

POWER LOOP MODELING AND SIMULATION USING LabVIEW COUPLED WITH RELAPS

A Thesis

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by

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**Authorization to Submit Thesis**

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## **Abstract**

The purpose of this thesis is to provide an additional tool to researchers and system analysts for use in simulation, testing, and development of the secondary loop of a PWR nuclear power plant. This new tool is a coupling of LabVIEW and RELAP5 that has been created by using each code to model half of a PWR. By taking advantage of the strengths of both programs, a more powerful, adaptable, and user friendly system model is developed that links directly to the instrumentation of the system.

This work includes the development of the LabVIEW secondary loop model, the coupling methods for linking the two software packages, and a comparison of the secondary loop outputs to typical RELAP5 outputs as well as a third party source.

## **Acknowledgments**

I would like to recognize my major professor Dr. Fatih Aydogan for his dedication in assisting me in accomplishing this work in combination with the various publications, which would not have been possible without his guidance.

### **Dedication**

This work is dedicated to my wife, Heidi, who put up with many long evenings without a husband.

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### List of Abbreviations

A	Heat transfer area or flow area (m <sup>2</sup> )
ATHLET	Analysis of Thermodynamics of Leaks and Transients
ATWS	Anticipated Transients Without Scram
C	Heat exchanger heat capacity rate (W/K)
CD-ADAPCO	Computational Dynamics-Analysis & Design Application Company
CFD	Computational Fluid Dynamics
COBRA	Coolant Boiling in Rod Arrays
D or d	Tube diameter (m)
DLL	Dynamic Link Library
GUI	Graphical User Interface
KAERI	Korea Atomic Energy Research Institute
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LVOUTPUT, LVINPUT	Subroutines added to RELAP5
LOCA	Loss of Coolant Accident
NI	National Instruments
NTU	Number of transfer units
MARS	Modular Accident Response System
MCUF	Modeling of Coolant Systems with a Unique Framework
P	Pressure (Pa)
PANBOX	AREVA's 3-dimensional PWR transient core neutron kinetic simulator
PARCS	Purdue Advanced Reactor Core Simulator
PVM	Parallel Virtual Machine
PWR	Pressurized Water Reactor

RELAP	Reactor Excursion and Leak Analysis Program
q	Heat transfer rate (W)
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
$\widetilde{Re}$	Two phase Reynolds number
SB-LOCA	Small Break Loss of Coolant Accident
SG	Steam Generator
STAR-CCM+	Simulation of Turbulent flow in Arbitrary Regions Computational Continuum Mechanics
T	Temperature (K)
t	Time (sec)
TH	Thermal Hydraulic
TRAC	Transient Reactor Analysis Code
TRACE	TRAC/RELAP Advanced Computational Engine
TRNCTL, TRNSET, TRAN, TRNFIN, DTSTEP, TRIP, TSTATE, HTADV, HYDRO, RKIN, CONVAR, HT1TDP, HTCOND, INPUT, STRIP	Titles given to subroutines contained within RELAP5
US-NRC	United States Nuclear Regulatory Commission
v	Specific Volume (m <sup>3</sup> /kg)



v	Velocity (m/s)
VI	Virtual Instrument
W	Work (kJ/kg)
1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional

**List of Symbols**

$c$	Specific Heat (kJ/kg*K)
$dt$	Time step (sec)
$g$	Acceleration due to gravity (m/sec <sup>2</sup> )
$h$	Convective heat transfer coefficient (W/m <sup>2</sup> *K)
$h_{fg}$	Enthalpy of formation (kJ/kg)
$K$	Turbine performance constant
$k$	Conductive heat transfer coefficient (W/m*K)
$\dot{m}$	Mass flow rate (kg/sec)
$N$	Heat exchanger tube row number
$ncount$	Time step variable used in coupling
$Q$ or $q$	Heat flux (W)
$U$	Overall heat transfer coefficient (W/m <sup>2</sup> *K)
$U$	internal energy (kJ)
$u$	Fluid velocity (m/s)
$\alpha$	Void Fraction
$\varepsilon$	Heat exchanger effectiveness
$\rho$	Density (kg/m <sup>3</sup> )
$\mu$	Viscosity (N*sec/m <sup>2</sup> )
$\eta$	Cycle Efficiency

**List of Subscripts and Superscripts**

c	Cold side
c,i	Cold side inlet
c,o	Cold side outlet
D	Tube diameter
f	Fluid
g	Vapor
h	Hot side
h,i	Hot side inlet
h,o	Hot side outlet
i	Tube side
l	Liquid
max	Maximum
min	Minimum
N	Nth tube row
o or sh	Shell side
P	Pump
p	Pressure
sat	Saturation
t	Turbine
1 or in	Inlet
2 or out	Outlet
w	Wall
·	Property/unit time
~	Mean, due to two phase fluid properties

## Preface

This Master's Thesis is based on three articles that Zheng Fu, Dr. Aydogan and I have written. The first, Modeling Primary and Secondary Coolant of a Nuclear Power Plant System with a Unique Framework (MCUF) by Pack, et al. (2015), was published in the Progress of Nuclear Energy Journal. This article discussed the initial development of the coupling of the LabVIEW and RELAP5 software programs. In this work I developed the complete functional secondary loop model with capabilities of being linked to the RELAP5 software. Zheng's efforts in this work include the modification of the RELAP5 software to allow the use of and coupling with LabVIEW. He also generated the Inputs necessary to run the simulations.

The second article is Qualitative and Quantitative Evaluation of Coupling Approaches for Coupling of RELAP5 and LabVIEW by Fu, et al. (2015) and is forthcoming in the Nuclear Science and Engineering Journal. Contained therein is the development of a second coupling method between the two software packages and the comparison of the two methods. For this work Zheng and I performed modifications to each of our respective previous works to allow for generation of a second coupling method.

The third article has been submitted to the Progress in Nuclear Energy Journal and is titled: Small-Break Loss of Coolant Accident Prediction with MCUF (Modeling Primary and Secondary Coolant of a Nuclear Power Plant System with a Unique Framework) and a Realistic Secondary Coolant System Design by Pack and Aydogan (2015). In this work I performed a more detailed study of the Rankine Cycle including more advanced cycles, and utilizes the coupling, performed in the other two publications, for additional application to LOCA predictions.

## Introduction

Within the study and design of a nuclear power plant, extensive system modeling is necessary to determine how the reactor is going to perform in any given situation, not only in the normal performance of the reactor but also to determine system response during transients including anticipated transients without scram (ATWS) and hypothetical accidents. Primary and other loops in multiple coolant loop systems in nuclear power plants can be modeled with nuclear system codes, such as Reactor Excursion and Leak Analysis Program (RELAP5), COBRA-TRAC, TRACE, and ATHLET, for the interaction and feedback effects between the coolant loops. In the recent years, new components, such as a turbine, coolant pump, advanced compact heat exchanger, valve, sensors, instrumentation and control systems, are being designed for use in the coolant systems. However, current system codes are not capable of integrating the computational model of the whole nuclear power plant system to an experimental apparatus. Therefore, this thesis proposes a new coupling between a system code and Laboratory Virtual Instrument Engineering Workbench (LABVIEW) in a unique framework (called Modeling of Coolant Systems with a Unique Framework -MCUF-) that allows integrating an experimental apparatus or a facility within a whole power plant model. MCUF allows online or interactive data exchange by using the powerful and flexible tools of LabVIEW. This thesis demonstrates how coupling between the primary and secondary coolant system of a typical Pressurized Water Reactor (PWR) can be performed by using MCUF. The primary and secondary sides of the PWR are modeled with RELAP5 and LabVIEW computer simulators, respectively. In MCUF, RELAP5 is being used for its capability to simulate the reactor and the associated Reactor Coolant System (RCS) components while LabVIEW is being used for modeling of the secondary coolant system. The coupling between RELAP5 and LabVIEW has been executed with steady state and transients, in this case a loss of coolant accident (LOCA) for a four loop PWR.

Often when simulating a LOCA in a PWR either the primary or the secondary coolant system is modeled with a set of boundary conditions that represent expected conditions of the coolant system that was not modeled, these conditions serve as the response for that system. These boundary conditions are generally based on realistic nuclear power plant performance and simulate pre-defined conditions for feedback effects, such as temperature and pressure, during the LOCA. To evaluate the performance of the MCF (Modeling Primary and Secondary Coolant of a Nuclear Power Plant System with a Unique Framework) code, which doesn't use any hard coded, or preset, boundary conditions, a Small Break LOCA has been modeled with Reactor Excursion and Leak Analysis Program (RELAP5) which uses hard coded boundary conditions and MCF for code to code benchmark. This study also shows two different approaches to this coupling and makes qualitative and quantitative comparison between these approaches.

Additionally one of the prevalent studies for nuclear power plants is the use of hybrid energy systems, which uses nuclear power plant for generating electricity and also heat for facilities. In order to implement a hybrid energy system, the secondary loop or steam cycle in the nuclear power plant would require several design updates and experiments. Unfortunately, the current versions of **Reactor Excursion and Leak Analysis Program (RELAP5)** do not allow an online data stream from experimental facilities to the computational model of secondary steam loop. Therefore, this study develops a coupling between RELAP5 and LabVIEW to model primary and secondary coolant loops, respectively, so that LABVIEW models can easily be connected to an experimental apparatus to provide online data stream and online transient behavior of a whole nuclear power plant system.

A significant portion of this work includes the development of a secondary loop model of the Rankine Cycle of a power plant using LabVIEW which will be integrated into this coupling. Also shown is the capable of LabVIEW to be used for modeling both simple and more advanced

secondary loop configurations and be very easily modified to accommodate many situations. One of which has been compared with another secondary loop system to validate the modeling scheme used in LabVIEW.

## CHAPTER 1: Rankine Cycle Modeling Using LabVIEW

### 1.1. LabVIEW

LabVIEW is a graphical programming language that utilizes icons and graphics instead of lines of text in order to create applications. These applications are created using a set of tools and objects to build a user interface. The user then adds code using graphical representations of functions to control these objects (NI, 2003). There is an extensive collection of these graphical functions built into LabVIEW. The use of these functions ranges from analyzing input data from sensors and instrumentation to visual representations of the input data to providing the results of user generated programs.

Programming in LabVIEW is performed using Virtual Instruments (VIs). These VIs contain the functional tools, applications, and objects used to generate the software. A VI would be comparable to a text based program's subroutine.

This software platform was selected in order to utilize its Graphical User Interface (GUI) style of programming as well as its flexible computational model that can be used directly as the data interpretation software of the sensors of an experimental apparatus. With a graphical representation of the programs output a user will have improved response time and will also be able to observe the feedback of a modeled nuclear power plant if the computational model is fed by a sensor of an experimental apparatus. This GUI style can also be used to generate visual representations of the conditions within power system of the reactor. Thus LabVIEW not only provides the program that performs the calculations, it can also be used to generate the graphical output thereof, simplifying the training necessary for the operators that run the programs. This eliminates the need for additional graphical program coupling.

Where text based programming languages use subroutines LabVIEW is structured using VIs



is where the programming occurs and within these VIs are the icon based applications, tools, and objects with varying functions that are used to build the program. The following will show how a series of VIs have been generated for various functions and then integrated together in a larger program.

#### 1.1.1. Secondary Loop VI

The Secondary loop of the PWR as modeled in LabVIEW contains the major components of the loop including the turbines, condenser, main coolant pumps, and feedwater heaters.

An example secondary loop VI, as shown in Figure 1.1, is divided into four main sub VIs representing the Turbines, Condenser, Pump, and Feedwater Heaters annotated as sub VIs 1, 2, 3, and 4, respectively. The connections to each of these VIs represent the piping connections that exist in actual plants. With this coupling method the Steam Generator (SG) is modeled entirely in RELAP5 with the coupling locations at the secondary feed water inlet and steam outlet of the SG. Additional components of this VI not shown in the Figure 1.1 include the reading of the text file, which will be shown later, that is passed from the SG steam outlet in RELAP5; as well as writing a text file that is sent to RELAP5 that contains the SG feedwater input data.

Table 1.1 contains a list of some of the functions that are contained within LabVIEW VIs that have been developed for this work.

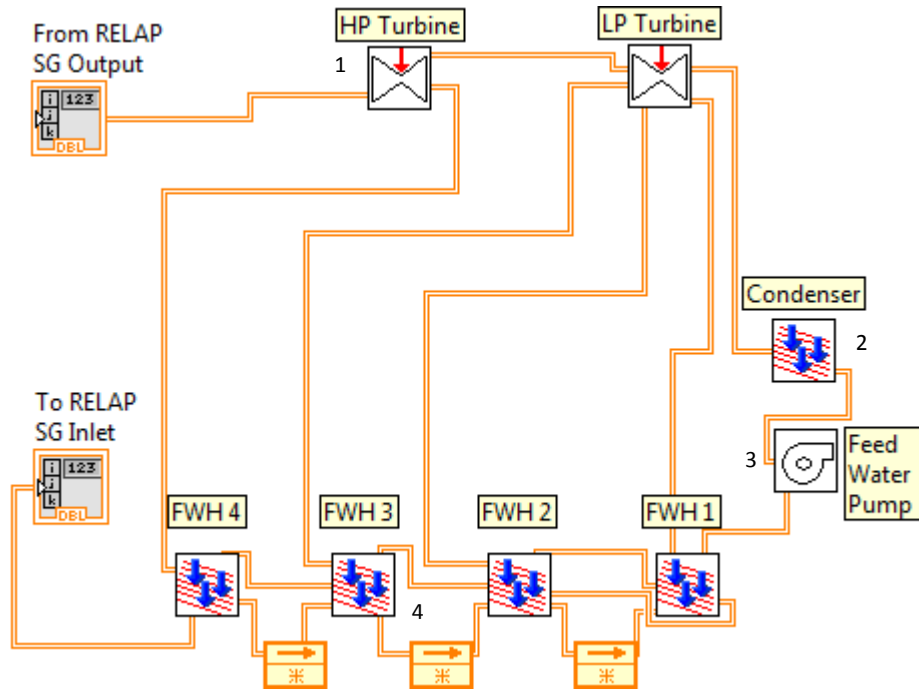




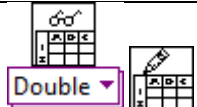

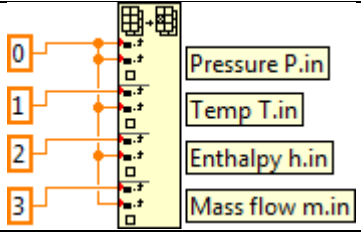



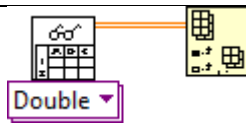

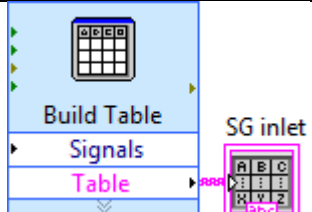
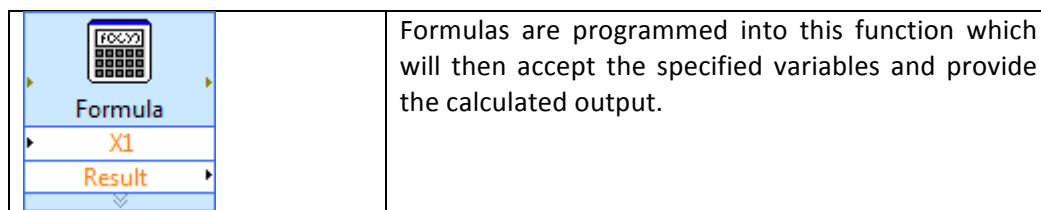


Figure 1.1 - Secondary Loop VI

Table 1.1 - Explanation of LabVIEW Icons

Icon	Function
	Arithmetic and logical operations between two variables
	Single variable and array variable input to and output from a VI
	The single line between icons is the communication of variable quantities between functions
	Feedback node. This function stores data from a previous run to be used in the current run
	Used to read from or write to a specified text file
	Used to extract data from an array
	Array allocation of fluid parameters, in this case for the inlet to a component
	Allocation of data into an array
	Icons for various VIs embedded within the current VI
	VI used for Interpolating saturated water properties. This VI extracts water properties from the saturated water tables based on pressure
	The double line between icons is the communication of array values between operations. To ensure the model remains orderly the fluid parameters are passed from VI to VI in arrays.
	Case structure accepts logical input and performs an operation which is based on the logical input.
	Builds tables for output based on input



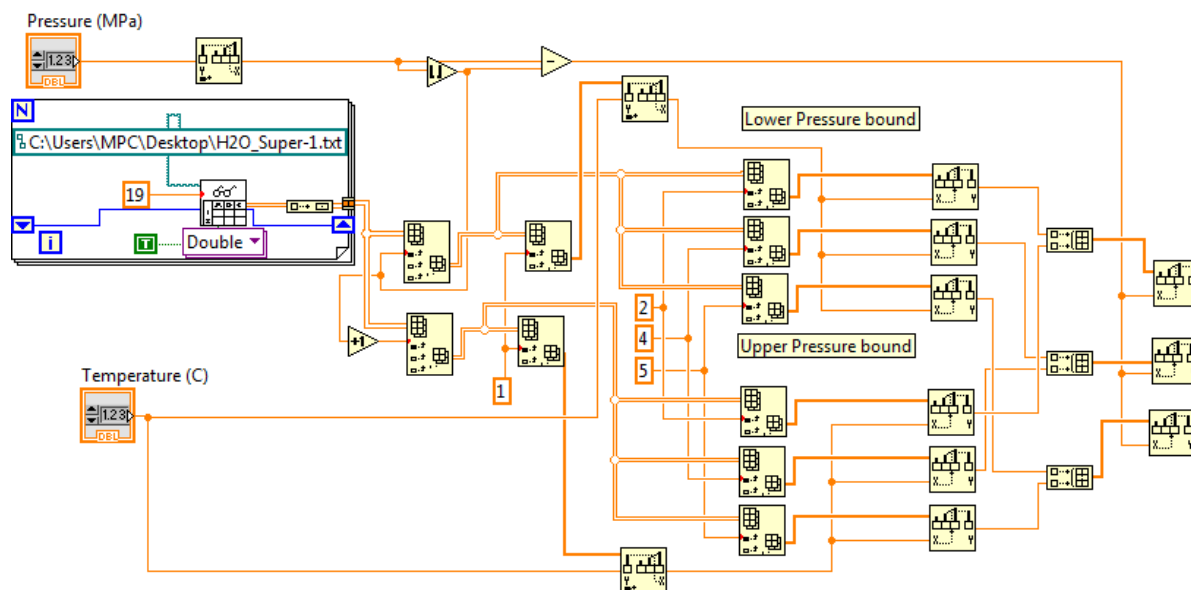
### 1.1.2. Water and Steam Properties

Integrated into each of the sub components of the second loop is a set of virtual instruments that are capable of reading, extracting, and interpolating data from the steam tables. These VIs vary depending on the fluid state (a saturated liquid or vapor, superheated steam, or sub-cooled liquid). Based on the fluid state, it generates the needed property data.

Double Interpolation is necessary for determining super-heated steam properties based on the tables. This is needed due to the specific nature of the super-heated steam table. It is defined as multiple tables that are based on pressure. The properties are then defined based on the temperature within that table. The interpolation must be performed based on the temperature and pressure, not just the single temperature or pressure as defined in the saturated steam tables. The VIs generated define steam properties of specific enthalpy, specific volume, and specific entropy, based on a given steam temperature and pressure.

The reading and interpolation within the water property VIs is performed with a series of graphical tools. The first tool reads the steam property table that is contained within a separate text file. Another tool determines a decimal numeric location that defines where the input pressure value fits among the list of pressures. Then a third defines a specific 1D array out of the 2D steam table array. This line defines the temperature array out of the steam table. The fourth determines the interpolation and outputs the actual numeric value of the desired property based on the decimal numeric location of the pressure defined by the second tool described above.

Figure 1.2 is an example of one of the steam property VIs developed.



**Figure 1.2 - Super-Heated Steam Double Interpolation VI**

### 1.1.3. Steam Generator

The steam generator (SG) is the link between the two programs, it being the energy transfer component between the primary and secondary loops. With regard to the coupling being performed this component is where the essential data exchange occurs. The main purpose of the SG VI is to accept the data from RELAP through the file containing the heat flux data which is read using the function shown in Figure 1.3 location 1, this data is used to perform the calculations necessary including equation (1) below then transfer the information into the remainder of the second loop VI. Refer to Table 1.1 for the specific icons and their associated functions.

Some of the main components of the SG contained within the VI are the performance of reading data from RELAP as noted previously as well as that from the pump noted at Figure 1.3 location 2. The heat transfer from the primary to the secondary side is calculated in Figure 1.3 location 3 using the equation:

$$(Q * A) / \dot{m} = h_2 - h_1 \quad (1)$$

Once heat flux is calculated, it is necessary to calculate the temperatures that are returned to RELAP5 for the calculation of the tube side outlet conditions. To perform this, the state of the fluid must be determined. This is performed using the conditional loops shown at Figure 1.3 location 4 that determine whether the fluid is in a sub-cooled, saturated, or super-heated condition. Also contained within these loops are the calculations to determine the temperature at the outlet of each control volume as well and the SG as a whole.

Additional information on the steam generator is provided in the coupling section of this paper. Figures 1.3 show the program code of the LabVIEW SG VI.

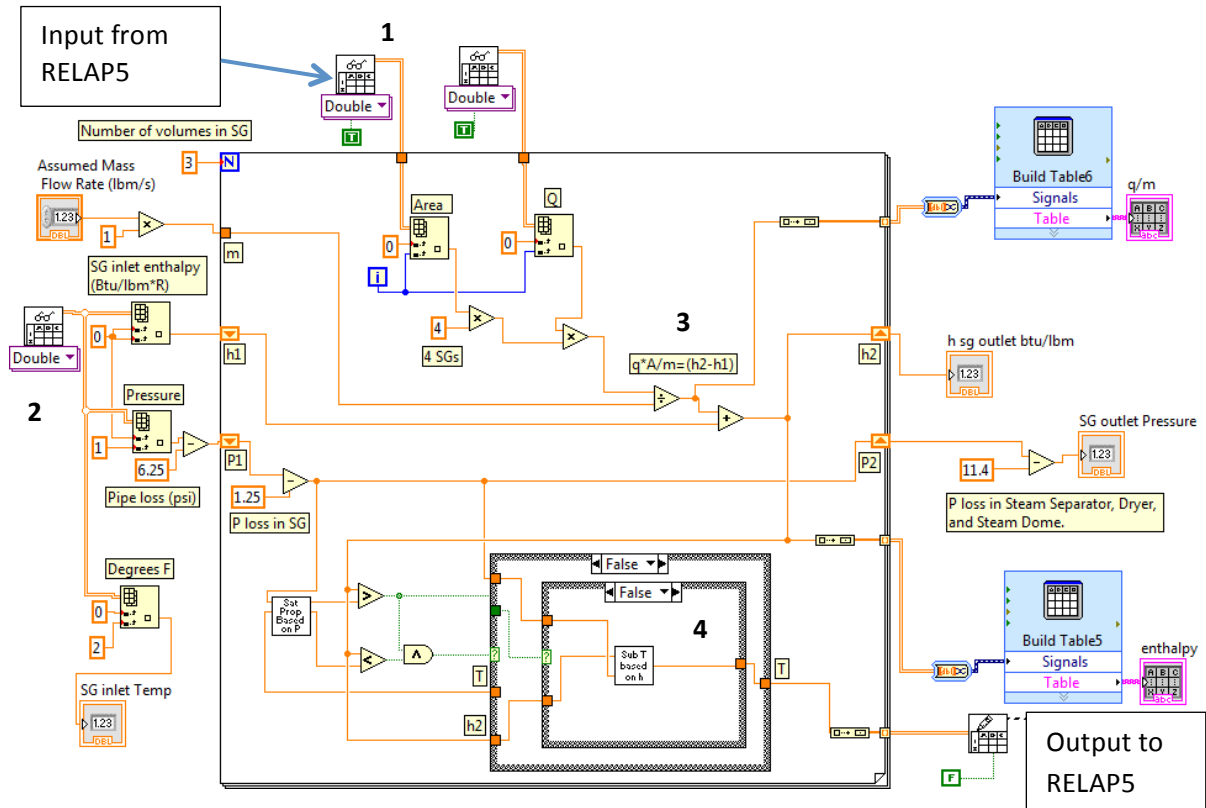


Figure 1.3 - Steam Generator (SG) VI Programming

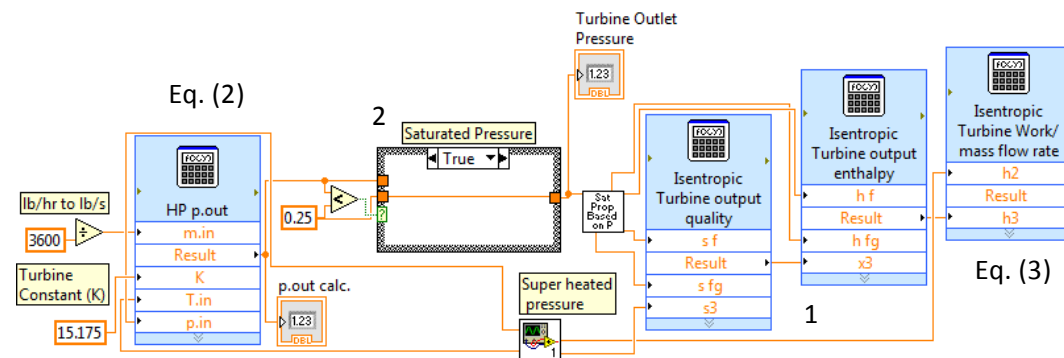
#### 1.1.4. Steam Turbine

The steam turbine has been modeled by including portions of a simplified model by Chaibakhsh (2008) as well as simple thermodynamic equations to represent the response normally

seen by a turbine, shown in location 1 of Figure 1.4.

