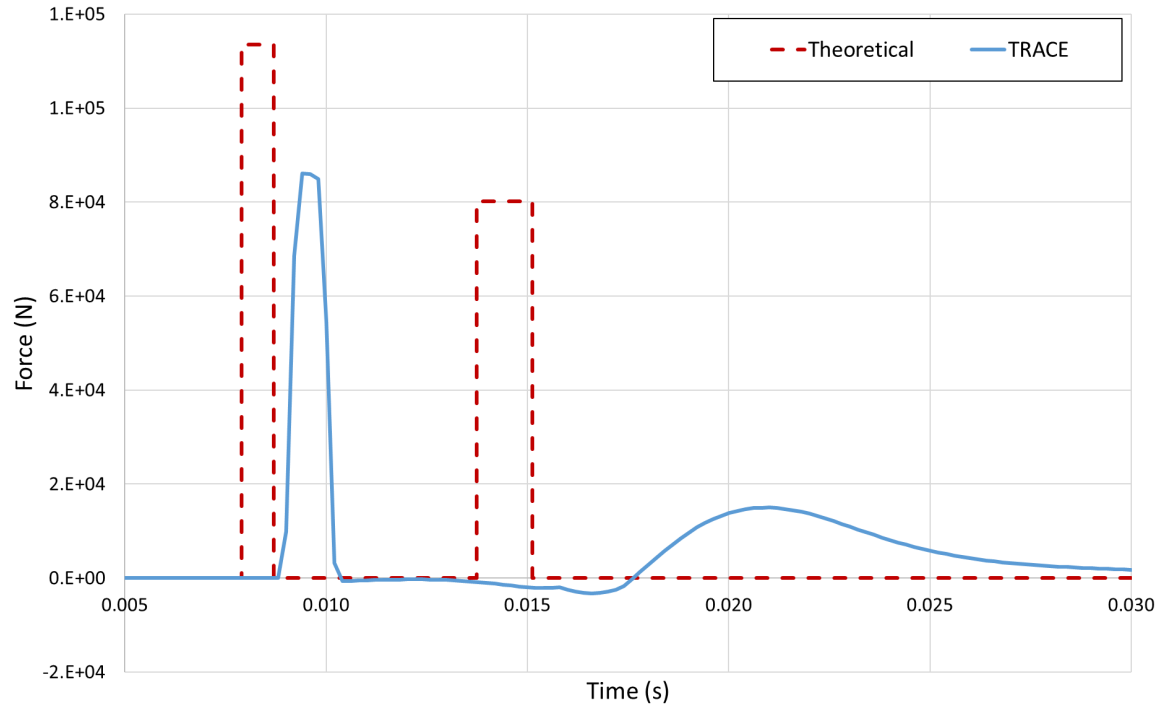
**Figure 31 Case 3 (SRV Saturated Water Discharge) Run No. 2 (with  $HTC=10^7 W/m^2K$ ): Temperature Profile at 30 ms**



**Figure 32 Case 3 (SRV Saturated Water Discharge) Run No. 2 (with  $HTC=10^7 \text{ W/m}^2\text{K}$ ): Gas Velocity Profile at 30 ms**

With this modification, the code is able to reproduce the shock wave created by the expanding mixture discharged by the SRV. However, it also creates another unrealistic behavior in the contact between the water-steam mixture and the nitrogen. The simulation shows a significant temperature drop at this point, due to evaporation of water since the presence of nitrogen reduces the saturation temperature.

According to the calculations, the maximum forces induced by the simulated transient are underestimated, especially the force created by the arrival of the steam-water mixture, see Figure 33. The forces shown here are in regard to a hypothetical segment of length 0.5 m located 5 m downstream of the SRV (the same configuration as in the steam discharge case 2).



**Figure 33 Case 3 (SRV Saturated Water Discharge) Run No. 2 (with  $HTC=10^7 W/m^2K$ ): Pipe Loads**



### 3 CONCLUSIONS

The shock tube problem and the discharge of an SRV into an empty pipe (i.e. filled with unpressurized nitrogen) were simulated for this study. The SRV discharge simulation includes the release of high-pressure steam and hot (flashing) water. Both cases were aimed at estimating the resultant pipe loads and were subsequently contrasted with an analytical solution in order to assess the accuracy of the results.