Figure 1.4 below shows the main portions of the turbine VIs. This portion of the VI is repeated for each of the turbine stages. The pressure drop within the turbine is calculated based on the equation from the turbine model by Chaibakhsh as follows which uses the inlet mass flow rate, temperature, and pressure to calculate the turbine outlet pressure:

$$\dot{m}_{in} = \frac{K}{\sqrt{T_{in}}} \sqrt{p_{in}^2 + p_{out}^2} \quad (2)$$



**Figure 1.4 - Turbine Stage VI**

In the Chaibakhsh model the turbine constant  $K$  is determined based on empirical turbine performance data. For this work turbine performance data was not available thus the constant  $K$  was adjusted based on the expected pressures, mass flow rate, and temperature used for each particular turbine stage. For the validation model this is the method that was used and it was necessary to adjust the turbine constant according to the expected conditions for the individual stages of each turbine. Additionally shown in Figure 1.4 location 2 is a check to ensure that if inlet pressures drop too low the output pressure will not drop below zero due to modeling constraints.

As the purpose of this model is to connect to an experimental apparatus or actual system, the model was established to easily accept the turbine performance data for the system of concern. This will be done in the same fashion that was utilized for the pump model, which will be

described later, by simply uploading the turbine performance data in the form of a text file and reading the data directly for use in the LabVIEW model.

For implementation of an appropriate turbine simulation, an assumption is made based on typical turbines as to the turbine efficiency. The turbine outlet enthalpy and quality are calculated using this efficiency in combination with additional thermodynamic equations, one of which is turbine work. The turbine work per mass flow rate is calculated based on the following equation as noted in Figure 1.4.

$$\dot{W}_t/\dot{m} = h_2 - h_1 \quad (3)$$

The result of this equation, which is determined using the turbine inlet and outlet enthalpies,  $h_1$  and  $h_2$  respectively, is used in the determination of the overall cycle efficiency.

#### 1.1.5. Condenser

In power plants various methods can be utilized to perform the removal of waste heat from the power generation cycle. A condenser is used in conjunction with an additional system that is used as a heat sink, such as a nearby ocean or river, the water from which is pumped into the cold side of a shell and tube heat exchanger. In this model the ultimate heat sink will be very simply modeled within the heat removal process performed in the shell and tube heat exchanger/condenser.

The condenser VI is split into two main sub-components the first being the heat exchanger and the second, the calculation of the condensation heat transfer coefficient to be used for the heat exchanger calculations.

##### 1.1.5.1. Condensation Heat Transfer Coefficient

Determination of the condensation heat transfer coefficient, see Figure 1.5, was based on the design considerations from Kakaç (2012) in the section on design correlations for condensers and evaporators. Therein the model is based on Butterworth's method that calculates the heat



transfer coefficient in accordance with the tube row (N) under consideration. The VI generated to perform these calculations uses this method and performs an average of the heat transfer coefficients calculated at representative locations throughout the tube bundle to generate an overall heat transfer coefficient,  $h_o$ . Figure 1.6, location 1 shows the portion of the VI that performs these calculations.

The heat transfer coefficient is calculated as follows: These calculations are performed in the VI shown in Figure 1.5.

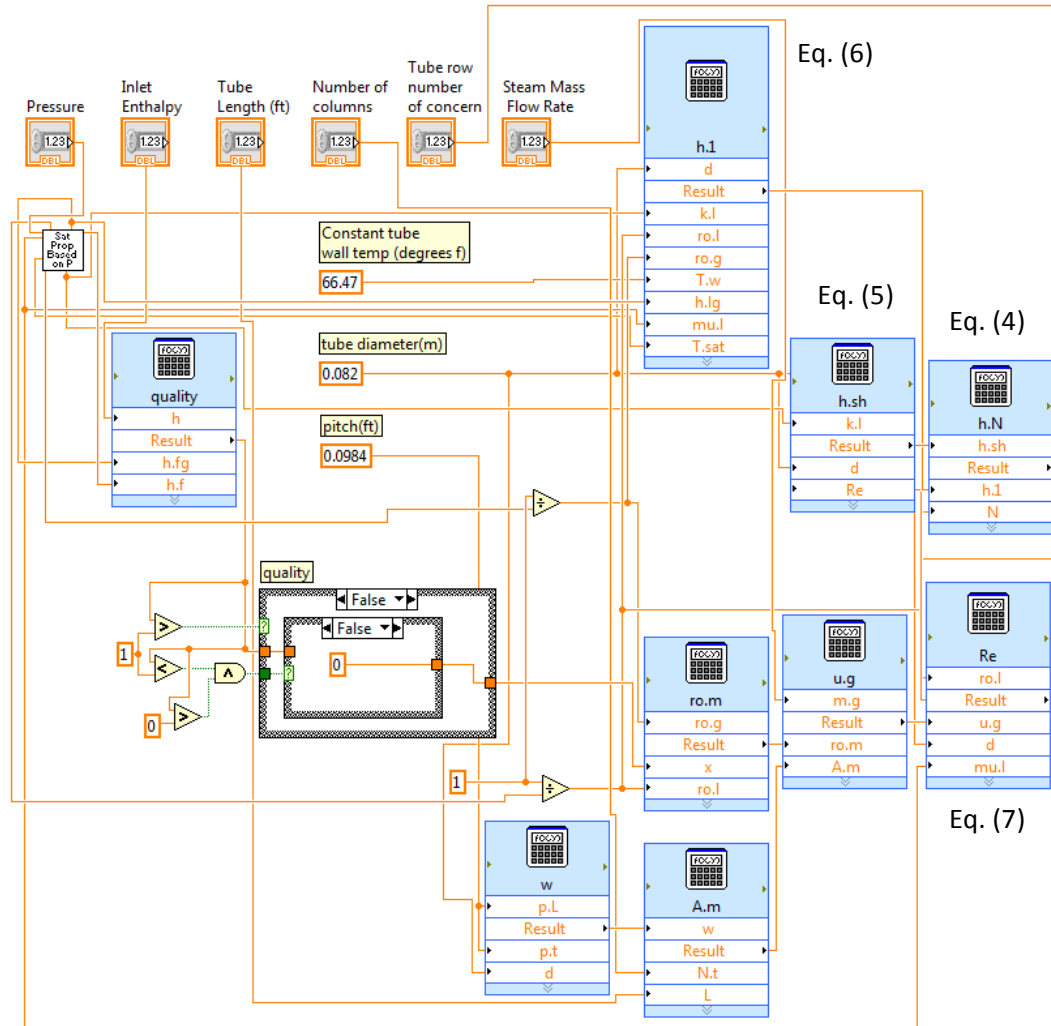
$$h_N = \left[ \frac{1}{2} h_{sh}^2 + \left( \frac{1}{4} h_{sh}^4 + h_l^4 \right)^{1/2} \right]^{1/2} \times [N^{5/6} - (N - 1)^{5/6}] \quad (4)$$

where:

$$h_{sh} = 0.59 \frac{k_l}{d} \widetilde{Re}^{1/2} \quad (5)$$

$$h_l = 0.728 \left( \frac{k_l}{d} \right) \left[ \frac{\rho_l (\rho_l - \rho_g) g h_{fg} d^3}{\mu_l (T_{sat} - T_w) k_l} \right]^{1/4} \quad (6)$$

$$\widetilde{Re} = \frac{\rho_l u_g d}{\mu_l} \quad (7)$$



**Figure 1.5 - Condenser Convective Heat Transfer Coefficient VI**

### 1.1.5.2. Heat Exchanger

The type of heat exchanger utilized for this simulation is the shell-and-tube heat exchanger. The geometric properties of the heat exchangers within these VIs were generated in accordance with similar equations to those shown herein as well as the optimum heat transfer rates and mass flow rates necessary for the energy balance of the RELAP5 model.

The calculated heat transfer coefficient is used in equations (8) through (15), which are the heat exchanger performance equations as contained in Incropera (2011). Figure 1.6 contains selections from the VI in which calculations with these equations are performed.

$$\frac{C_{min}}{C_{max}} = 0 \quad (8)$$

With the calculation of  $C_{min}$  and  $C_{max}$  (minimum and maximum heat capacity rates) being performed using the cold and hot fluid flow rates and their respective specific heat capacities.

$$NTU = \frac{U_h A_h}{C_{min}} \quad (9)$$

$$Nu_D = 0.023 Re_D^{4/5} Pr^{0.4} \quad (10)$$

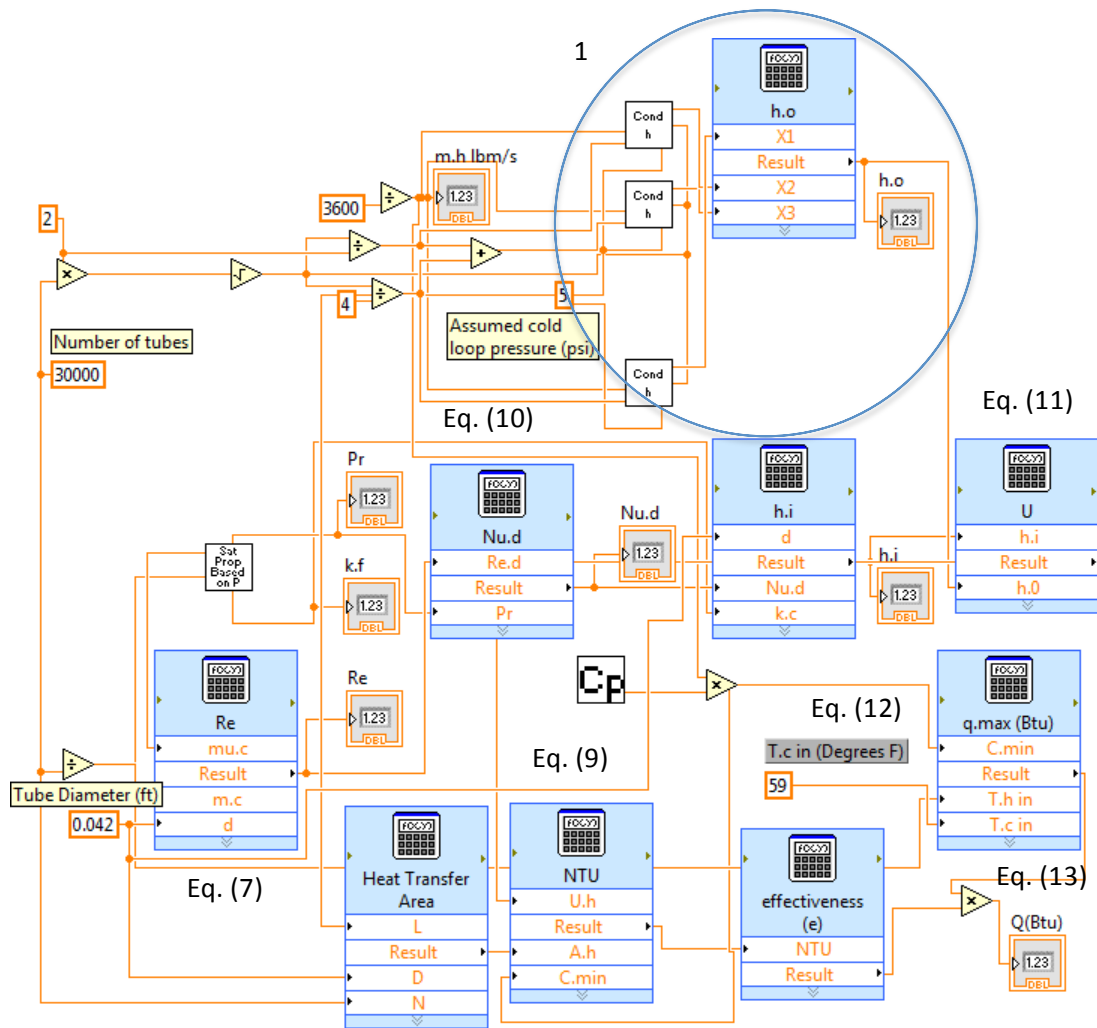
$$U_h = \frac{1}{(1/h_i) + (1/h_o)} \quad (11)$$

$$q_{max} = C_{min}(T_{h,i} - T_{c,i}) \quad (12)$$

$$q = \varepsilon q_{max} \quad (13)$$

$$T_{h,o} = T_{h,i} - \frac{q}{\dot{m}_h c_{p,h}} \quad (14)$$

$$T_{c,o} = T_{c,i} - \frac{q}{\dot{m}_c c_{p,c}} \quad (15)$$

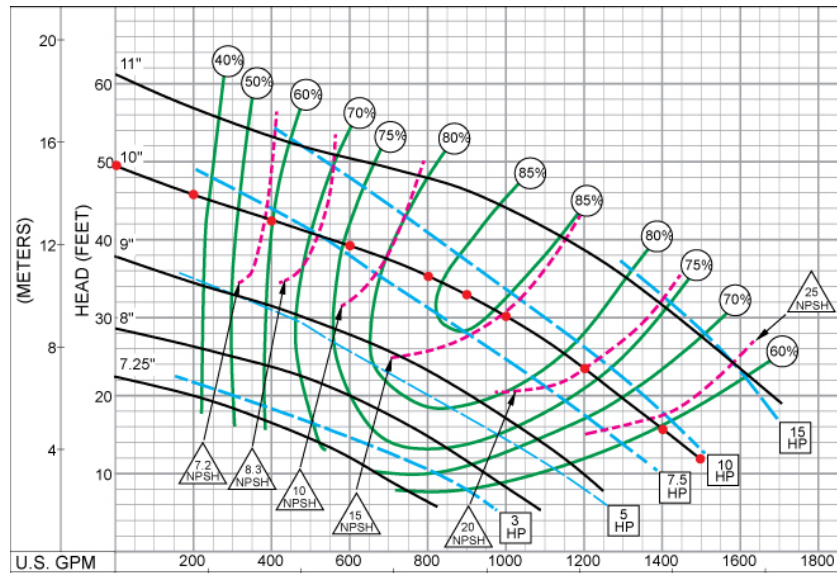


**Figure 1.6 – Condenser Heat Exchanger VI**

The output of the condenser, which is generated by the combination of the condenser heat transfer coefficient and heat exchanger correlations, is then transferred to the pump VI.

#### 1.1.6. Pump

In order to simplify the implementation of integration of this simulation to an actual system, empirical pump performance data based on a pump performance curve (Figure 1.7) from Engineered Software Inc. (2013) was used.



**Figure 1.7 - Pump Performance Curve**

Pump performance data was determined based on this curve, which was used as a reference for pump performance trends. The information extracted from this curve is read and interpolated in accordance with the pump inlet fluid conditions to provide the necessary pump outlet conditions. The following figure, Figure 1.8 is a portion of the VI that is used to read and interpolate this data. Section 1 of Figure 1.8 reads the pump curve data and performs the unit conversions necessary. Section 2 performs data extraction from the performance tables, with section 3 performing the interpolation of information. Section 4 is the pump output data based on the interpolated inputs.

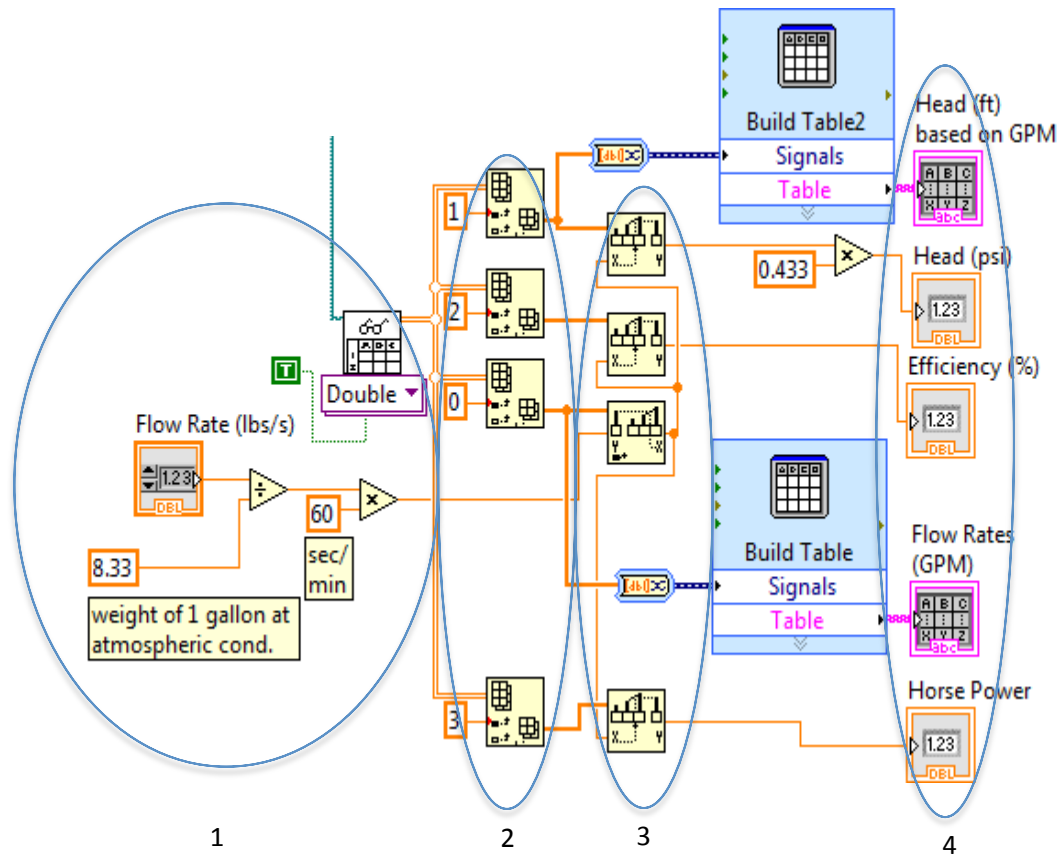


Figure 1.8 - Pump Data VI

The output data that is obtained from the VI above is used in conjunction with other thermodynamic equations to calculate any additional information needed from the pump for further calculations in the secondary loop simulation. Among these equations is the calculation of pump work data as shown in equation (16).

$$\dot{W}_p = v * (P_2 - P_1) \quad (16)$$

#### 1.1.7. Feedwater Heaters

The heat exchangers that make up the feedwater heaters were modeled using the same methods as the condenser but for the convection coefficient on the shell side the following equations were used from Incropera (2011).

Firstly the convection coefficient for the top row of tubes is calculated using equation (17) which is a slight modification of equation (6). Figure 1.9 is a portion of one of the feedwater heater VIs and points out where in the model these calculations are performed.

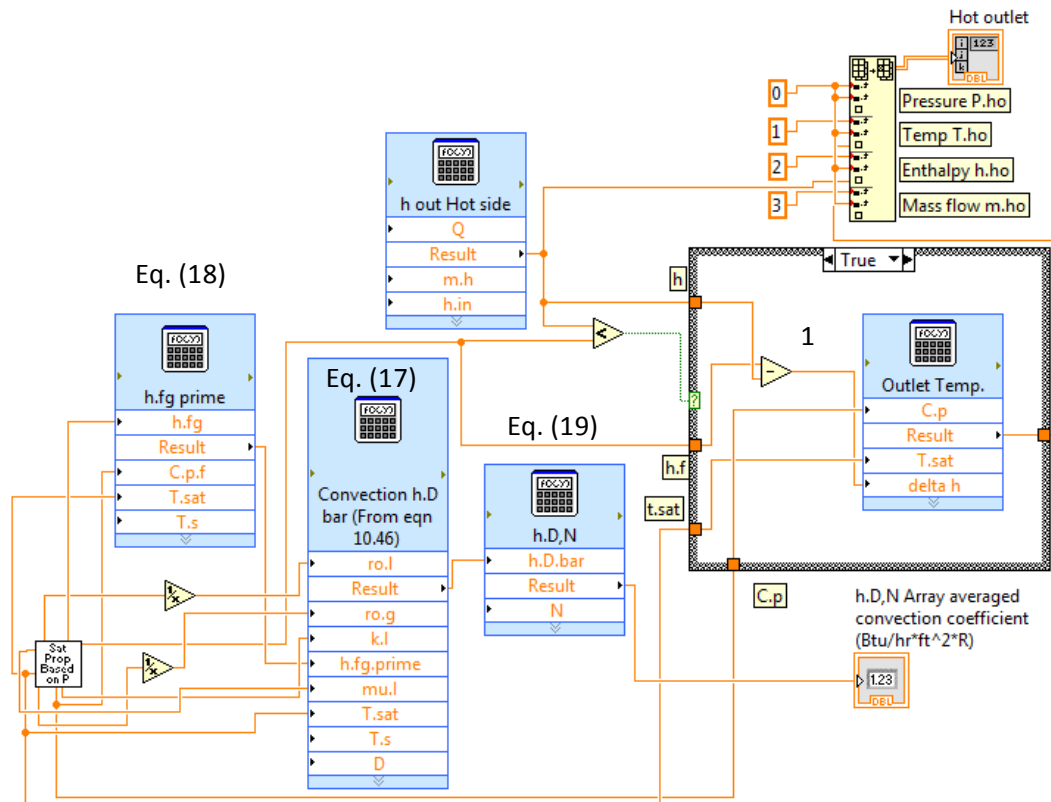
$$\bar{h}_D = 0.729 \left[ \frac{\rho_l g (\rho_l - \rho_v) k_l^3 h'_{fg}}{\mu_l (T_{sat} + T_s) D} \right]^{1/4} \quad (17)$$

where:

$$h'_{fg} = h_{fg} + 0.68 c_{p,l} (T_{sat} - T_s) \quad (18)$$

Following this set of equations the tube bundle array averaged convection coefficient is:

$$\bar{h}_{D,N} = \bar{h}_D N^{-1/6} \quad (19)$$



**Figure 1.9 - Feedwater Heater Heat Transfer Coefficient VI**

Following the calculations performed, location 1 in Figure 1.9 makes a determination as to the condition of the hot side fluid outlet of the feedwater heater and performs calculations to

determine the outlet temperature based on whether the fluid is a saturated fluid or has now become subcooled.

There is the same number of feedwater heaters in the validation model as there are in the schematic that the validation model was compared to, as seen in Figure 1.10 from B&W (2005). The number of feedwater heaters in the advanced model coupled with RELAP5 was reduced to four, due to the lack of a schematic to compare with the model.

## **1.2. Validation Of Secondary Loop Components**

For this work the validation of the model is a validation of the methods and formulas used to generate the components of the secondary loop. It was necessary to perform the validation this way due to the way in which the secondary loop components were designed having been based on specific component geometries and capacities. The method check has been performed by generating an additional secondary loop simulation, Figure 1.11, which is to be compared against the system description and conditions shown in Figure 1.10. This system was not used for coupling to RELAP5 due to the energy balance necessary for coupling with the RELAP5 input deck which utilizes a system with significantly different capacity than that from the validation model. Thus this exercise is a method validation for the secondary loop and associated components.

As stated, the models that have been generated are specific to given component geometries, which are based on plant parameters. The purpose of this method is to more closely simulate plant conditions as well as to simulate the modeling of specific power plants. Similar models to the ones generated will be able to be implemented into different systems by making only a few simple changes including incorporating plant specific pump and turbine performance data as well as component geometry of the feedwater heaters and condensers. With these modifications the program can be applied to many power plants.



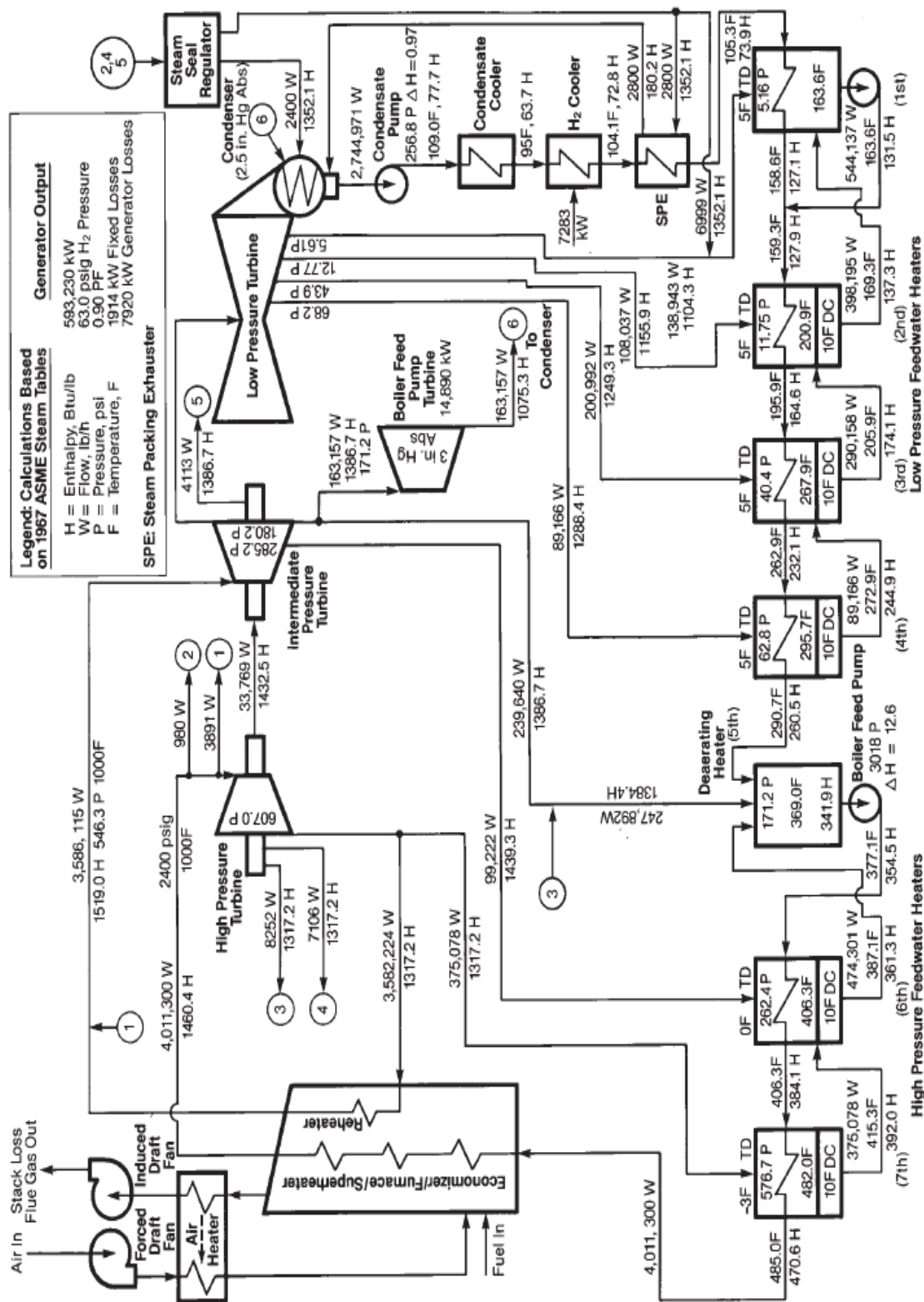
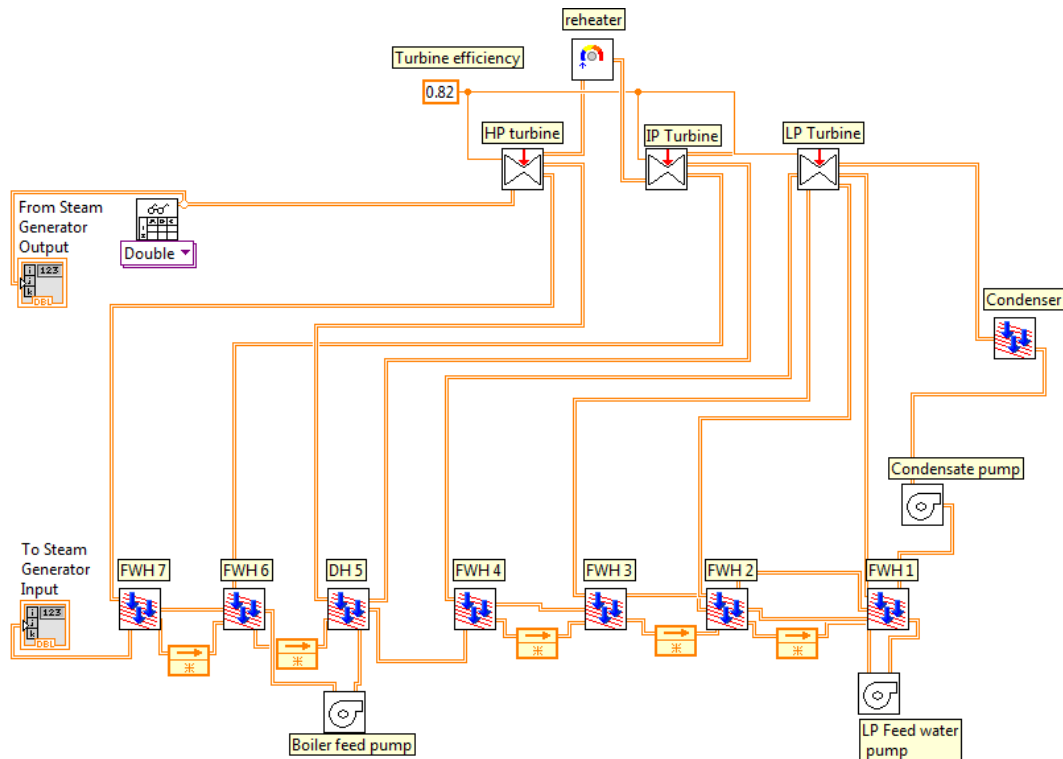


Figure 1.10 - Secondary Loop Validation Model (B&W, 2005)

The LabVIEW VI generated to simulate the schematic shown in the previous figure is shown here as Figure 1.11. For the validation purposes of these calculations, a few of the components have been omitted including the boiler feed pump turbine and condensate cooler.



**Figure 1.11 - LabVIEW Validation VI**

Figure 1.12 contains an example of the output format that LabVIEW produces this format provides the user a very quick reference to be able to observe the conditions of the plant, or simulation in this case. The box in the top left of the figure gives the order of the parameters within the arrays that are displayed in each.

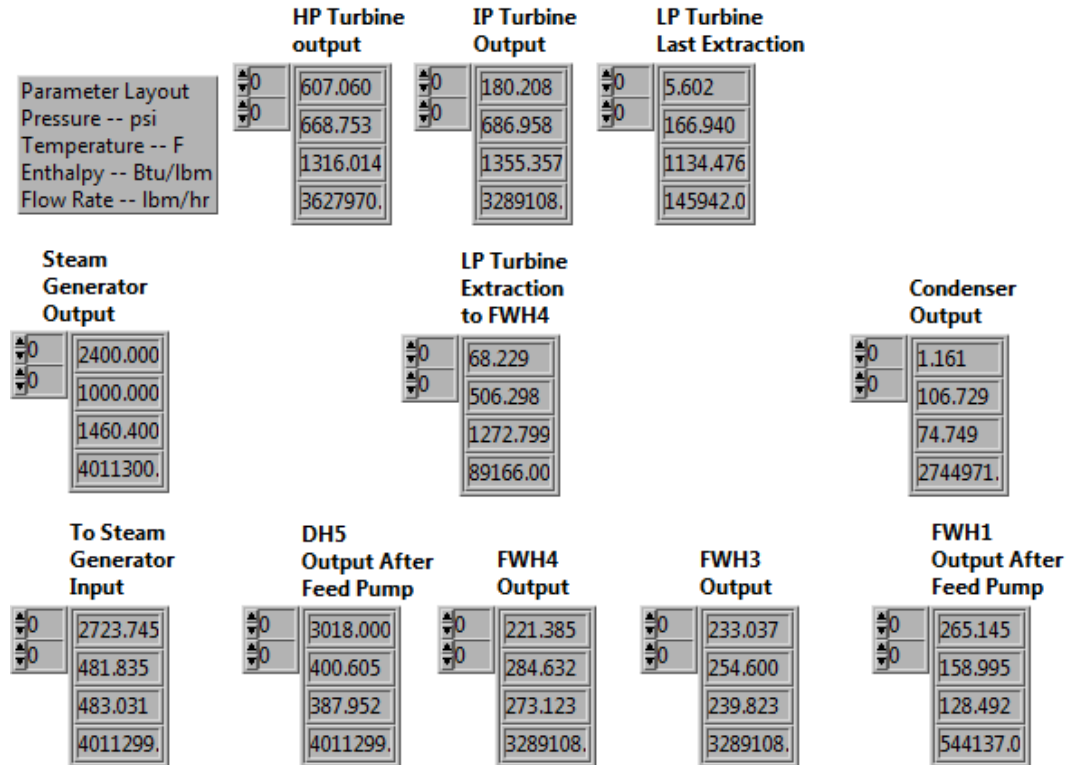


Figure 1.12 - LabVIEW Secondary Loop VI output

Contained within Table 1.2 are the results produced by the validation VI in Figure 1.11. These data demonstrate that the model is capable of generating results within 2.64% of the system description provided in Figure 1.10. The difference between these two models will be reduced with the utilization of actual plant performance and geometric data of the plant components. Without this plant data assumptions were made for feedwater heater geometries as well as turbine and pump performance.

With the model methods validated a model similar to Figure 1.11 is shown in Figure 1.1 which will be used to couple with RELAP5 as a demonstration of more advanced capabilities of the coupling.

**Table 1.2 - Tabulated Results Comparison of Validation Model**

<b>Location and Parameter</b>	<b>LabVIEW Result</b>	<b>Validation Model Result (Figure 3.9)</b>	<b>Percent Difference</b>
<u>High Pressure Turbine Output:</u>			
Pressure (psi)	607.06	607.0	0.00988
Enthalpy (Btu/lb)	1316.014	1317.2	0.09003
<u>Intermediate Pressure Turbine Output:</u>			
Pressure (psi)	180.208	180.2	0.00443
Enthalpy (Btu/lb)	1355.357	1386.7	2.26025
<u>Low Pressure Turbine Extraction to Feedwater Heater 4:</u>			
Pressure (psi)	68.229	68.2	0.04252
Enthalpy (Btu/lb)	1272.799	1288.4	1.21088
<u>Condenser Output/ Feedwater Heater 1 Input:</u>			
Temperature (Degrees F)	106.729	105.3	1.35707
Enthalpy (Btu/lb)	74.749	73.9	1.1488
<u>Feedwater Heater 1 Feedwater Output:</u>			
Temperature (Degrees F)	158.995	159.3	0.19146
Enthalpy (Btu/lb)	128.492	127.9	0.46286
<u>Input to Steam Generator From Feedwater heater 7:</u>			
Temperature (Degrees F)	481.853	485.0	0.64886
Enthalpy (Btu/lb)	483.031	470.6	2.64152

### 1.3. Conclusions

This research and development of a Rankine Cycle or secondary loop utilizing the LabVIEW software has successfully demonstrated both simple and advanced secondary loop systems can be modeled using LabVIEW. This has been validated by comparing the LabVIEW modeling methods against the outputs of an actual secondary loop with values within 2.7% of those produced by an actual power plant.

The Advanced Regenerative Rankine Cycle LabVIEW model that was used for the purpose of method validation will be capable of being utilized with the coupling code once the RELAP5 simulator is redesigned for the appropriate energy balance for such a cycle.

## CHAPTER 2: Coupling of LabVIEW and RELAP5

### 2.1. Introduction to Coupling of RELAP5 and LabVIEW

In a PWR system there are typically two closed loops (Figure 2.1). The primary loop includes the reactor (Figure 2.2) and its associated pumps and piping up to the tube side of the steam generator. The secondary loop, or power loop as it is often called, includes the components starting with the shell side of the steam generator including the steam separators, driers, and super-heaters; the high and low pressure turbines, the condenser, pumps, feedwater heaters, etc. Often the heat sink loop is considered to be a separate third loop but for this work it is included in the second loop.

A simplified version of a PWR including primary and secondary loops, and as components of the secondary loop: a steam generator, a turbine, a condenser, and a pump, was modeled in the scope of this study. The secondary loop is a Rankine cycle. Figure 2.1 by Tong (1996) shows how the primary system, which includes the reactor as shown in Figure 2.2, and secondary system were modeled using RELAP5 and LabVIEW respectively. The secondary (or power) system includes the steam turbine, condenser, and associated pumps and components. The Steam generator (Figure 2.3) is the component which provides the connection between primary and secondary sides in the developed coupling between RELAP5 and LabVIEW. Two methods for performing this coupling are to be addressed: the first in Figure 2.1 will connect in the heat exchanger of the steam generator and the second in Figure 2.1 connects at the inlet and outlet of the steam generator.

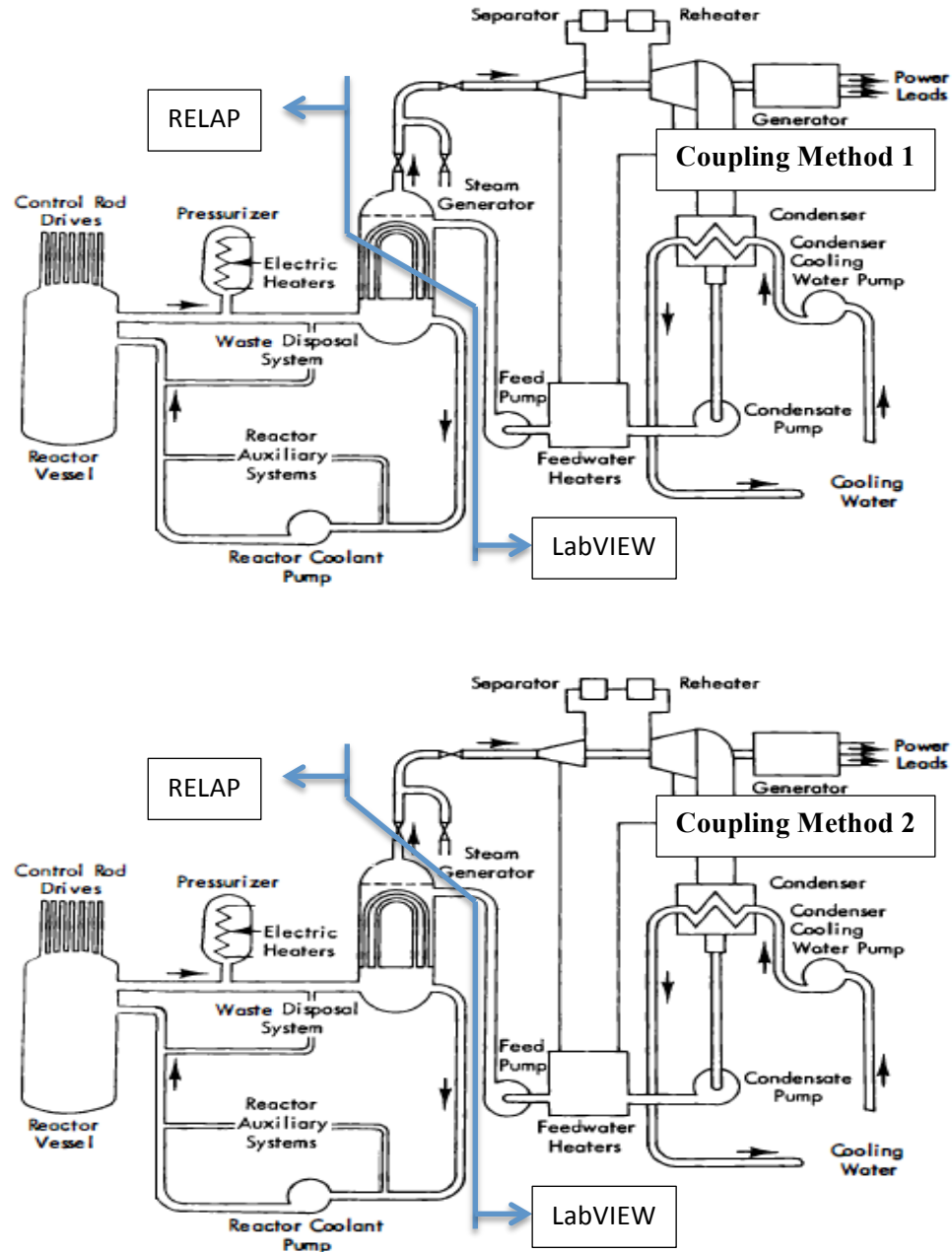


Figure 2.1 - Typical PWR System (Tong and Weisman, 1996) Coupling Methods 1 and 2

This Thesis demonstrates modeling of both primary and secondary loops with RELAP5 and LabVIEW codes coupled, as well as how these codes are coupled. The developed coupling is performed by the exchange of parameters such as heat flux and temperature between primary and secondary side of steam generator.

In most other coupling works, some of the challenges with integrating the two independent simulators are: firstly, that they use different time steps, and secondly that each simulation takes into account different parameters and equations. The coupling of RELAP5 and LabVIEW contained in this work provides a foundation for future work by showing that these codes are compatible, and with their coupling can produce results similar to those obtained with RELAP5 alone. Additionally the effect modifications to the secondary loop may have on the primary loop can more easily be studied by taking advantage of the instrumentation interface capabilities of LabVIEW.

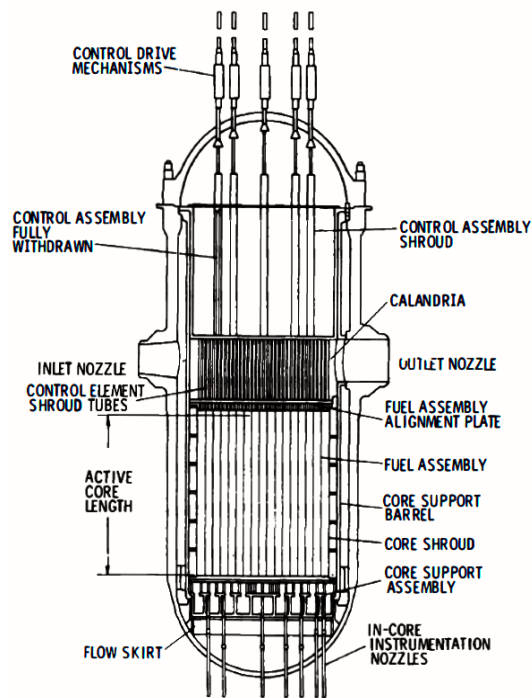
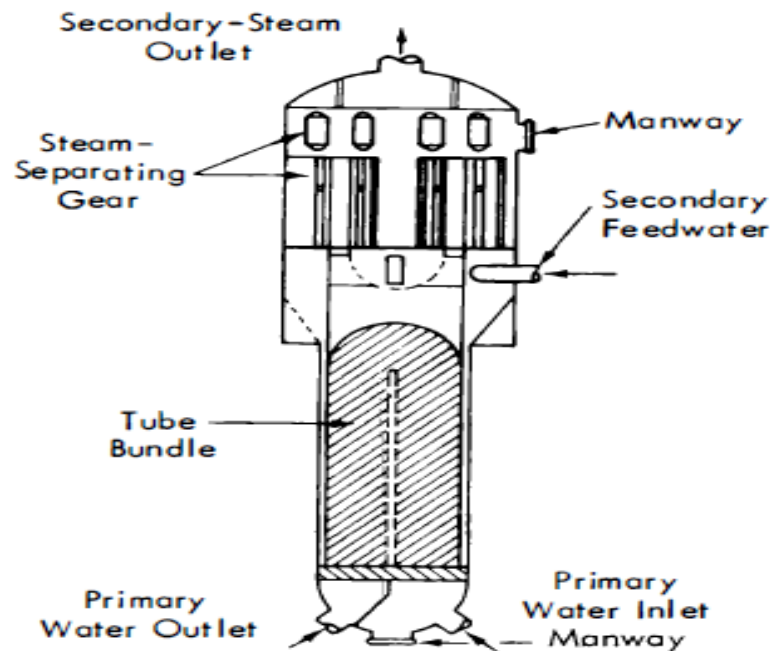


Figure 2.2 - Vertical Cross Section of a PWR Vessel (Farbman, 1965)



**Figure 2.3 - Vertical U-Tube Single Drum Steam Generator (Farbman, 1965)**

In the literature, several systems codes' advantages and disadvantages have been discussed by Roth and Aydogan (2013, 2014a, 2014b). The coupling approach between system codes and others address the weaknesses identified by Roth and Aydogan (2013, 2014a, 2014b). IAEA report (2003) mentions the benefits of coupling:

- The interface data are frequently exchanged between the codes, the code predictions of coupled codes are generated faster than running the codes separately,
- Coupling focuses on the interface where coupling occurs and needs not modify significant portions of the program, the software development effort is minimized,
- The interface data between the coupled codes can be adjusted while additional assumptions, data averaging, and reductions are minimized.
- The effort for verification and validation is minimized since well-established codes are coupled.



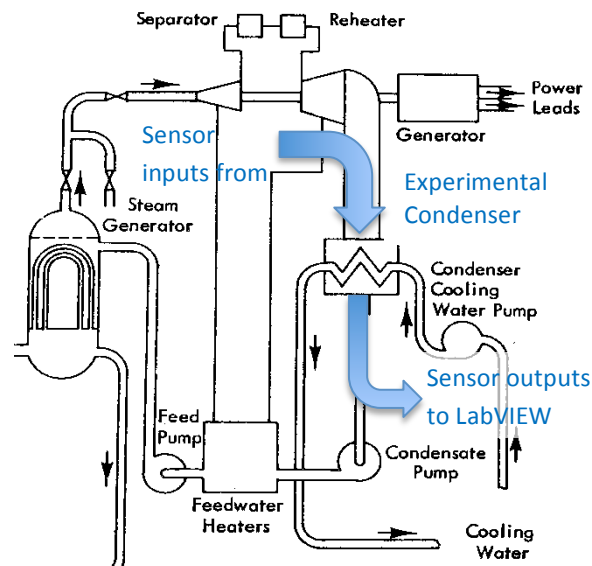
There are several existing studies that demonstrate the coupling between RELAP5 and other computer codes. Some of the examples are given as,

1. The IAEA (2003) held a conference discussing the use and application of coupled thermal-hydraulic codes. IAEA classified the coupling in three categories:
  - a. Coupling between neutronics and thermal-hydraulics
  - b. Coupling between local behavior and system behavior, such as,
    - i. System (or Thermal Hydraulics -TH-) code and sub channel code,
    - ii. System/TH code and fuel behavior code,
    - iii. System/TH and Computational Fluid Dynamics (CFD) code
  - c. Coupling between TH code and mechanical codes, such as,
    - i. TH code and structure mechanics codes
    - ii. TH codes and containment code.
2. Other works to couple RELAP5-3D with other software include the work by Martin (1995) who utilized the Parallel Virtual Machine (PVM) software to generate a method for coupling of RELAP5-3D with other codes. PVM works with the RELAP5-3D version.
3. Aumiller et al. (2001) coupled RELAP5-3D with CFD software in order to generate a more accurate model when computational time is allowed.
4. Salah and D'Auria (2006) also performed a work to couple RELAP5-3D with PARCS to perform an analysis of the Peach Bottom reactor. This work is contained mostly within the primary loop.
5. Jackson and Finnemann (1995) coupled RELAP5-3D with PANBOX in order to perform a plant safety analyses with a three dimensional neutron kinetics model.
6. Additionally CD-ADAPCO has developed a socket based coupling method between RELAP5-3D and STAR-CCM+ which is also a CFD code (Volpenhein, 2013).