The selected variables for the simulation assessment were the ones involved in the load calculation (fluid velocity and density). In addition, pressure and temperature were also included in the assessment to show how such phenomena are represented in the simulation. Some of the most salient results of this study are the following:

#### **Shock Tube Problem With Ideal Gas**

The TRACE code was able to reproduce all the relevant phenomena occurring during the pressurization and depressurization of each region of the shock tube. The calculated fluid variables show an acceptable match with the analytical results.

The shock wave induced pipe load was calculated from the simulation results, finding a slight underestimation of the maximum load. The timing and evolution of the calculated forces show some inaccuracies but they constitute a good representation of the overall phenomena.

Numerical diffusion are found to be an issue in TRACE's ability to estimate transient loads created by changes in the fluid density. It has not been possible to achieve acceptable results that could have been used for the piping stress analysis. Nevertheless, such loads are not particularly relevant for the piping and support design for a steam discharge.

The use of a time step based on the existing criteria (i.e. less than one-tenth of the acoustic Courant limit) is found to be a good reference. The use of smaller time steps in simulating the studied phenomena did not yield significantly better results. The small improvement did not justify the increased calculation time nor the added numerical noise.

The force vs. time profile was accurately replicated using a cell length of 0.1 m, resulting in six cells along the 0.6-metre-long PIPE. Reducing the cell length to 0.05 m did not yield any significant improvement. However, using fewer elements in the pipe segment (with a cell length of 0.2 m) quickly led to a deterioration in the results, characterized by pronounced numerical smearing.

#### **Safety Valve Steam Discharge**

The simulated steam discharge shows results that are analogous to the shock tube. While the load estimation could be used for design purposes, caution should be exercised because of the calculation inaccuracies. Determination of the required allowance may require further study on a per case basis. The loads created by the density changes undergo the same large numerical diffusion; they should not be used for piping stress analysis. At most, they could be taken only as an estimate of the order of magnitude if they are not particularly relevant in a specific case.

#### **Safety Valve Discharge With Saturated Liquid**

The flash boiling phenomenon plays a major role in the simulation of the SRV water discharge and the estimation of loads. Simulation with the default calculation options did not reproduce the

shock wave formation even though it produced realistic results on a longer time frame (after one second). The effect of the interfacial heat transfer coefficient was checked, and it was found that the evaporation rate during flash boiling is considered a likely cause of this issue. Furthermore, the simulation did not yield an accurate force estimation for the passage of the steam/water mixture, which is a sizeable contribution to the induced loads in a two-phase flow.

Because of these reasons, identifying a suitable setting that enables the use of TRACE for estimating pipe forces during very fast transient events involving flash boiling and two-phase flow remains a challenge, but represents an opportunity for further refinement and future work.

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A. Hsieh, NRC Project Manager

11. ABSTRACT (200 words or less)

This document assesses TRACE v.5 Patch 9 code for its ability to calculate hydraulic piping loads during fluid transients (i.e., water hammer). Current software for water hammer analysis assumes liquid flow at low Mach numbers and rather limited cavitation. However, nuclear power plants must also be designed for fluid transients that fall beyond the capabilities of programs commonly used for water hammer analysis because of the appearance of two-phase flow at high speed (in other words, with a Mach number close to or greater than 1). Examples of these special fluid transients are pipe break, safety relief valve discharge and steam pocket collapse. So far, RELAP5 has been the tool commonly used for analyzing these types of fluid transients, but RELAP5 is now being phased out, so a replacement is needed. TRACE is designed to replace RELAP5 for analyzing the transient thermal-hydraulics in nuclear reactors. The aim of this study, then, is to determine if TRACE may be used to calculate the hydraulics loads during fast fluid transients. In this study, the TRACE code was used to calculate several representative cases in which significant pipe loads may arise due to the formation and propagation of shock waves.

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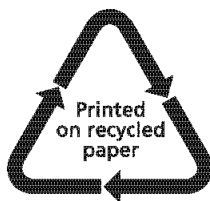
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