7. University of Zagreb's coupling between the system code of RELAP5 and the sub channel code of COBRA. Even though RELAP5 and COBRA have similar conservation equations, COBRA in a coupling is preferred to model the thermal hydraulic modeling of coolant channels. Other examples of coupling between system and sub channel codes are given below (IAEA, 2003):

- a. Korea Atomic Energy Research Institute's (KAERI) coupling between MARS (a system code) and COBRA,
- b. The coupling between RELAP5 and COBRA by Tractebel Energy Marketing Inc.

The work to couple RELAP5 with LabVIEW is meant to allow the coupling of the primary and second loops, to give a more visual representation of the outputs, and allow for the direct link of any instrumentation in the plant or an experimental apparatus to the software in use. See Figure 2.4 (modified from Tong 1996) as an example for a potential experimental apparatus setup.



**Figure 2.4 - Possible Experiment Configuration**

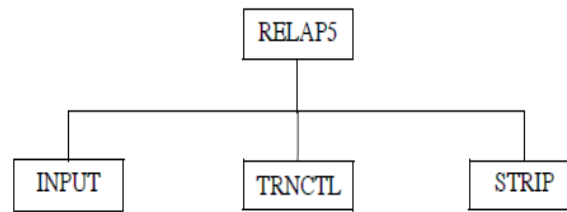
## 2.2. RELAP5 (US-NRC version)

The version of the Reactor Excursion and Leak Analysis Program (RELAP) used for this work is NRC RELAP5/MOD3.3Patch04. RELAP5 is a two-phase thermal-hydraulic program used for analyzing Loss of Coolant Accidents (LOCAs) within Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs). The analysis is performed within 1-D volumes by solving eight field equations for eight primary dependent variables including phasic velocities, pressure, phasic specific internal energies, boron density, vapor/gas volume fraction, and non-condensable quality. The governing and closure equations along with these eight equations are given in the RELAP5 manual (Nuclear Safety Analysis Operations, 2010).

### 2.2.1. RELAP5 Code Structure

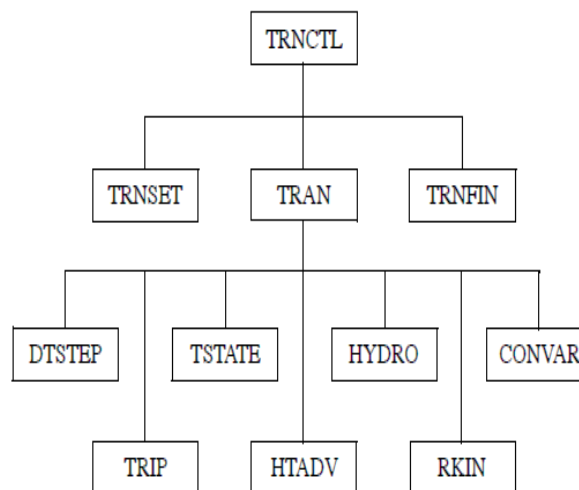
RELAP/LabVIEW coupling requires modifications to the RELAP5 source code. Part of this modification includes the addition of two new subroutines that allow for sending data to LabVIEW as well as receiving data from LabVIEW, then incorporating this data into the RELAP5 model. In addition to these subroutines there is another file that is generated by LabVIEW called a Dynamic Link Library (DLL) which contains all of the LabVIEW VIs. With these files and subroutines RELAP5 controls the coupling of the two codes and governs when LabVIEW is run, in doing so we obtain a real time coupling with the time step being controlled completely within RELAP5.

A brief explanation of code structure is presented in Figure 2.5. RELAP5/MOD3.3 has been coded in a modular fashion using top-down structuring. Figure 2.6 gives the RELAP5 top-level code structure NSAO (2010). The coupling framework of RELAP5 and LabVIEW requires modifications which change the code structure in the RELAP5 source code. These modifications are presented in sections 2.3 and 2.4.



**Figure 2.5 - RELAP5 Top Level Structure**

The INPUT block processes the input deck to prepare simulations; the STRIP block extracts data from a plot file into a smaller strip file for use by auxiliary programs. The TRNCTL block handles both steady-state and transient options. TRNCTL contains logic code to call on lower level subroutines including TRNSET, TRAN, and TRNFIN. The sublevel diagram of transient/steady-state block is shown in Figure 2.6 NSAO (2010).



**Figure 2.6 - Transient/Steady-State Block Structure**

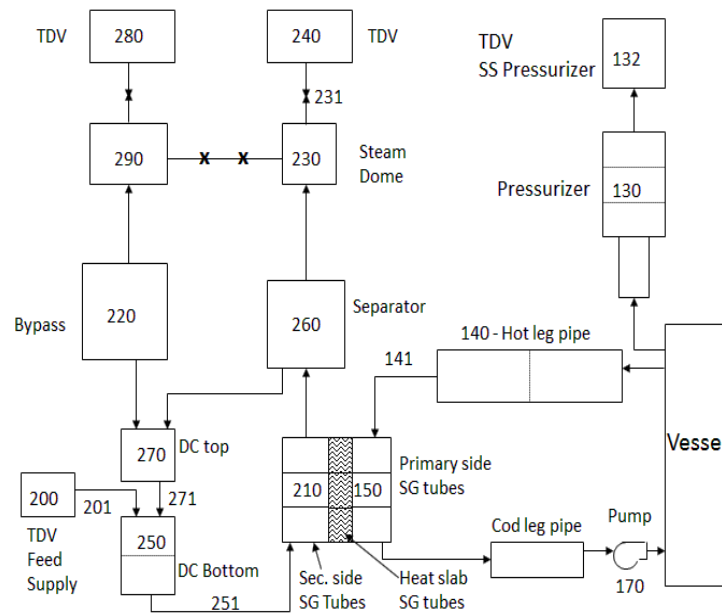
The TRAN block is the driver of the transient advancement of the solution and it uses nearly all the execution time. Any code changes that are required to achieve RELAP/LabVIEW coupling are done in or under the TRAN block level.

Two subroutines in TRAN are important to be understood for the coupling work: HTADV block and HYDRO block. HTADV is the heat structure block, which advances heat

conduction/transfer solutions. The hydrodynamics block-HYDRO advances the hydrodynamic solution. The details of RELAP5 source code modifications are presented in the following sections.

### 2.2.2. RELAP5 Model Description

Both steady state and transient simulations are tested with the coupling code. These two simulations use different models, which will be explained in the results section. For simplicity, the steady state model is described here and used for demonstrating how the coupling code works in the following section. The transient model is more complicated than the steady state one, but the means of exchanging data between LabVIEW and RELAP5 are the same. A simplified PWR simulation is modeled to reach a steady state condition. The system contains a single loop and one steam generator. The nodalization is shown in Figure 2.7.

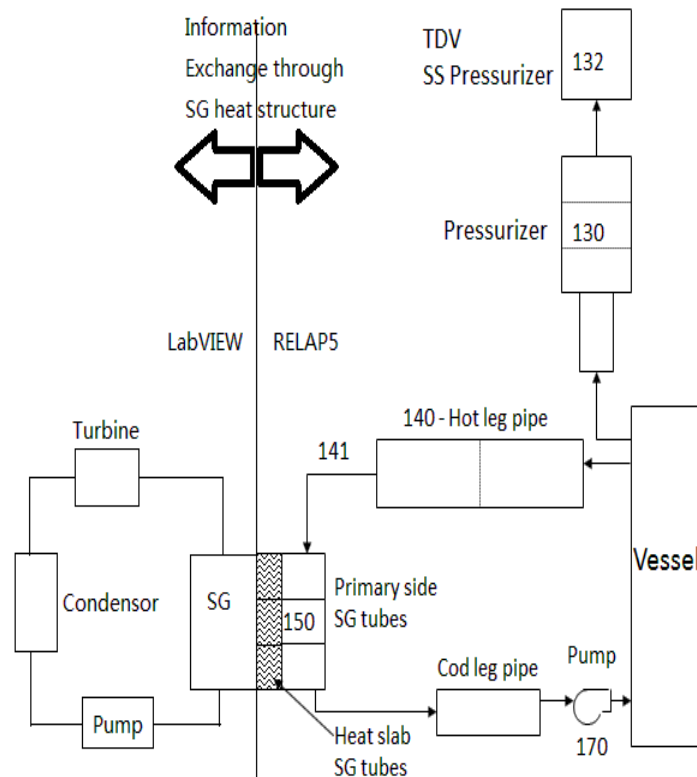


**Figure 2.7 - Simplified PWR Nodalization Diagram (ISS, 2014)**

Heat structures 15001(top), 15002(middle), and 15003(bottom) are the shaded areas in nodalization. These are the volumes used to simulate the wall of the steam generator tubes. The volumes connect the primary side volume 150 and the secondary side volume 210. The surface of

the heat structure connecting to primary side (volume 150) is defined as the right side of the slab; the surface of heat structure in contact with the secondary (volume 210) is the left side.

In the coupling code RELAP5 nodalization Figure 2.7 becomes Figure 2.8. The primary side uses the RELAP5 simulation and the secondary side is modeled with LabVIEW.



**Figure 2.8 - Simplified PWR Coupling Nodalization Diagram**

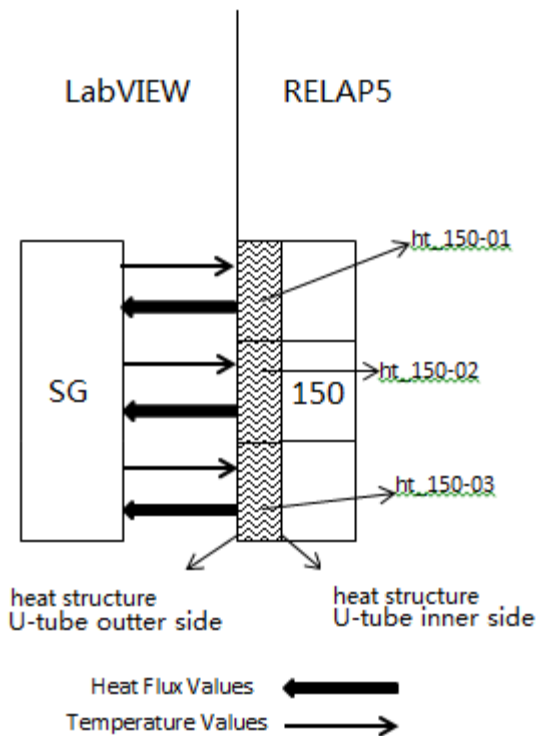
The information is exchanged through the Steam Generator tube wall. RELAP5 models the thermal hydraulic behavior of the primary side Steam Generator tubes and it is also responsible for computing heat transfer within the Steam Generator heat slab. LabVIEW is used to simulate the secondary side thermal hydraulic behavior. This is demonstrated by Figure 2.8

### 2.3. Data Exchange Between LabVIEW and RELAP5

#### 2.3.1. Data Exchange for Coupling Method One

The steam generator coupling nodalization is given again in Figure 2.9 with data exchanging between the two loops. Heat flux at the outer surface of the Steam Generator is computed from

RELAP5 and passed to LabVIEW. RELAP5 receives temperature values from LabVIEW and stores them as the outer surface temperature variables. The steam generator is divided into three volumes and each volume attaches to one heat structure. Consequently, three heat flux values are transferred into LabVIEW from RELAP5 and three temperature values transfer back from LabVIEW to RELAP5. Figure 2.9 shows which information exchanges between two codes and in which direction they exchange.

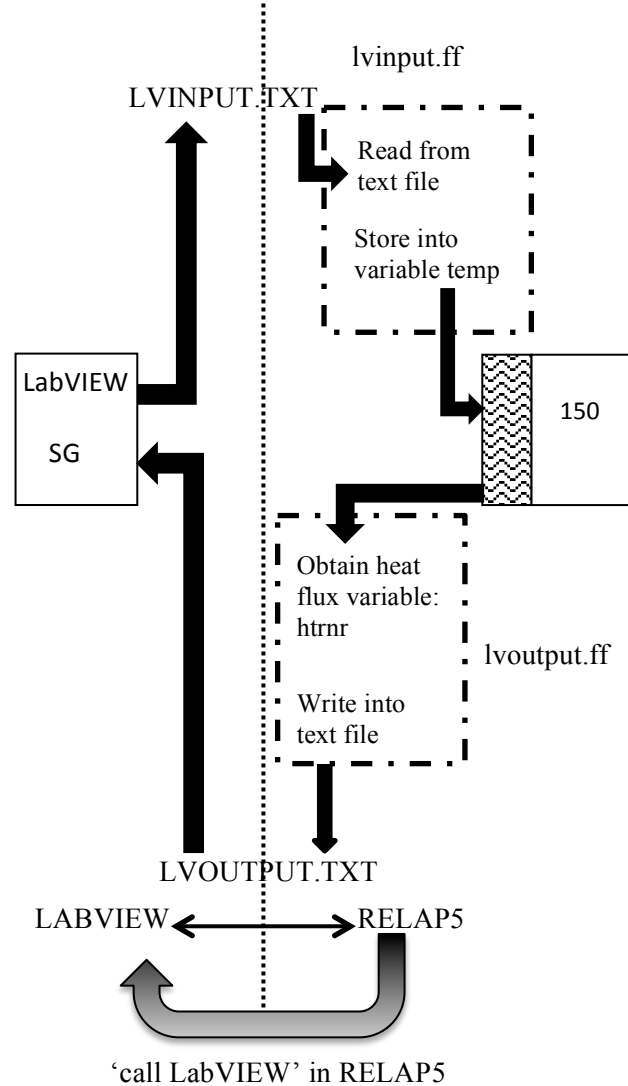


**Figure 2.9 - Diagram of Data Exchanging in Steam Generator**

There are two new subroutines that were created in RELAP5 source code to handle the information exchange. Lvoutput.ff searches for steam generator heat flux variables computed from RELAP5 and writes them into a text file named lvoutput.txt. This subroutine is introduced at the end of the TRAN block since, at the end, the transient is advanced and new time step heat flux values are obtained.

The other subroutine is called `lvinput.ff`, which reads a LabVIEW-generated temperature text file called `lvinput.txt`. It then stores temperature values into heat structure surface temperature variables. These surface temperature values are used for computing the heat structure inner temperatures and heat flux going into the primary side. The computations are done in subroutine `HT1TDP` which is called within the `HTADV` block, which calculates heat transferred across solid boundaries of hydrodynamic volumes. And subroutine `HTCOND` returns left and right boundary conditions for a heat structure. Figure 2.10 presents the flow diagram of the parameters exchanged between LabVIEW and RELAP5.





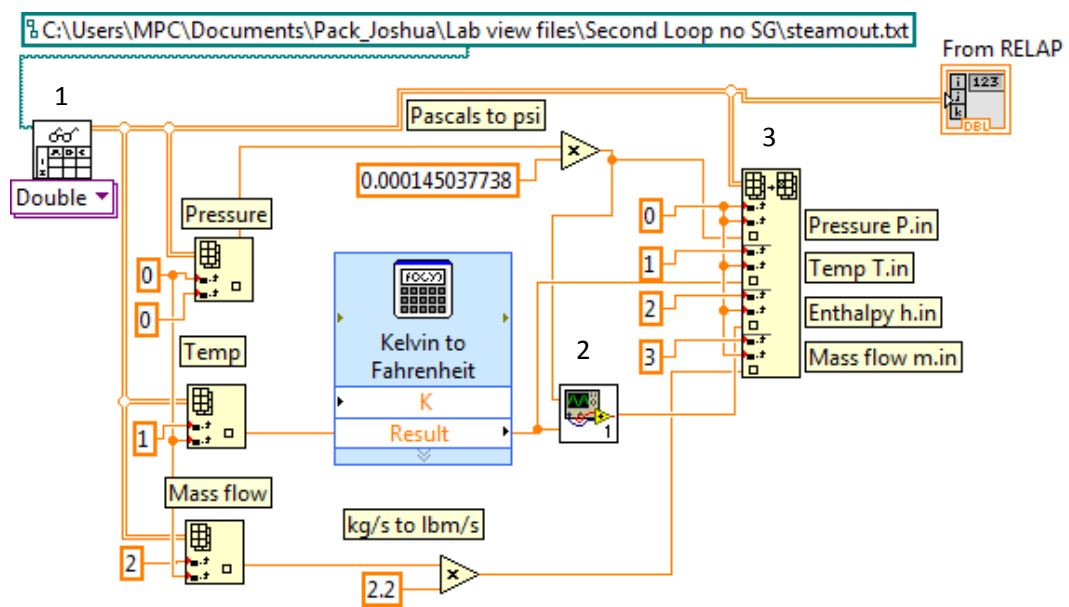
**Figure 2.10 - Flow Diagram of Parameters Exchange Between LabVIEW and RELAP5 Through Steam Generator**

### 2.3.2. Data Exchange for Coupling Method Two

The second method of coupling RELAP5 and LabVIEW is also referred to as 'new LabVIEW' in the plots presented later. The data exchange between RELAP5 and LabVIEW for the second coupling method is significantly simpler than the first method. The exchange of data is performed simply by each program exchanging data using two text files that contain the fluid conditions for the inlet and outlet of the secondary side of the steam generator. RELAP5 writes the steam output

fluid data to a file that is read by LabVIEW which then returns the input fluid data for the secondary side of the steam generator. This data is read by RELAP5 and utilized in determining the steam outlet conditions to be sent back to LabVIEW.

For the second coupling method, all modeling of the steam generator, including primary and secondary sides, is done within RELAP5. LabVIEW delivers and receives fluid data at the steam generator cold water inlet and the steam outlet. Figure 2.11 is a portion of the VI that receives the data from RELAP5 through the text file denoted at the top of the figure. At location 1 the text file is read into LabVIEW, once the data is read there is unit conversion performed and at location 2 the VI determines the enthalpy based on the inlet conditions. Location 3 allocates the data into an array

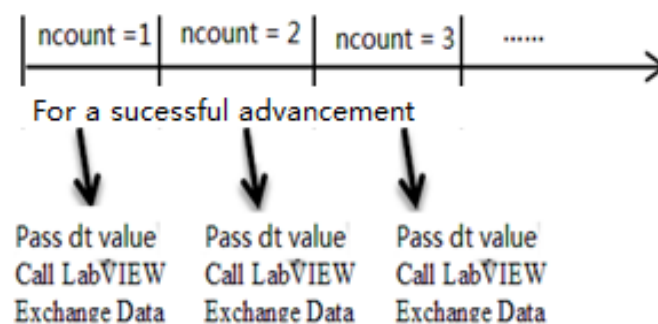


**Figure 2.11 - Receiving and Reading Text Files from RELAP5**

The same programming, only backwards, is used to return the SG feedwater inlet data to RELAP5.

## 2.4. Interface Management in Coupling

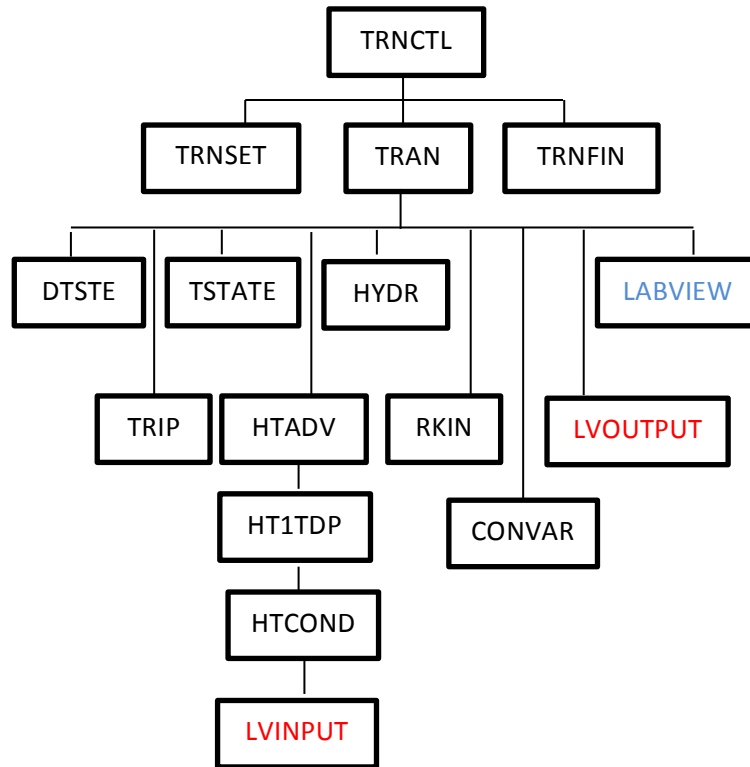
The LabVIEW application is invoked inside RELAP5. It is called after calling the lvoutput subroutine. There are two benefits of using RELAP5 to control LabVIEW. First, since RELAP5 is used for interface management, there is no need for another interface management code. This saves the effort to create an upper level code to control the two codes and to handle the information exchange between them. Moreover, by invoking LabVIEW within RELAP the TRAN block achieves a real time coupling. Since TRAN controls the time step advancement, lvinput, LabVIEW, and lvoutput this enables RELAP to run LabVIEW and exchange data at every time step. Another parameter that is exchanged between RELAP5 and LabVIEW is the variable 'ncount'. This variable is used to inform LabVIEW what RELAP5s current time advancement is for the current time step. The ncount variable records the number of time steps and uses 'dt' to store time advancement. 'dt' is one parameter used by LabVIEW at every time step in order to achieve synchronization. Figure 2.12 demonstrates how, for a successful transient advancement, RELAP5 first passes time step value, calls LabVIEW, and then manages to exchange data in order to avoid the information loss due to de-synchronization.



**Figure 2.12 - Synchronization**

A modified transient/steady-state block structure is shown in Figure 2.13. There are three new blocks appearing in the new structure: LVINPUT, LVOUTPUT, and LabVIEW. As mentioned above, LVINPUT and LVOUTPUT are two new subroutines added into the RELAP code. However,

LabVIEW is not a RELAP subroutine. Instead, it is a dynamic link library known as labview.dll which is generated through a LabVIEW application. In order for RELAP to recognize and use subroutines in labview.dll, labview.lib has to be linked to the RELAP executable file.



**Figure 2.13 - Transient/Steady-State Block Structure Coupled with LabVIEW**

## 2.5. Differences Between Coupling Methods at the Steam Generator

In the first coupling method the link between the two programs occurs between the primary and secondary sides of the heat exchanger within the Steam Generator (SG). With regard to the coupling being performed in coupling method 1 this component is where the essential data exchange occurs. The main purpose of the SG VI is to accept the data from RELAP through the file containing the heat flux data from RELAP5, this data is used to perform the calculations necessary including equation (20) then transfer the information into the remainder of the second loop VI.

The main components of the SG contained within the VI are the performance of reading data from RELAP as well as SG inlet data from the pump. The heat transfer from the primary to the secondary side is calculated using the equation:

$$(Q * A)/\dot{m} = h_2 - h_1 \quad (20)$$

At that point it is necessary to calculate the temperatures that are returned to RELAP5 for the calculation of the tube side outlet conditions. To perform this, the state of the fluid must be determined. This is performed using the conditional loops within the programming that determine whether the fluid is in a sub-cooled, saturated, or super-heated condition. Also contained within these loops are the calculations to determine the temperature at the outlet of each control volume as well and the SG as a whole.

## 2.6. Conclusions

Coupling method 1 between RELAP5 and LabVIEW is achieved by choosing the steam generator as a connecting point and transferring heat flux and surface temperature. Two text files are used as temporary data storage for the information being transferred through the steam generator. An interface manager is needed to control two codes and handle the data transfer between them. The manager invokes RELAP call, LabVIEW call, and writes and reads text files and subroutines in a correct sequence. In order to reach synchronization, RELAP5 is used as the interface manager and it needs to pass LabVIEW the parameter – ‘dt’, the time step. At each time step advancement RELAP5 writes heat flux values into a text file, passes data to LabVIEW, invokes LabVIEW dynamic link library to compute new time surface temperatures, and uses temperature values to calculate heat flux going into LabVIEW. RELAP5 performs this procedure at an advancement to avoid losing data due to de-synchronization.

The second method is significantly simpler by removing the SG component from the LabVIEW model and using RELAP5 to do all calculations for the steam generator from the feed water inlet of the steam generator to the steam outlet of this major component.

Coupling of these two codes is achieved by choosing the steam generator as a connecting point and transferring heat flux and surface temperature data between LabVIEW and RELAP5. Two text files are used as temporary storages for the information being transferred through the steam generator. An interface manager is needed to control these two codes and handle the data transfer between them. The manager invokes the RELAP call, LabVIEW call, and write and read text file subroutines in the correct sequence. In order to reach synchronization, RELAP5 is used as the interface manager and it needs to pass another parameter to LabVIEW – 'dt', which stores time used to advance every time step. At each time step, RELAP5 writes heat flux data into a text file, passes time advancement to LabVIEW, invokes the LabVIEW dynamic link library to compute new time surface temperatures, and uses temperature values to calculate heat flux going into LabVIEW. RELAP5 performs this procedure at an advancement rate to avoid losing data due to de-synchronization.

## **CHAPTER 3: Simulations with Coupling of RELAP5 AND LabVIEW**

### **3.1. Introduction to Coupling Simulations**

Multiple simulations were performed with various LabVIEW and RELAP5 configurations. The first simulations performed were using simple secondary loops in LabVIEW as well as simpler steady state models in RELAP5. The simulations continue to increase in complexity both in RELAP5 and LabVIEW and more components are utilized in the LabVIEW secondary loop and RELAP5 models are modified to include more sophisticated nodalizations as well as the simulation of transients.

The simplified PWR input deck models a steady state problem. There is short period of transient behavior in the first few seconds of steady state simulation due to the fact that the control systems try to balance the plant condition. The control system in the primary loop is a pump controller. The given initial conditions in the input deck may not be close to the steady state conditions, so the control systems adjust accordingly. And it results in a short period of transient behavior before the plant reaches a steady state condition.

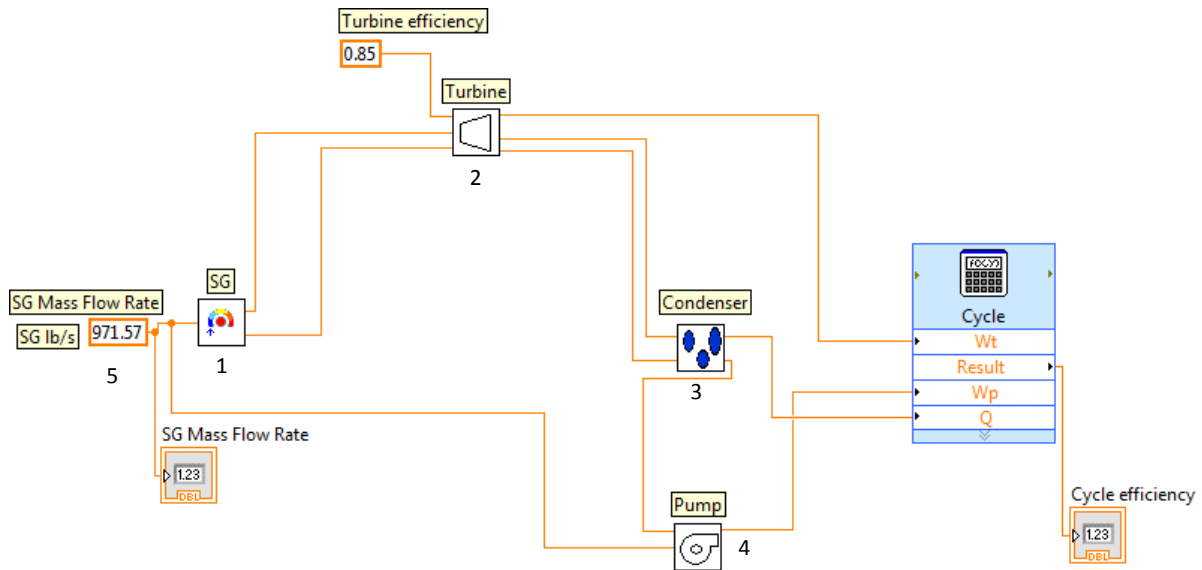
A typical PWR input deck is used to test the Loss of Coolant Accident (LOCA) transient event. The typical PWR is a four-power-loop system and the model simulates a small size break in one of its loops. The break triggers a core scram in the primary system.

### **3.2. Coupling Method One Simulations**

#### **3.2.1. Steady State Simulations**

The following simulations were performed using coupling method one and the secondary loop in Figure 3.1. This figure is divided into four sub VIs representing the Steam Generator (SG), Turbine, Condenser, and Pump annotated as sub VIs 1, 2, 3, and 4 respectively. The link between the pump and the steam generator isn't shown due to the necessity to store data from one

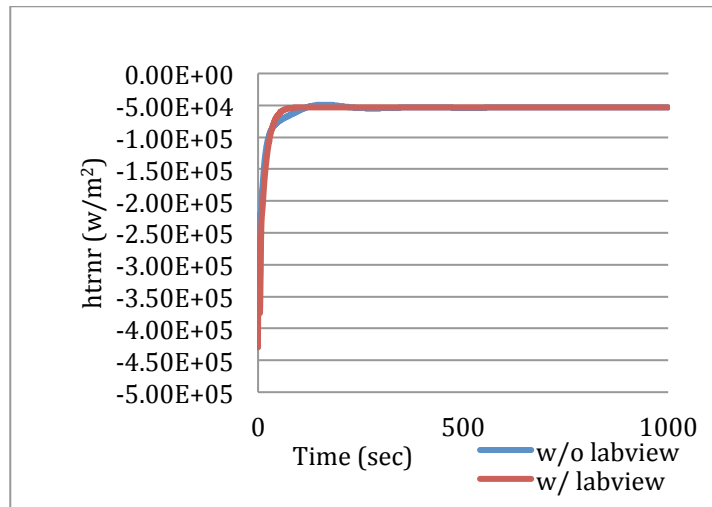
evolution of the VI to the next, thus the pump VI writes to a text file and the Steam Generator VI reads the text file that the pump outputs.



**Figure 3.1 - Simplified Secondary Loop VI**

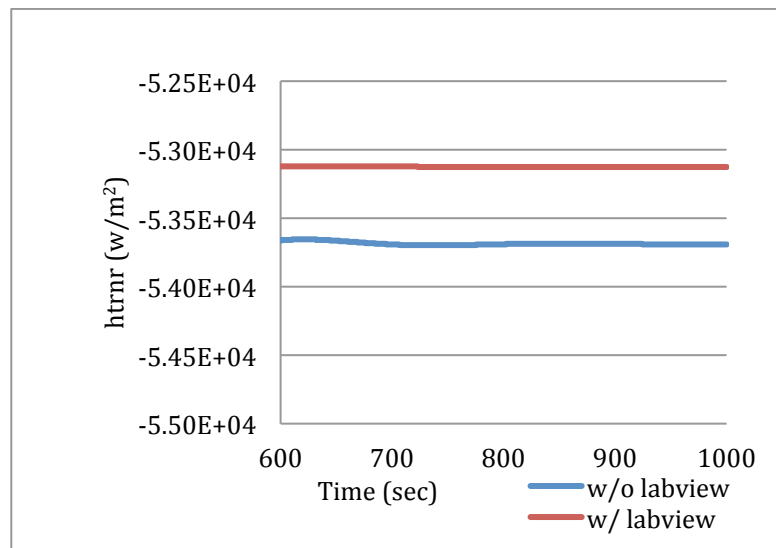
The simulation predicts that a relatively stable condition in the reactor is reached at around 250 seconds. The simulation runs for another 1000 seconds of problem time in which the condition remains stable. The heat flux values exchanged between the steam generator secondary side and primary side is shown in Figure 3.2. In the following figures, the code predictions of RELAP5 alone and the coupled codes are given. Even though the model of RELAP5 without coupling to LabVIEW covers the first coolant loop, hard coded data in RELAP5 model is used to simulate the interaction between first and second loops at the interface between them. The comparisons between the coupling code and RELAP5 show that coupled framework's predictions have close agreements with the code predictions by RELAP5 alone.





**Figure 3.2 - Heat Structure 150-03 Primary Side Heat Flux Steady State Comparison**

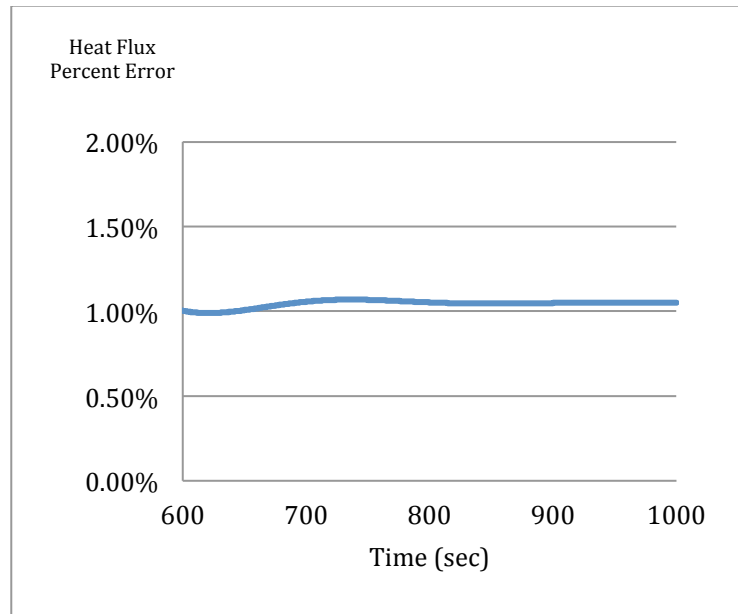
Figure 3.3 plots heat flux coming out of primary loop into the heat structure bottom level after 600 seconds simulation time.



**Figure 3.3 - Heat Structure 150-03 Primary Side Heat Flux Steady State Comparison After 600 Seconds**

Firstly, the flux on primary side has negative values. Negative values mean that heat is transferring from the primary loop into the heat structure. In contrast, losing heat out of a heat structure gives positive heat flux values. This is reasonable since the primary side is losing heat to the secondary side. Moreover, these heat flux values are computed by RELAP5 based on heat

structure surface temperature computed by LabVIEW. The difference of heat flux values in two tests is small after reaching a stable condition and, after 600 seconds, the percentage error of heat flux from the primary loop is about 1%, as shown in Figure 3.4.



**Figure 3.4 - Heat Structure 150-03 Primary Side Heat Flux Percent Error after Reaching Steady State**

Heat structure surface temperatures are computed by LabVIEW. Comparison of surface temperature at the bottom of the primary side steam generator is given in Figure 3.5. Differences are also observed in the temperature comparisons. When reaching steady state, the two sets of surface temperature values approach each other. The percentage difference is about 1.2% (Figure 3.6). This small discrepancy is reasonable.

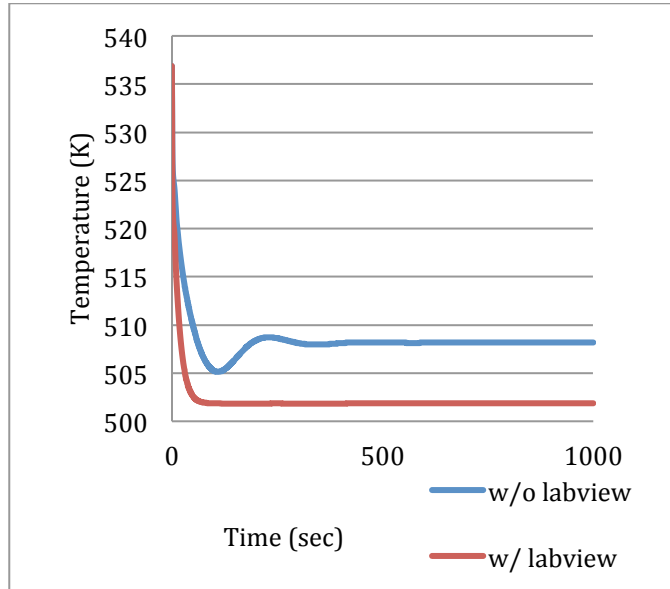


Figure 3.5 - Heat Structure 150-03 Primary Side Surface Temperature Steady State Comparison

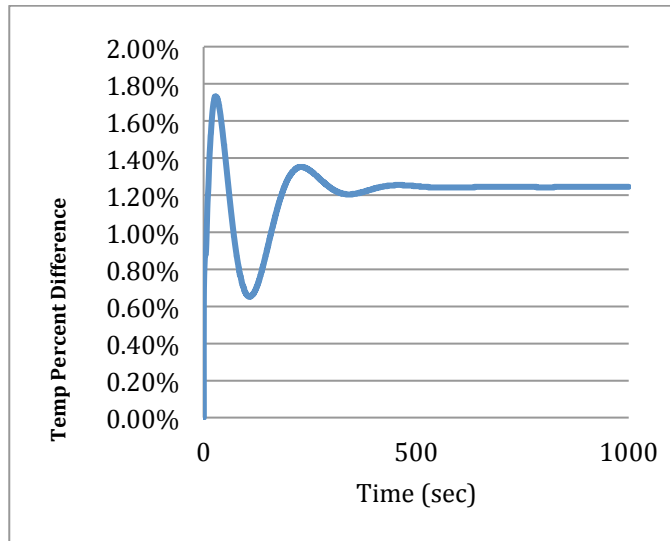
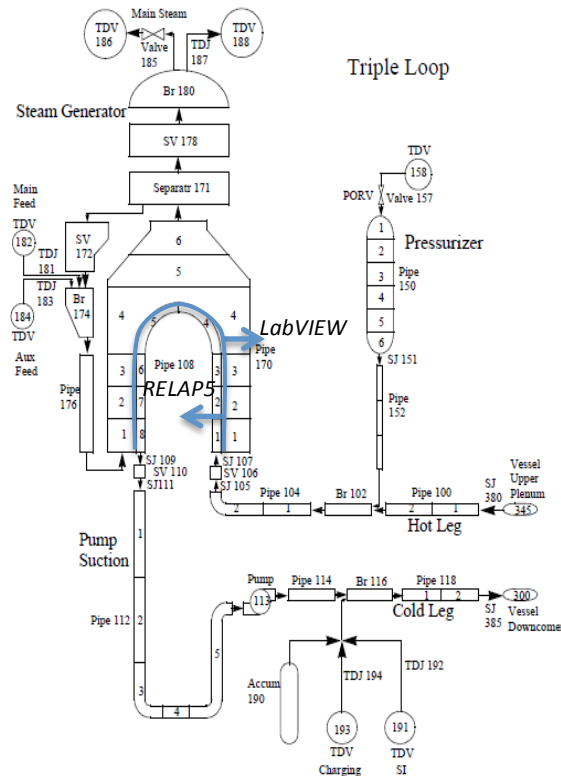


Figure 3.6 - Heat Structure 150-03 Secondary Side Surface Temperature Percent Error

### 3.2.2. Transient Simulation

For a transient test, a typical four-loop PWR (Figure 3.7) with a Loss of Coolant Accident (LOCA) scenario is used.

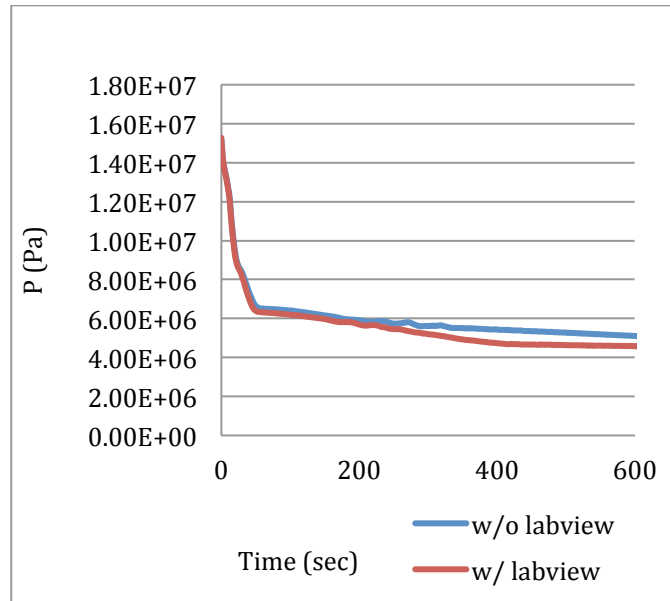


**Figure 3.7 – Typical PWR Nodalization**

The coupling process is the same as the method used in the steady state test. The secondary side is modeled with LabVIEW and the primary side uses RELAP5. The heat flux and temperature data are exchanged in the steam generator, as shown in Figure 3.7. One of the differences between the two models is that the typical PWR model uses more hydraulic volumes and heat structures to simulate U-tube section. Therefore, when comparing to the steady state test, more pairs of temperature and heat flux data are transferred during the LOCA test.

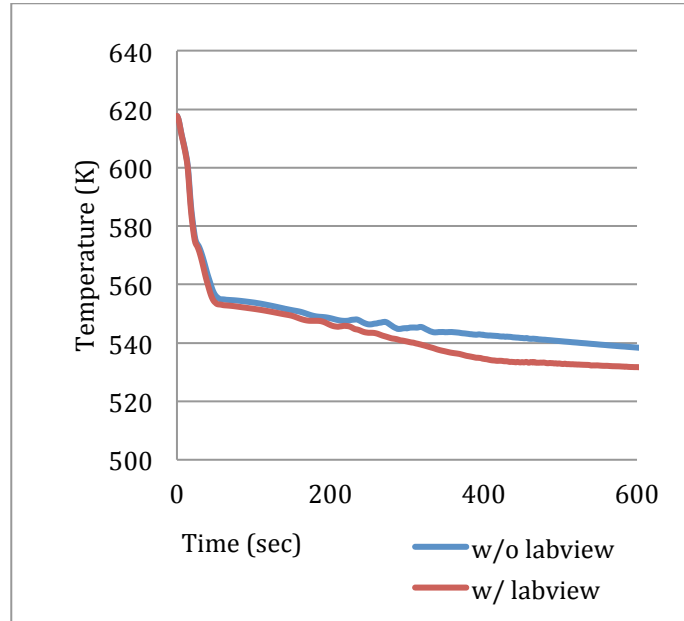
The break is modeled in one of the four coolant loops. The other three loops are coalesced into one loop. The break is initiated at the beginning of the simulation. Scram signal, RC pump,

steam generator main feed water, and main steam outlet are triggered when pressurizer pressure drops below 1860.0 psi. After 15 seconds, the auxiliary feedwater is initiated. Once coolant starts leaking out from the break loop, pressure in the primary system decreases quickly. The test runs up to 600 seconds to reach a relatively stable condition. Figure 3.8 presents the pressure reaction in the primary side during the LOCA transient.



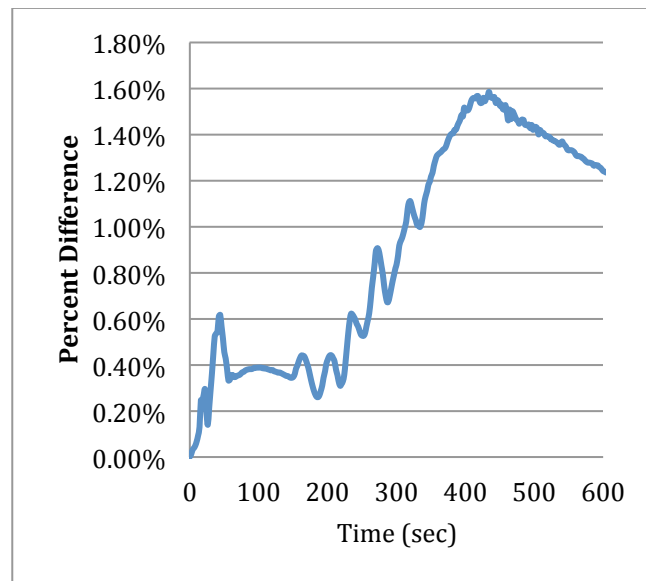
**Figure 3.8 - Primary System Pressures During LOCA**

The trends of pressure in each simulation are similar. Both pressures decrease quickly right after the break is initialized. The average percent difference between coupling code and RELAP5 code is about 7%. As pressure decreases, the primary loop temperature also decreases as shown in Figure 3.9.



**Figure 3.9 - Primary System Liquid Temperatures During LOCA**

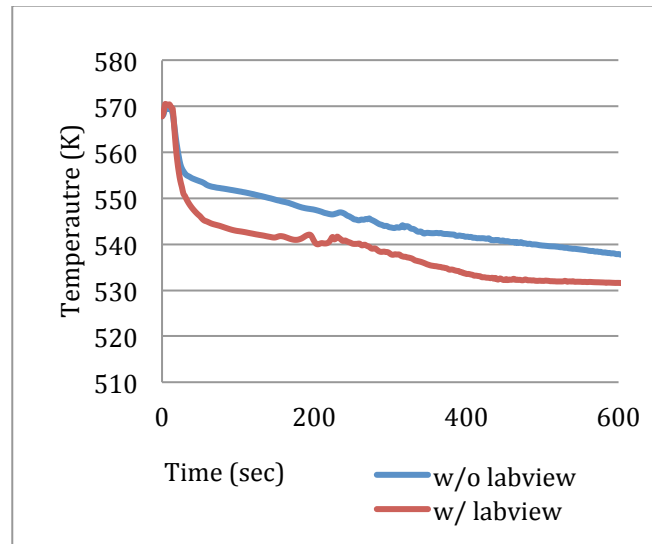
The percentage differences of primary system temperature between coupling code and RELAP5 code is shown in Figure 3.10. The average difference is less than one percent.



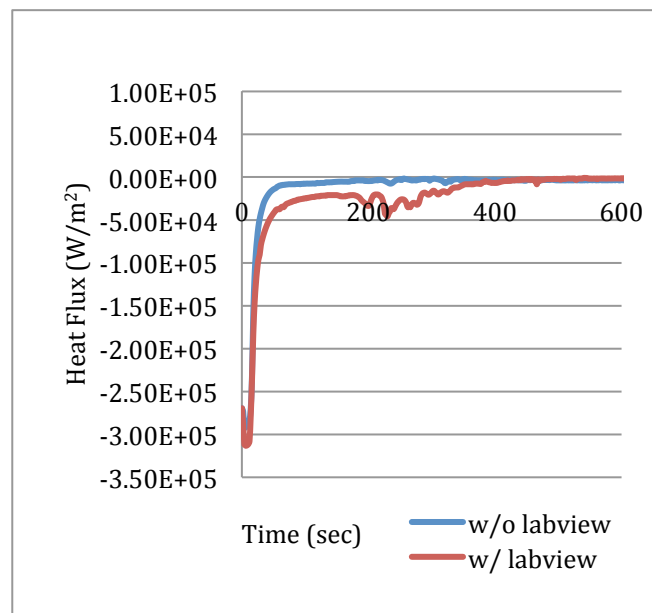
**Figure 3.10 - Primary System Temperature Differences During LOCA**

The primary loop temperature and pressure in Figure 3.8 and Figure 3.9 are not computed by LabVIEW since only the secondary system is modeled by LabVIEW. However, these plots

demonstrate that the coupling simulation is similar to RELAP5 simulation and LabVIEW modeled secondary system does not alter the behavior of RELAP5 modeled primary system very much. Next, the LabVIEW computed parameters are compared with RELAP5 results. Figures 3.11 and 3.12 present the steam generator heat structure quantities.

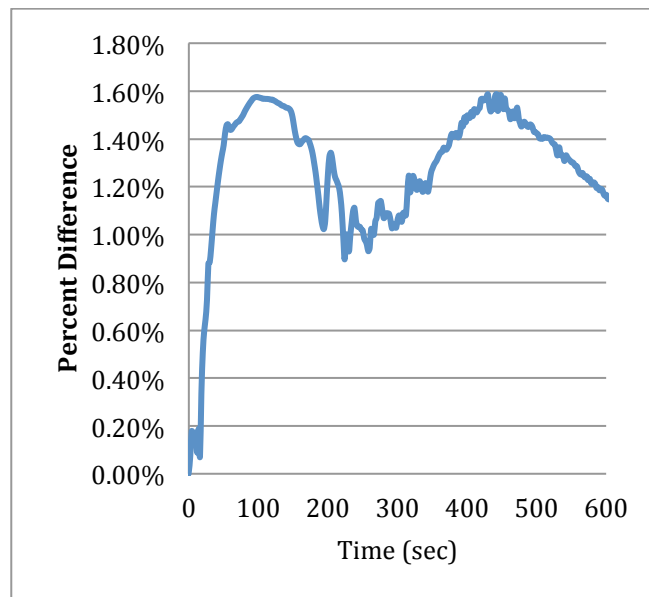


**Figure 3.11 - Heat Structure Surface Temperatures on Primary Side Steam Generator**



**Figure 3.12 - Heat Structure Heat Flux on Primary Side Steam Generator**

Figure 3.11 compares heat structure temperatures on steam generator surface between coupling code and RELAP5 code. Figure 3.12 presents the steam generator heat flux values from the two codes. LabVIEW is able to predict heat flux between the primary and secondary system correctly. The heat flux trend resulting from coupling code is similar to RELAP5's. The heat flux starts with a negative value since heat transfer is defined to be positive from the steam generator to primary system thus negative flux means that heat is being transferred from the primary system to secondary system. Then, heat flux suddenly approaches a small value as predicted by both codes. Since a LOCA event triggers both a primary side pump trip and a secondary side main feedwater trip, it decreases mass flow rate through steam generator. This reduces the effect of heat convection in steam generator, so the heat transfer is diminished quickly right after leaking occurs. At the end, the percentage difference of temperatures is plotted in Figure 3.13. The two codes provide a small difference in the heat structure temperature values.



**Figure 3.13 - Percent Difference of Heat Structure Surface Temperatures on Primary Side Steam Generator Between Coupling Code and RELAP5 Code**

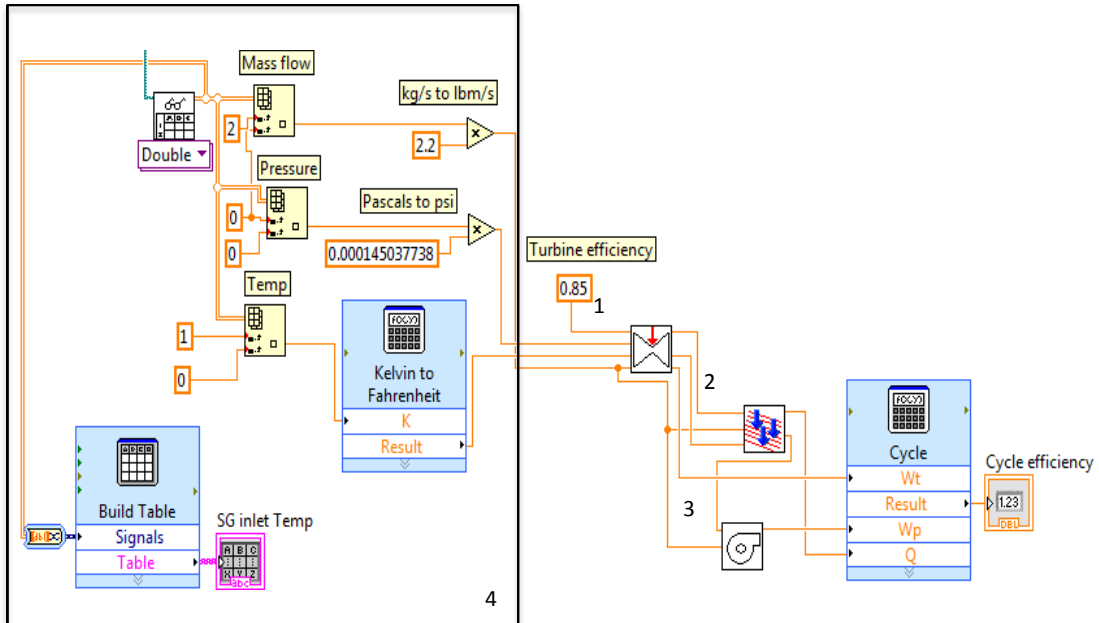
These simulation results show that the data is successfully transferred between the two codes. Comparing steam generator heat structure surface temperatures at steady state condition,



LabVIEW gives comparable results; the percentage difference of heat is about 1.2%. RELAP5 also returns reasonable heat flux values to LabVIEW. The coupling code gives about 1.0% difference in heat flux values during steady state simulation. A more complicated model for a four-power-loop PWR is used to test a transient event, or LOCA. One of four loops simulates a mid-size break in the primary piping system; the other three loops are coalesced together and modeled as one intact loop. Comparing steam generator heat structure surface temperatures during the transient, LabVIEW gives comparable results; the percentage difference of surface temperature is less than 1.6%. Coupling code also correctly predicts the steam generator heat flux behavior during LOCA transient event.

### **3.3. Coupling Method Two Simulations**

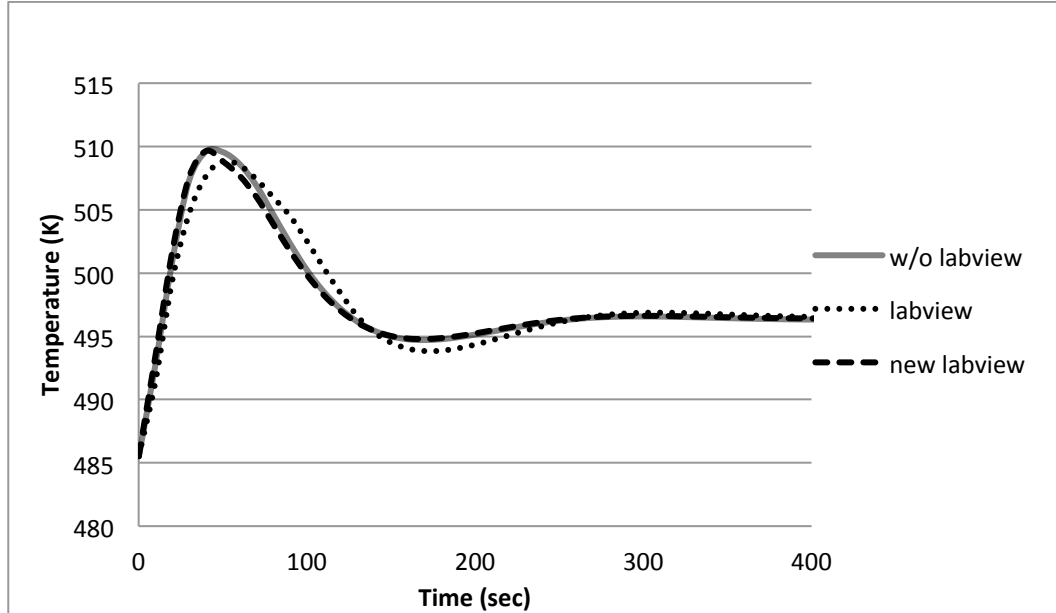
A typical PWR input deck is used to test Loss of Coolant Accident (LOCA) transient event. The typical PWR is a four-loop system and the model simulates a small size break in one of its loop. Break triggers core scram in primary system and other transient behavior in secondary side including closing down main steam valve and shutting down main feedwater. Figure IIIIII is a portion of the programing used for the simulation utilizing coupling method two. Locations 1, 2, and 3 on Figure 3.14 represent the turbine, condenser, and pump respectively with location 4 representing the programing for reading the text file from RELAP5 as well as performing any necessary unit conversions.



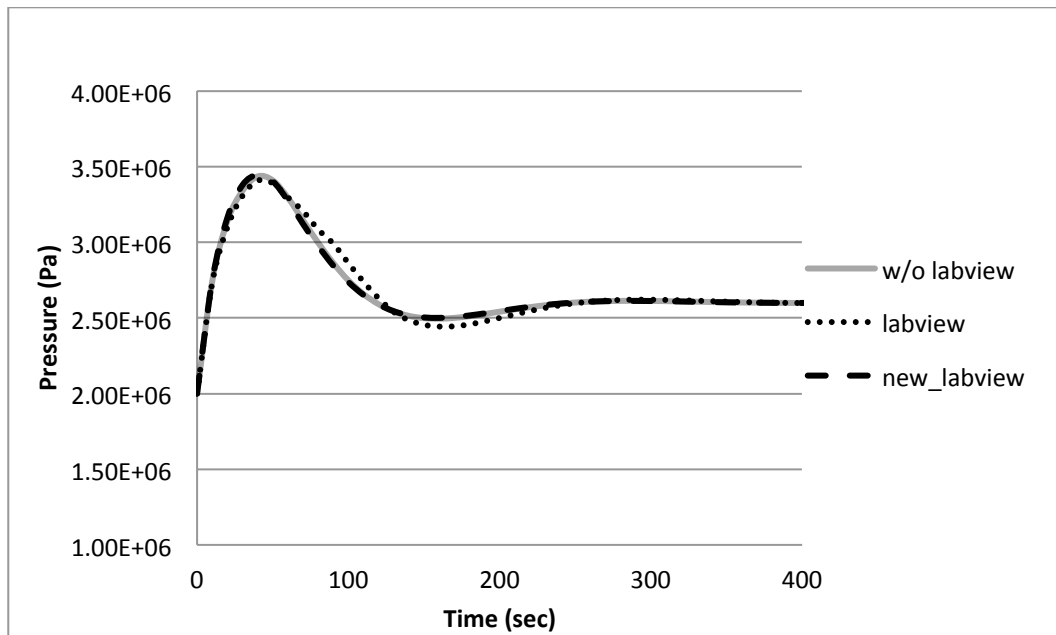
**Figure 3.14 - Simplified Secondary Loop VI Coupling Method Two**

### 3.3.1. Steady State Simulations

In comparison the steady state condition of the feedwater downcomer liquid temperature for both the first and second methods are shown in Figure 3.15 as well as the steam dome pressure for both methods as shown in Figure 3.16 demonstrating that the second method more closely follows the results obtained with the RELAP5 code alone.



**Figure 3.15 - Feedwater Downcomer Liquid Temperature Comparison Between Coupling Methods**



**Figure 3.16 - Steam Dome Pressure Comparison Between Methods**

### 3.3.2. Transient Simulations

Figure 3.17 represents the nodalization used in the transient simulation for the primary side components of one of the four primary coolant loops.

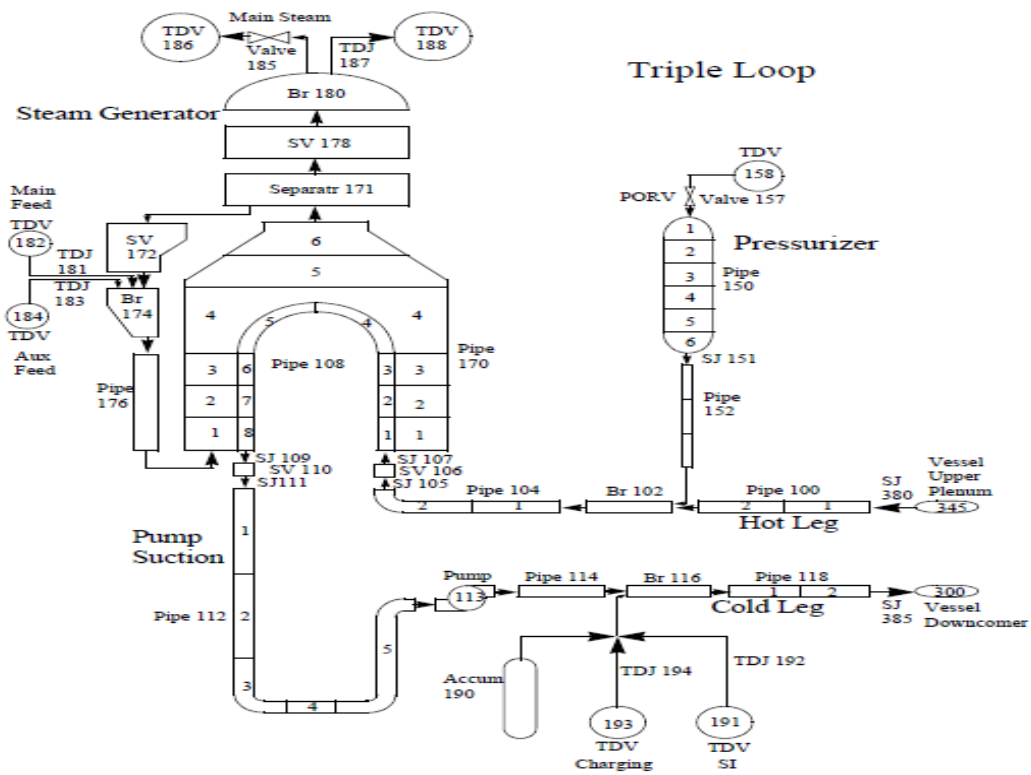
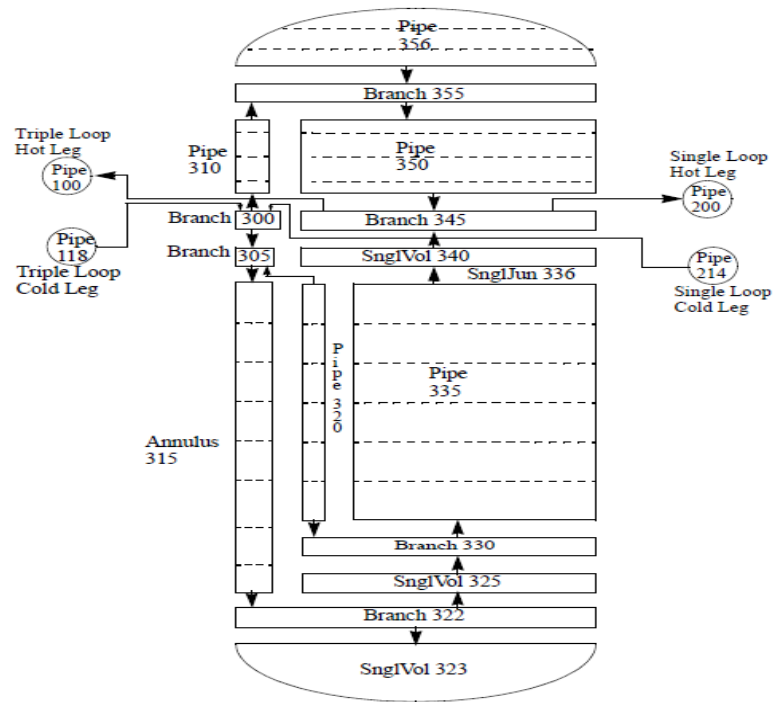
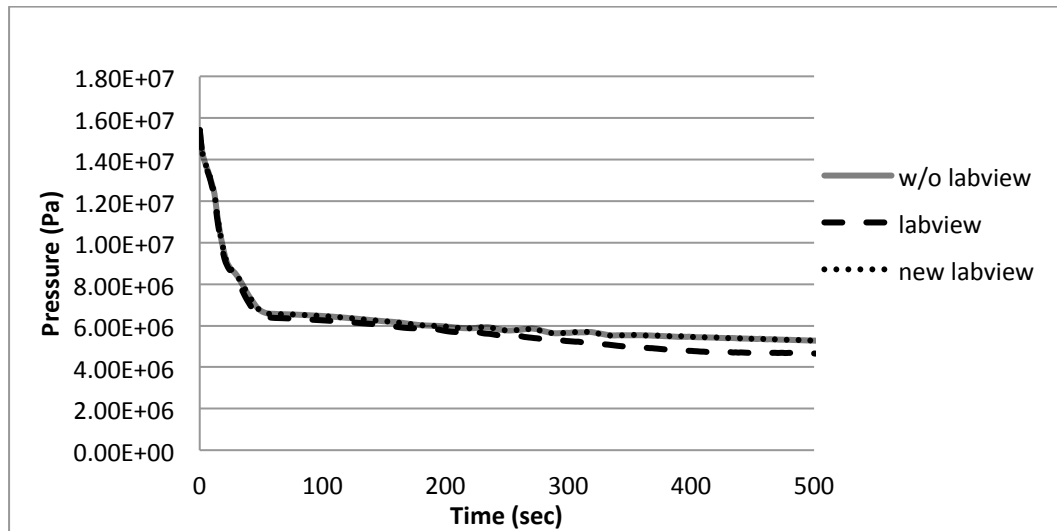


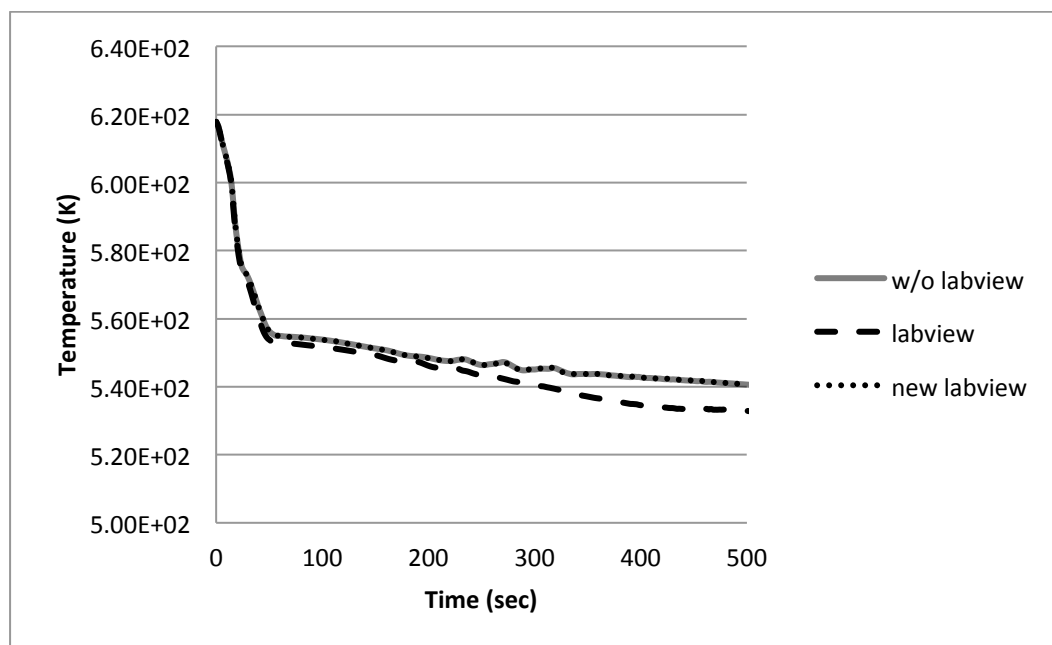
Figure 3.17 - Vessel (top) and Triple Loop (bottom) Nodalization (ISS, 2014)

Once coolant starts leaking out from the break loop, the pressure in the primary system decreases quickly. Figure 3.18 presents the pressure reaction in the primary side during a LOCA transient.



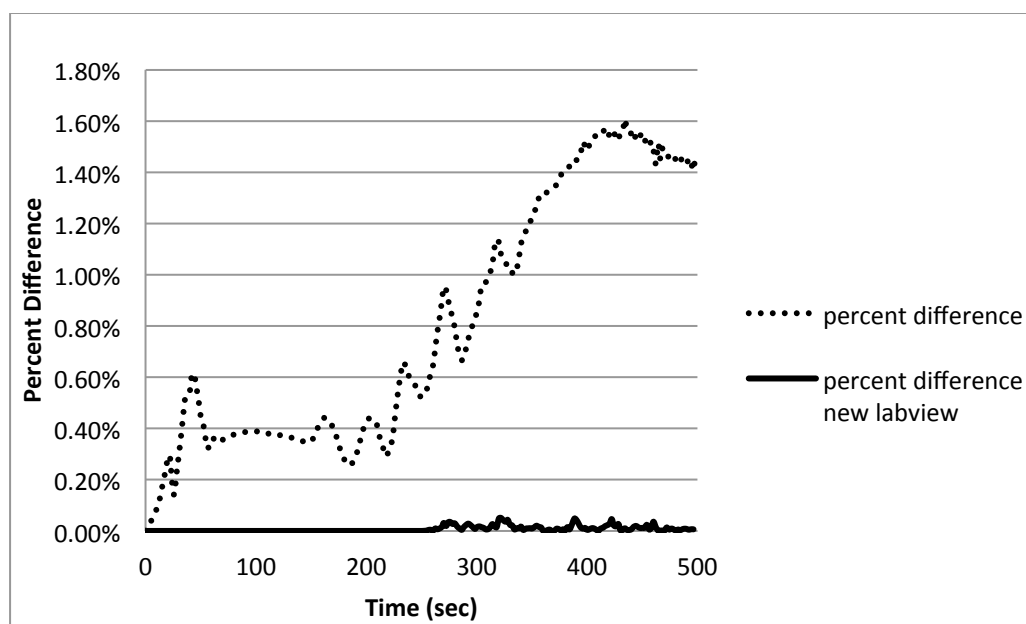
**Figure 3.18 - Primary System Pressures during LOCA**

The trends of pressure in these simulations are similar. The pressures decrease quickly right after the break is initialized. The average percent difference between method one coupling code and RELAP5 code is about 7% while the percent difference between method two and RELAP5 is negligible. As pressure decreases, the primary loop temperature also reduces as shown in Figure 3.19.



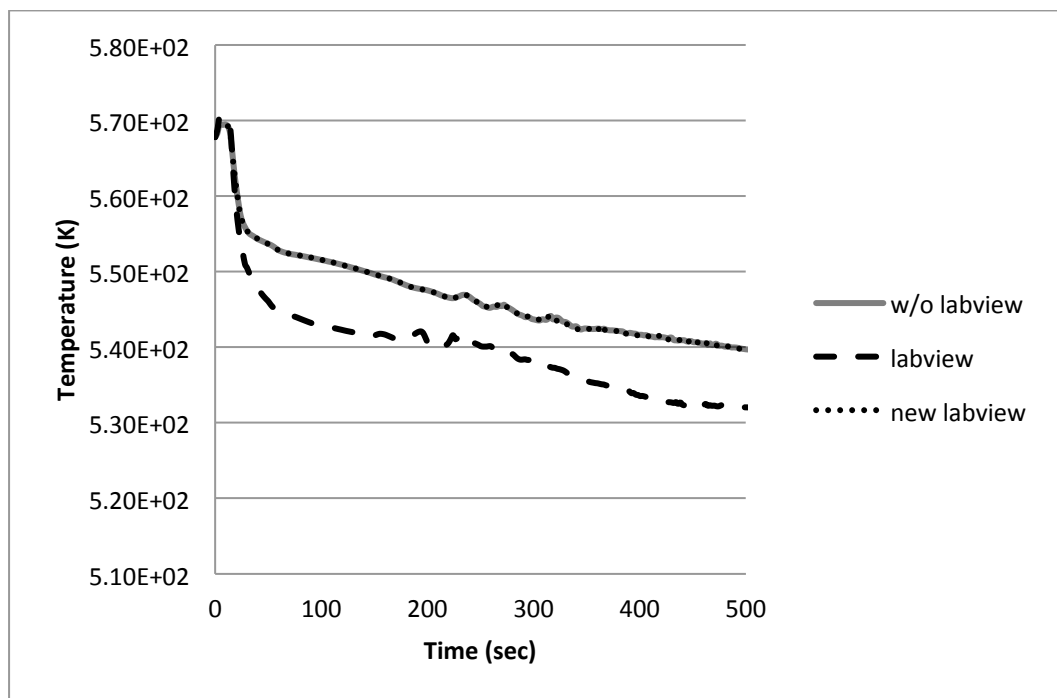
**Figure 3.19 - Primary System Liquid Temperatures during LOCA**

The percentage differences of the primary system temperature between the coupling code and the RELAP5 code are shown in Figure 3.20. The average difference is less than one percent for method one and less than 0.1% for method two.

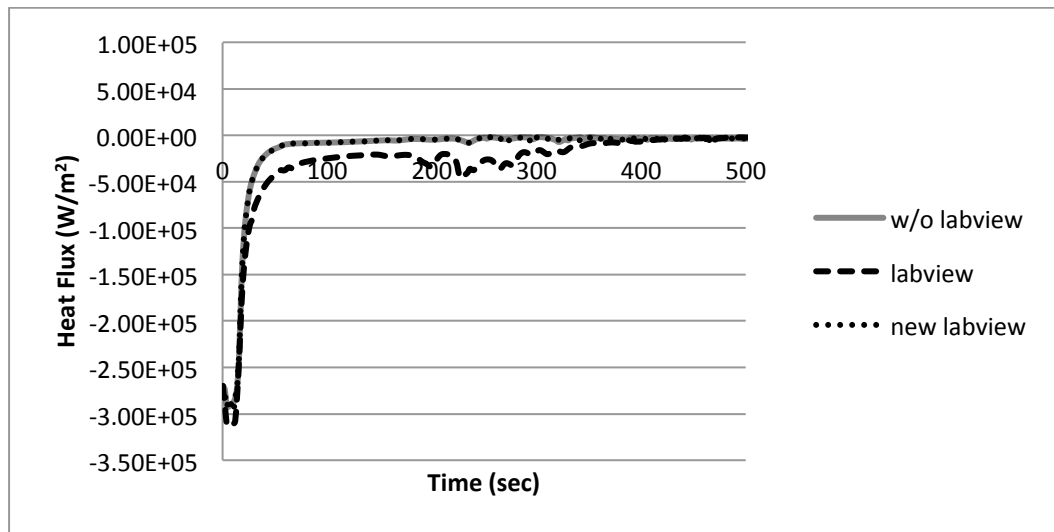


**Figure 3.20 - Primary System Temperatures Percent Difference During LOCA**

The primary loop pressure and temperature in Figure 3.18 and Figure 3.19 are not computed by LabVIEW since only secondary system is modeled by LabVIEW. However, the plots demonstrate that the coupling simulation is similar to RELAP5 simulation and that the LabVIEW modeled secondary system does not alter the behavior of RELAP5 modeled primary system much. Next, LabVIEW computed parameters are compared with RELAP5 results. Figure 3.21 and 3.22 present the steam generator heat structure quantities.



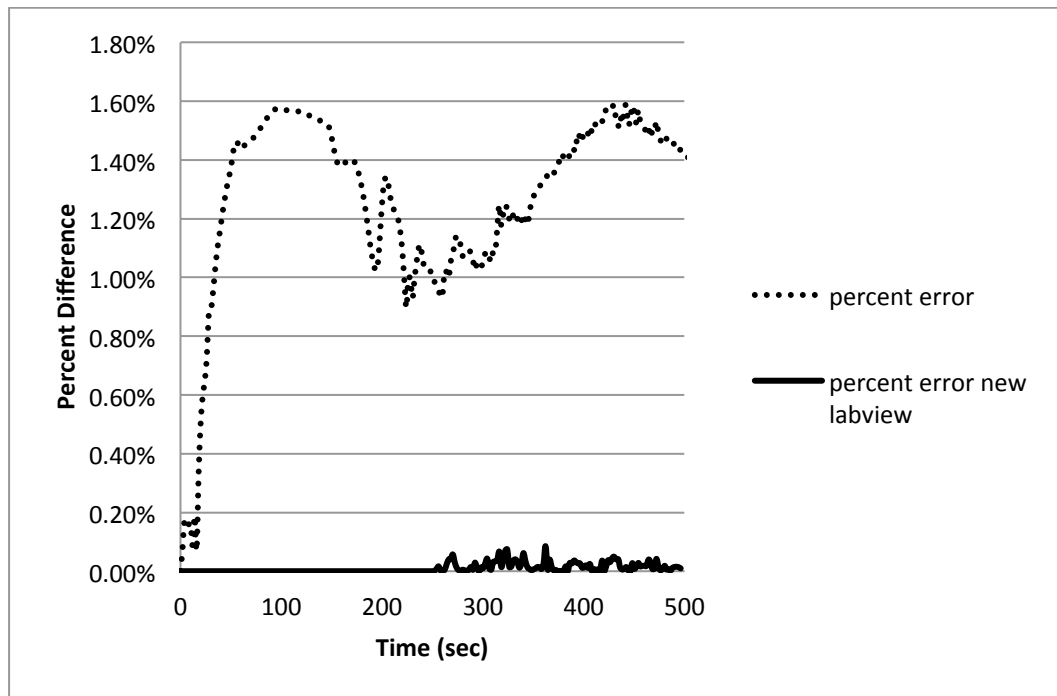
**Figure 3.21 - Heat Structure Surface Temperatures on Primary Side Steam Generator**



**Figure 3.22 - Heat Structure Heat Flux on Primary Side Steam Generator**

Figure 3.21 compares heat structure temperatures on steam generator surface between coupling code and RELAP5 code. Figure 3.22 presents the steam generator heat flux values from two codes. LabVIEW is able to predict heat flux between primary and secondary system correctly. The heat flux trend result from coupling code is similar to RELAP5's. Heat flux starts with negative value since heat transfer is defined positive from steam generator to primary system and negative flux means that heat is transferred from primary system to secondary system. Then, heat flux suddenly approaches to a small value as predicted by both codes. Since LOCA event triggers both primary side pump trip and secondary side main feedwater trip, it decreases mass flow rate through steam generator. This reduces the effect of heat convection in steam generator, so the heat transfer is diminished quickly right after leaking occurs. At the end, the percentage difference of temperatures is plotted in Figure 3.23. Two codes result a small difference on heat structure temperature values.





**Figure 3.23 - Percent Difference of Heat Structure Surface Temperatures on Primary Side Steam**

#### **Generator Between Coupling Code and RELAP5 Code**

Comparing the steam generator heat structure surface temperatures during the LOCA transient, LabVIEW gives comparable results; the percentage difference of surface temperature for method one is less than 1.6% but once again is proven to be far less in method two on the order of 0.1%. Both coupling codes accurately predict the steam generator heat flux behavior during LOCA transient event but this work has shown that there are better methods to perform these coupling works. In this case, that proved to be method two. Depending on the application of this software to an actual plant or testing apparatus, either coupling method may be preferred over the other. For example the experiment may need to be performed in the steam generator which would require the use of LabVIEW for modeling the steam generator and monitor the sensors used therein thus coupling method one may be preferred. However, if the study is being done

elsewhere in the secondary loop the second coupling method may provide the most accurate results.

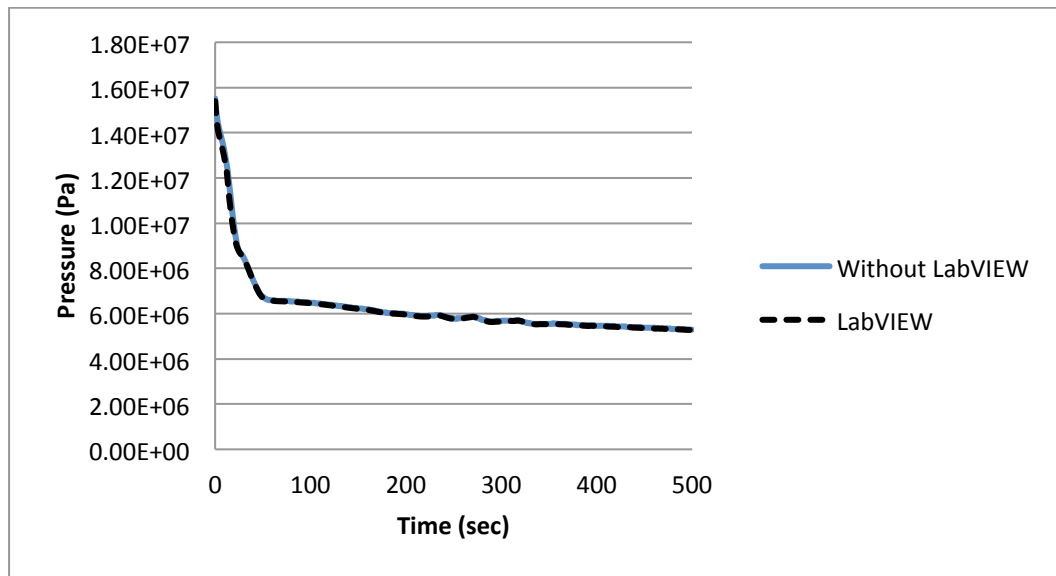
#### **3.4. Simulation Using an Advanced Secondary loop**

The second coupling method was used for coupling with the advanced secondary loop. For this portion of the research no additional work for steady state was performed using the advanced secondary loop. This advanced loop that was developed is shown in Figure 1.1.

The transient simulation is considered of the most significance to study the performance of the reactor and its sub-components during an accident scenario. Thus for this model a steady state simulation was not performed.

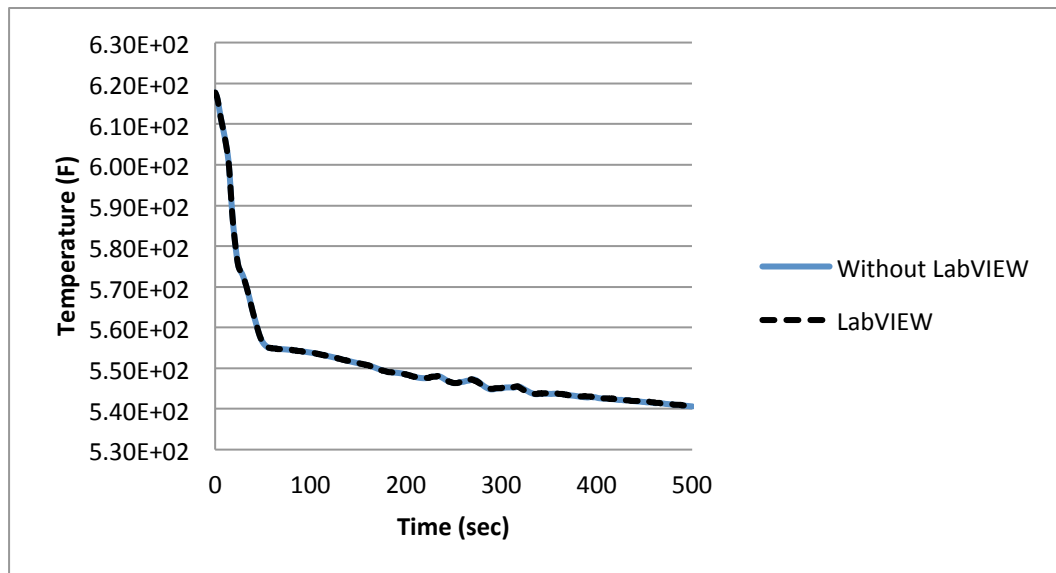
The break is initialized at the beginning of the simulation. When the pressure in the pressurizer falls below 1860.0 psia, the reactor scram is initialized. Fifteen seconds after the break is reached, auxiliary feedwater is initialized. Once coolant starts leaking from the break loop, the pressure in the primary system begins decreasing quickly. The results of such simulations are demonstrated as follows with the results of the coupling system that was run using the second loop in Figure 1.1. The graphical simulation results are based on simulation time which begins with the LOCA. For comparison, the results from the same PWR simulation in a non-coupled configuration are included on the same plots as the coupled results. The difference between the non-coupled and coupled results are very similar so the results may appear to be the same on a good portion of the plots which is why the non-coupled data is in a solid line and the coupled data a dashed or dotted line.

Figure 3.24 presents the pressure prediction in the pressurizer during LOCA transient simulations using RELAP5 alone as well as the coupled simulation.



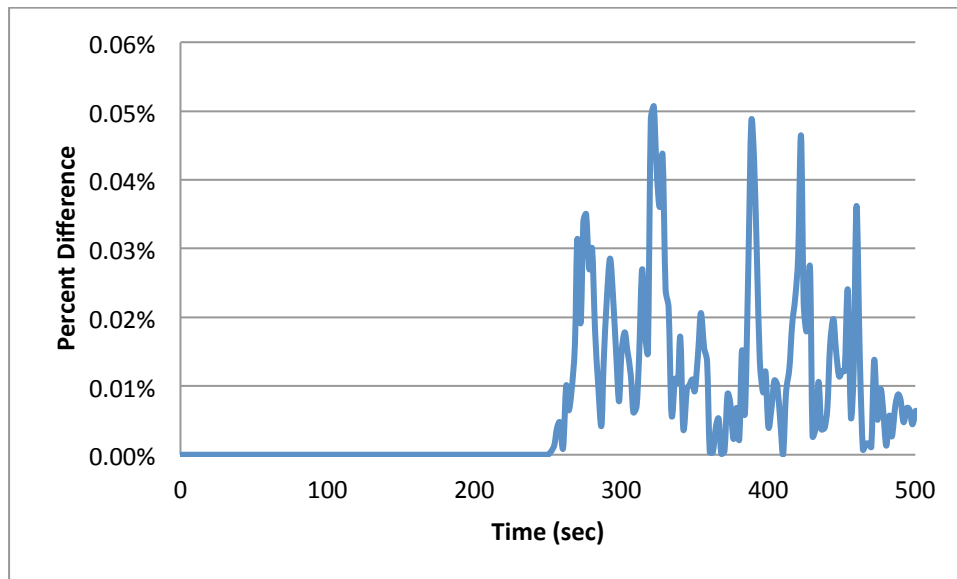
**Figure 3.24 - Pressurizer Pressures During LOCA**

As shown above, the pressure trends between the two models are almost identical. Immediately after the pipe break occurs the pressure begins to decrease. With the decrease in pressure, the primary loop pressurizer temperature also decreases as shown in Figure 3.25

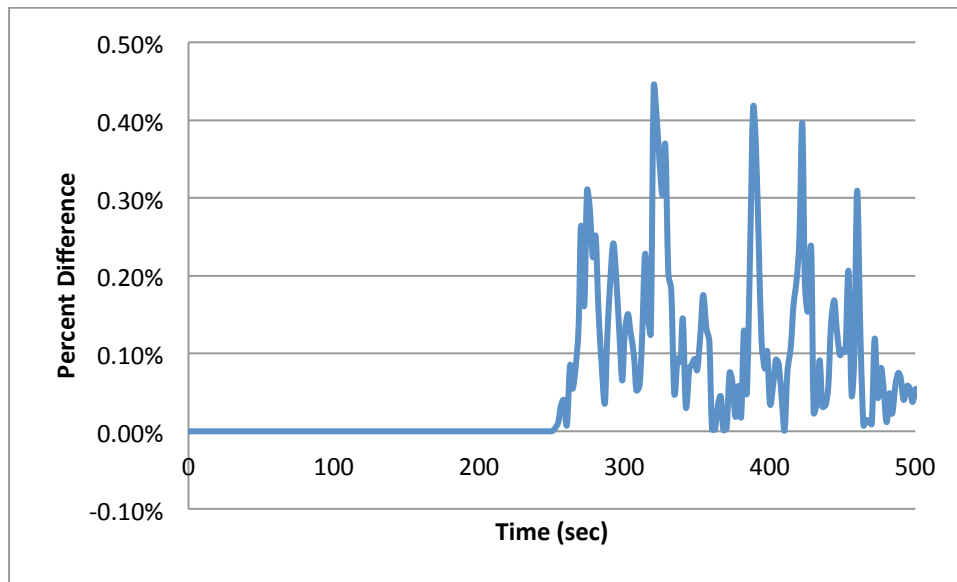


**Figure 3.25 - Pressurizer Liquid Temperatures During LOCA**

Because the secondary system is modeled using only LabVIEW, the pressurizer temperature and pressure in Figures 3.24 and 3.25 are modeled with RELAP5. Independent of which program generated the plots, they demonstrate that the coupling simulation has produced results that are very similar to the RELAP5 simulation and that the LabVIEW modeled secondary system does not significantly alter the behavior of the RELAP5 modeled primary system. Such that as shown in Figure 3.26 the maximum temperature percent difference between the two simulations is less than 0.05%. Additionally Figure 3.27 demonstrates the maximum pressure percent difference between the coupled and non-coupled simulations to be less than .45%.

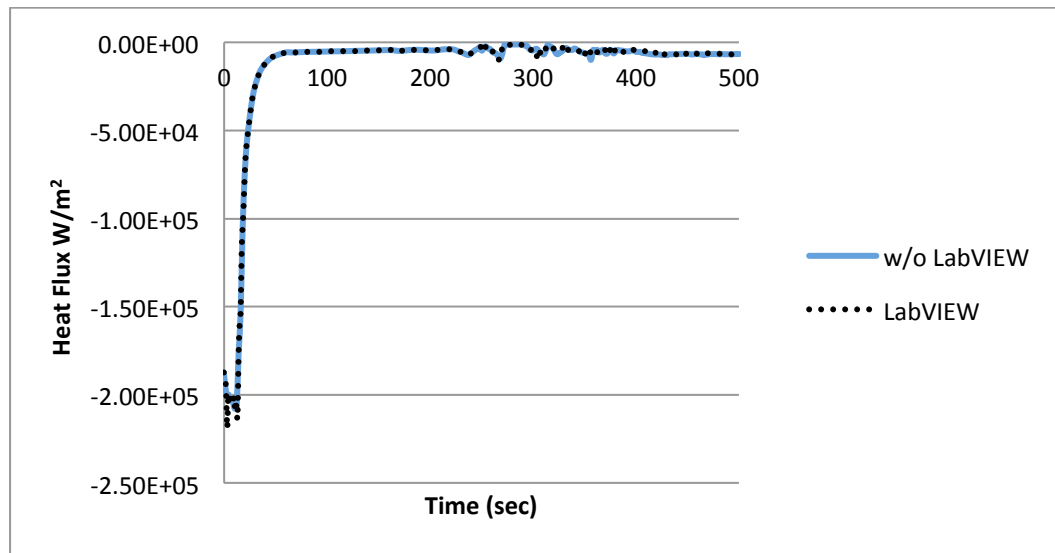


**Figure 3.26 - Pressurizer Temperature Percent Difference Between the Coupled Simulation and the Non-Coupled Simulation**



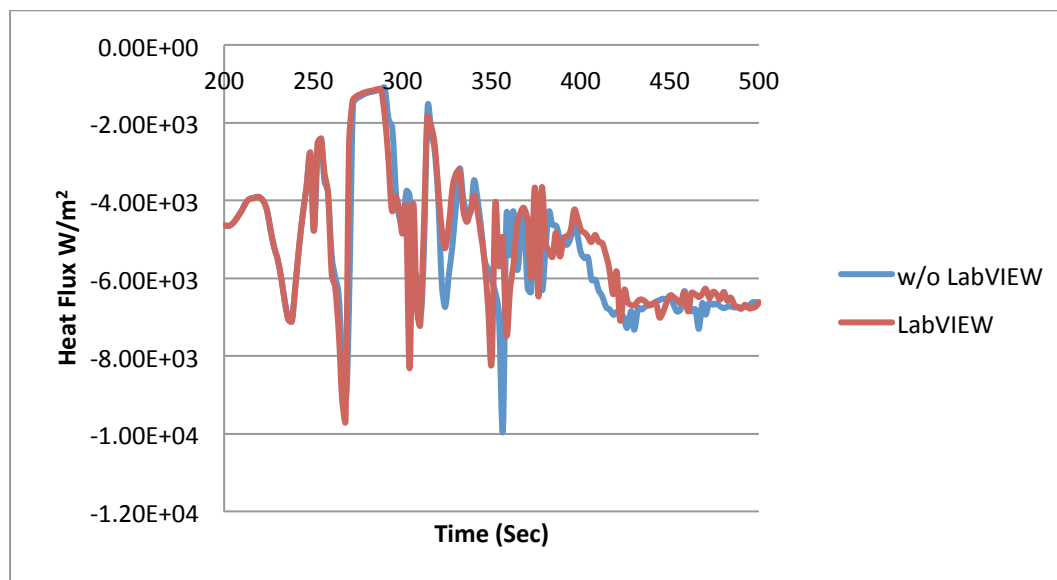
**Figure 3.27 - Pressurizer Pressure Percent Difference Between the Coupled Simulation and the Non-Coupled Simulation**

Within the steam generator of the broken loop on the primary side tubing the following fluid parameters are recorded and compared to those in a non-coupled configuration. The heat flux on the broken loop was recorded as shown in Figure 3.28:

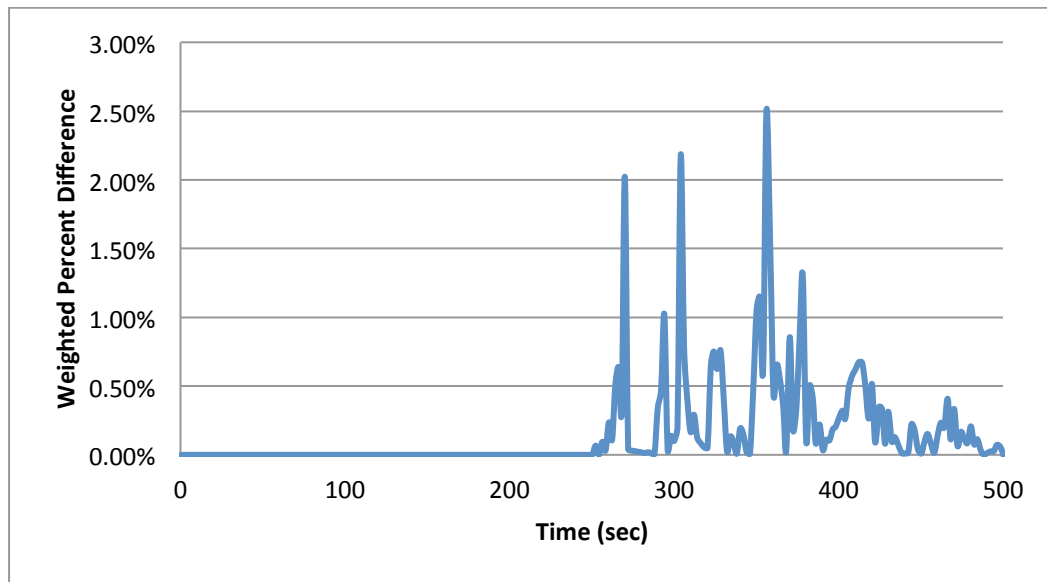


**Figure 3.28 – Heat structure Heat Flux on the Primary Side Steam Generator**

Once again, as shown in Figure 3.28 that in a different location of the primary loop and utilizing a different parameter the results from the two simulations are comparable. The heat flux starts with a negative value since heat transfer is defined as positive when heat is transferred from the steam generator to primary system thus a negative heat flux means that heat is being transferred from primary system to secondary system. Heat flux is suddenly and significantly reduced as predicted by both codes. Since the LOCA event triggers both the primary side pump trip and the secondary side main feedwater trip, it causes a decrease in the mass flow rate through the steam generator. This reduces the effect of heat convection in the steam generator, so the heat transfer is diminished quickly right after leaking occurs.



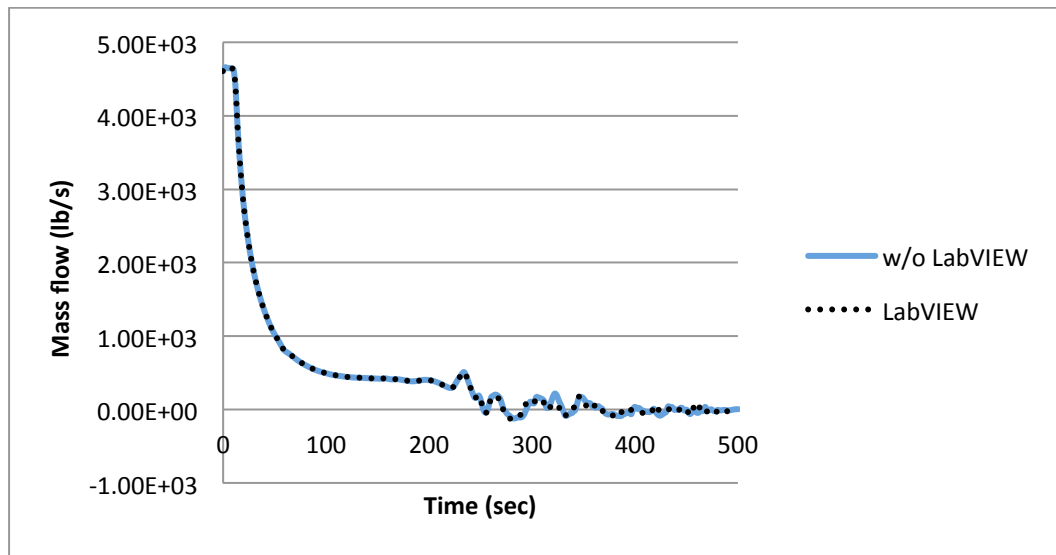
**Figure 3.29 – Close-up of Heat structure Heat Flux on the Primary Side Steam Generator Between 200 and 500 sec**



**Figure 3.30 – Heat structure Heat Flux on the Primary Side Steam Generator Weighted Percent Difference Between the Coupled Simulation and the Non-Coupled Simulation**

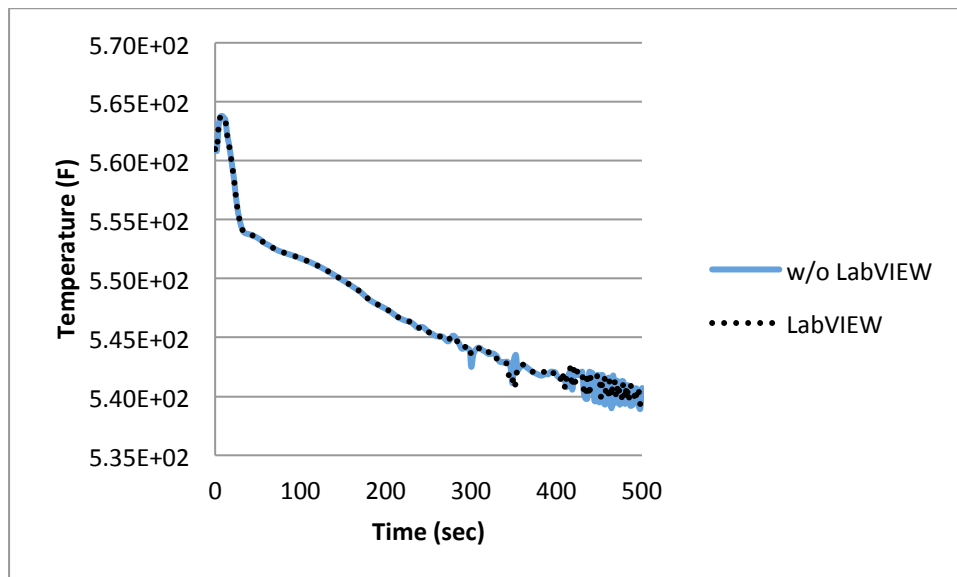
Figures 3.29 and 3.30 show a close-up of the unstable region in the simulation that is demonstrated in the percent difference plot. Even though these two simulations are in an unstable region they are both following the same trends, additionally this plot shows that when the simulation stabilizes toward the end of the 500 seconds the two models are showing a percent difference in the order of around 1%.

In a similar fashion to what is occurring with respect to the heat flux the mass flow shown in Figure 3.31 demonstrates a similar trend which is to be expected. And once again the two simulations are showing very similar results.



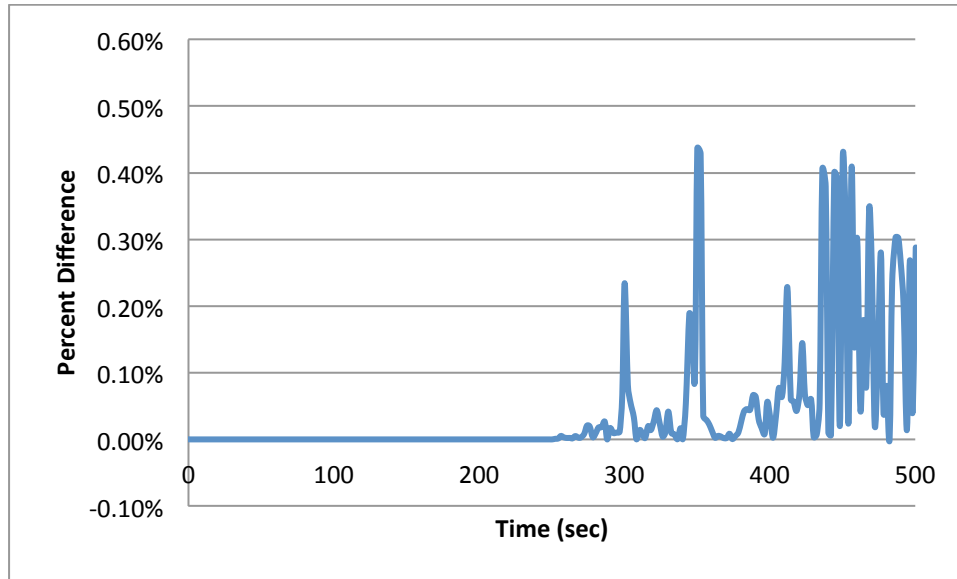
**Figure 3.31 – Primary Side Steam Generator Mass flow Rate**

Figures 3.32 through 3.35 show the temperature and pressure along with their associated percent difference that were recorded within the steam generator at the same location as the heat flux and mass flow rate in Figures 3.28 and 3.29. The pressure trend at this location follows the same trend as that in the pressurizer. This gives another confirmation that the coupling will produce results very comparable to those from the simulation run with RELAP5 alone.

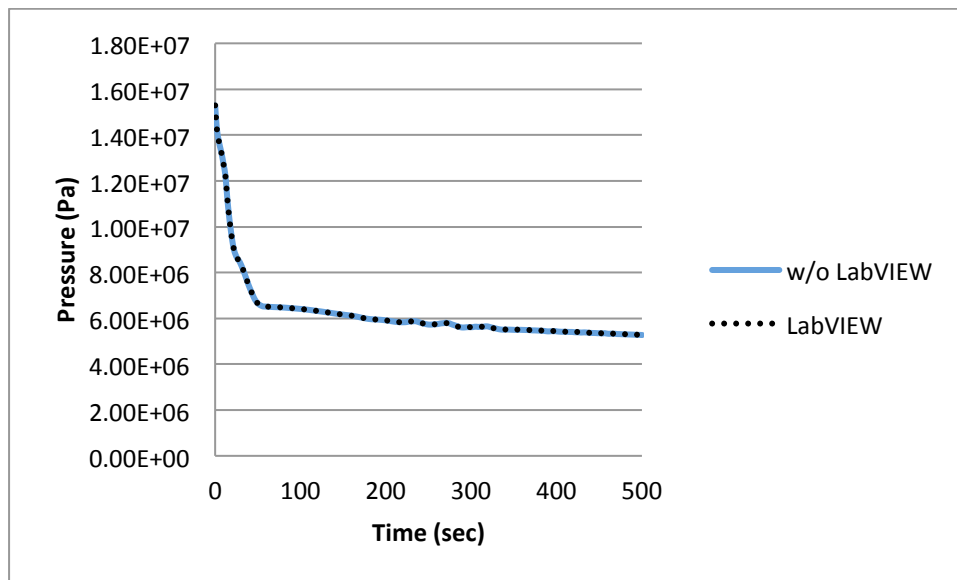


**Figure 3.32 – Primary Side Steam Generator Temperature**

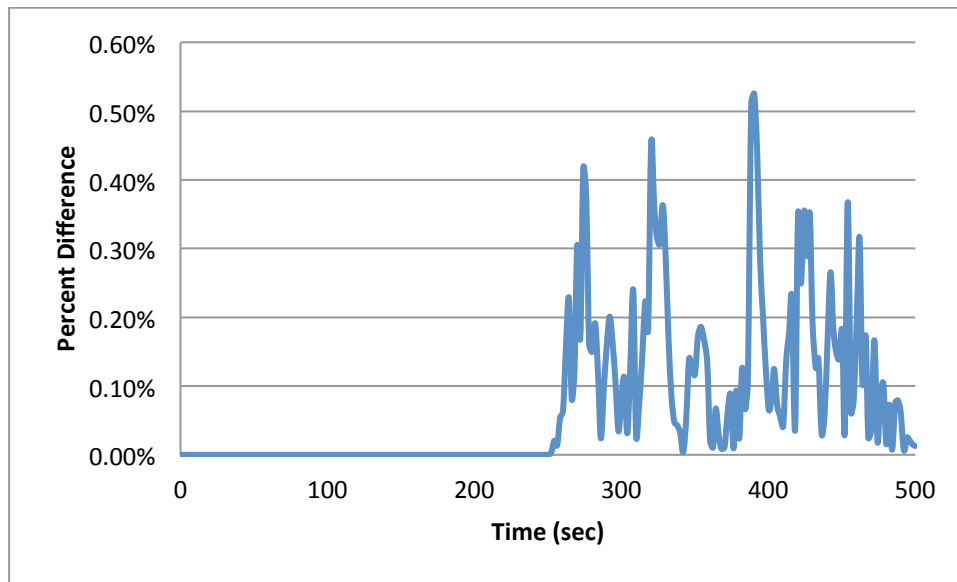




**Figure 3.33 – Primary Side Steam Generator Temperature Percent Difference Between Coupled and Non-Coupled Simulations**

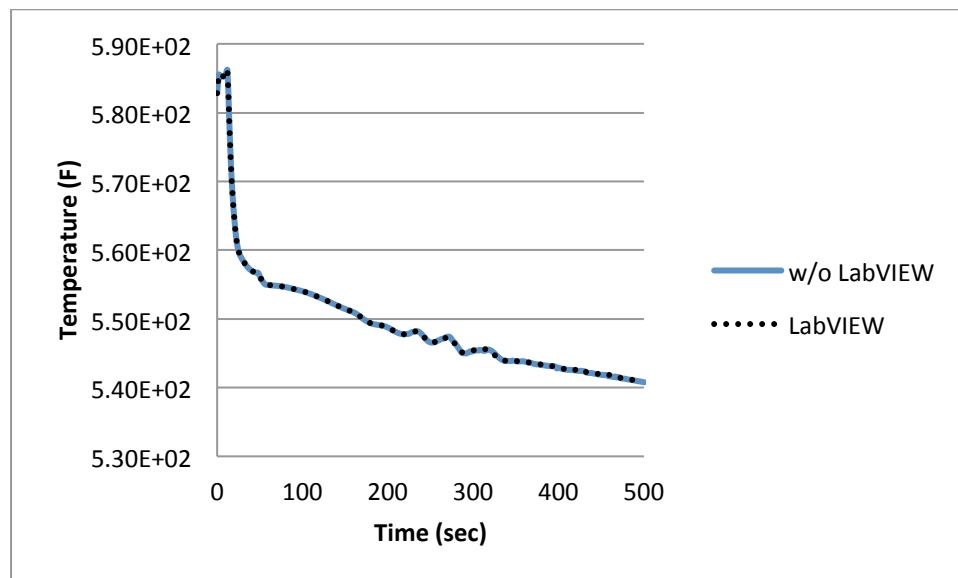


**Figure 3.34 – Primary Side Steam Generator Pressure**



**Figure 3.35 – Primary Side Steam Generator Pressure Percent Difference Between Coupled and Non-Coupled Simulations**

The following figures are a series of additional comparisons between the coupled and non-coupled simulations at different locations throughout the system including the reactor core. These plots provide further evidence that with the LabVIEW model coupled to RELAP5 there is little variation to the results in comparison to those in a non-coupled simulation.



**Figure 3.36 – Reactor Core Fluid Temperature**

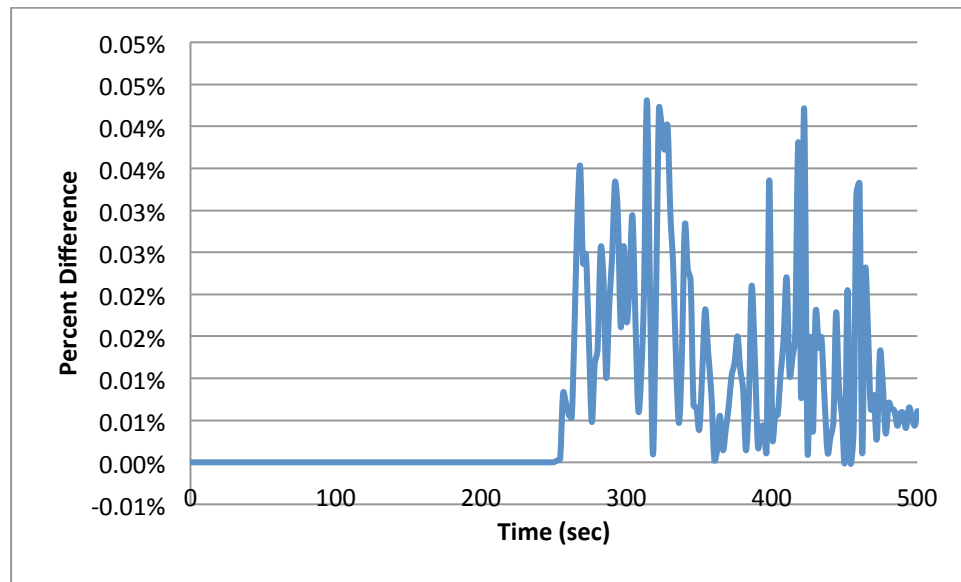


Figure 3.37 – Reactor Core Fluid Temperature Percent Difference Between Coupled and Non-Coupled Simulations

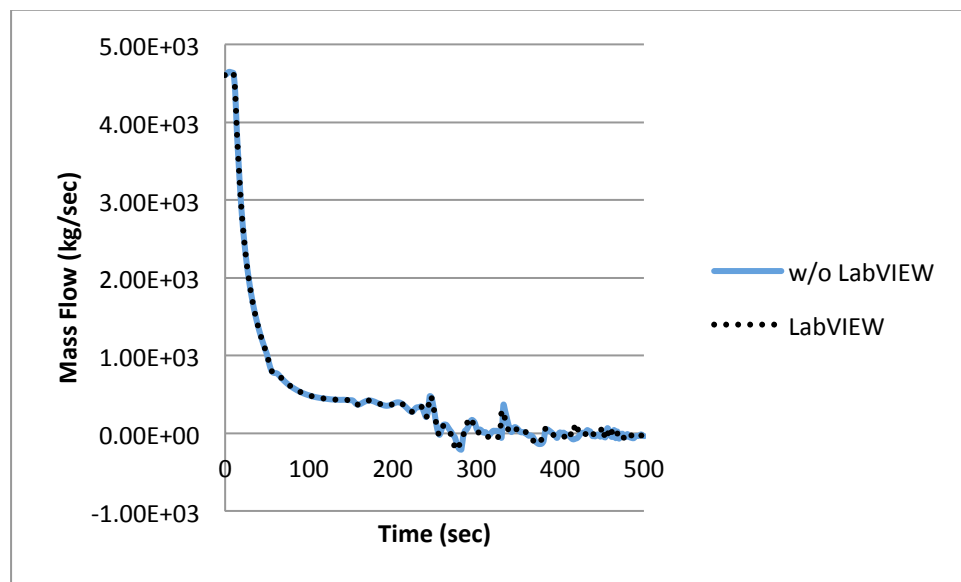


Figure 3.38 – Reactor Core Outlet to Single or Broken Loop Mass Flow Rate

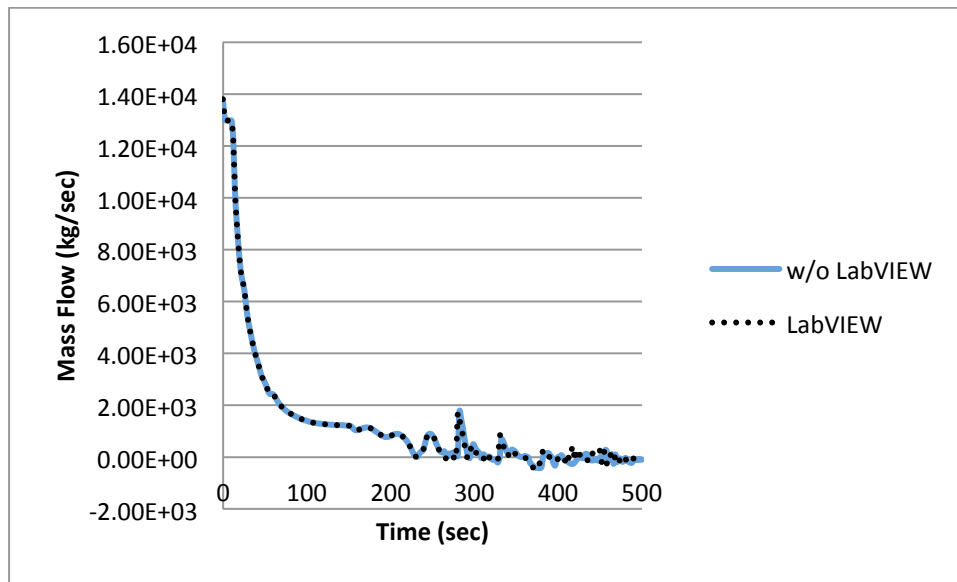


Figure 3.39 – Reactor Core Outlet to Triple or Intact Loop Mass Flow Rate

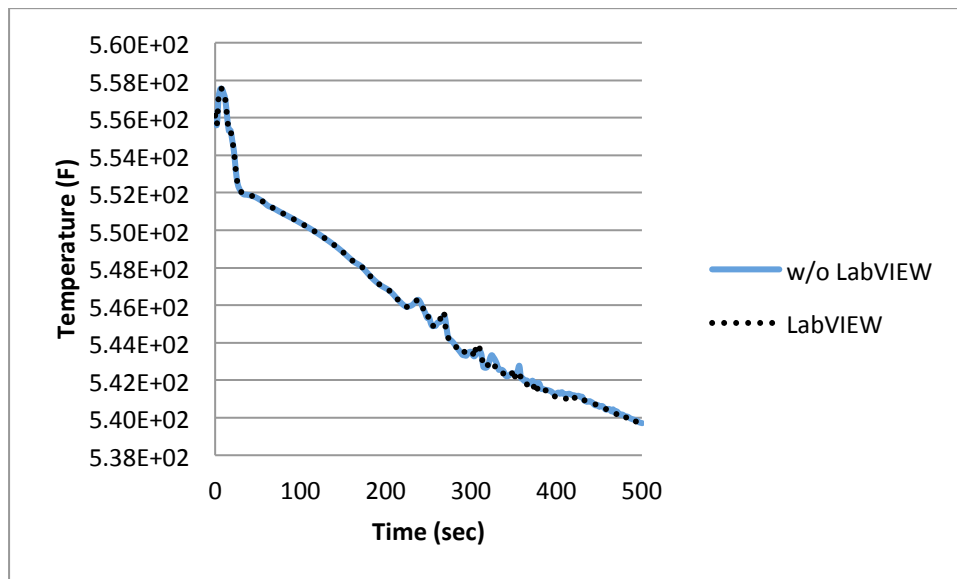
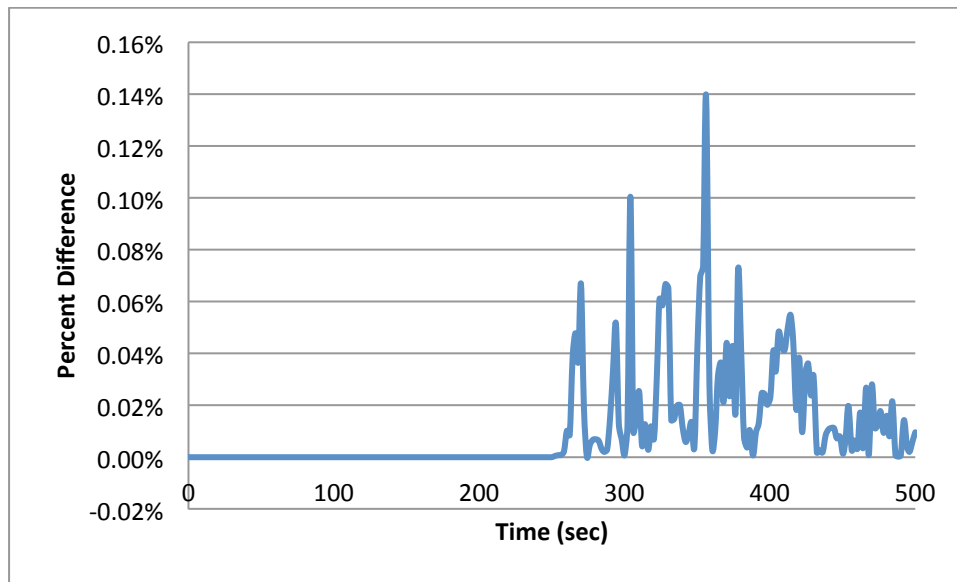
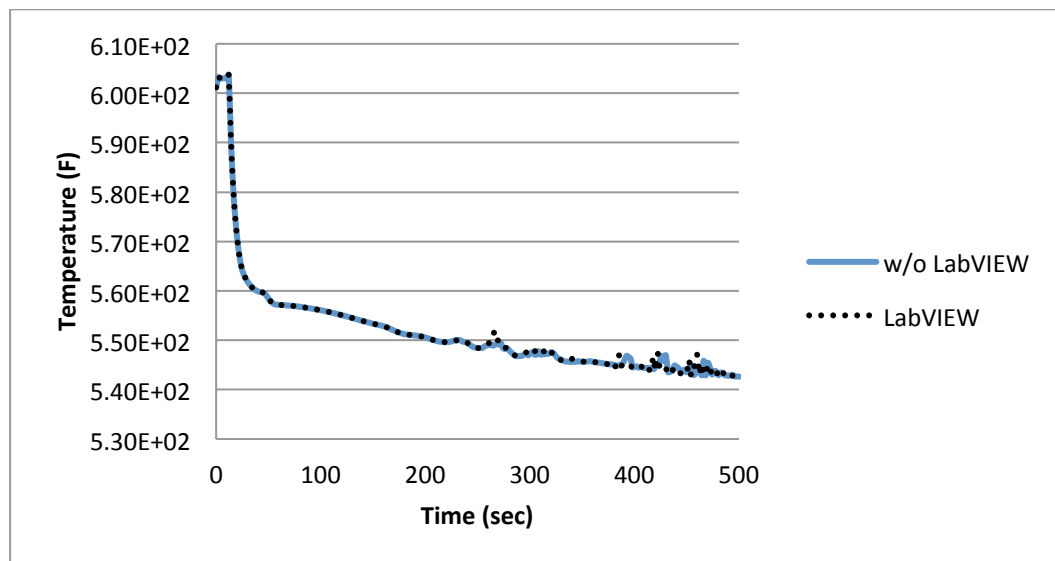


Figure 3.40 – Secondary Side Heat Exchanger Tube Surface Temperature

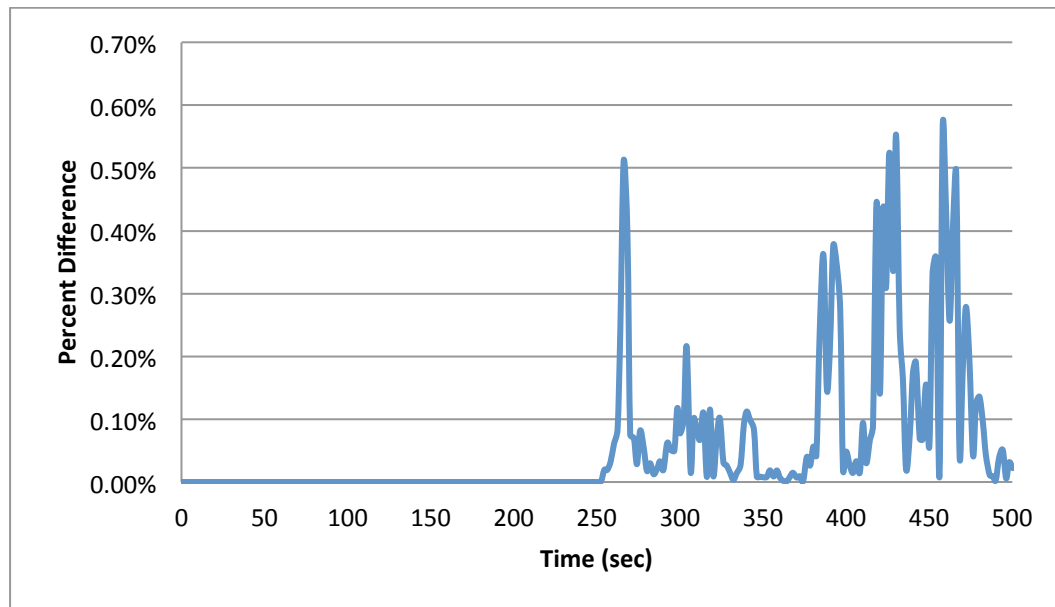


**Figure 3.41 – Secondary Side Heat Exchanger Tube Surface Temperature Percent Difference Between Coupled and Non-Coupled Simulations**

The final comparison made between the two codes is that of the peak cladding surface temperature in Figure 3.42 which provides the determination of the final condition of the reactor core after an accident scenario. Once more the percent difference between the two simulations as shown in Figure 3.43 is less than 0.6%.



**Figure 3.42 – Peak Cladding Surface Temperature**



**Figure 3.43 – Peak Cladding Surface Temperature Percent Difference Between Coupled and Non-Coupled Simulations**

### 3.5. Conclusion

When comparing the coupling methods a simplified one loop pressurized water reactor model is used to test steady state. The steady state and transient results not only show that data is successfully transferred between two codes but that the second coupling method proved to be simpler program with more accurate results than method one. This was done by changing the coupling locating which reduced the amount of data transfer necessary between the programs. Comparing steam generator heat structure surface temperatures at steady state condition, LabVIEW gives comparable results; the percentage difference of heat for method one is about 1.2% and for method two is far less. A more complicated model is used to test a transient event – Loss of Coolant Accident (LOCA). Test is done with a four-loop typical Pressure Water Reactor (PWR) model. One of four loops simulates a small break in the primary piping system; the other three loops are coalesced together and modeled as one intact loop. Comparing the steam generator heat structure surface temperatures during the LOCA transient, LabVIEW gives comparable results; the

percentage difference of surface temperature for method one is less than 1.6% but once again is proven to be far less in method two on the order of 0.1%. Both coupling codes accurately predict the steam generator heat flux behavior during LOCA transient event but this work has shown that there are better methods to perform these coupling works, in this case that proved to be method two. Depending on the application of this software to an actual plant or testing apparatus either coupling method may be preferred over the other. For example the experiment may need to be performed in the steam generator which would require the use of LabVIEW for modeling the steam generator and monitor the sensors used therein thus coupling method one may be preferred. However, if the study is being done elsewhere in the secondary loop the second coupling method may provide the most accurate results.

This research provides an additional tool to laboratories and utilities for the testing of experimental components that are designed for existing or future nuclear power plants. This is done by utilizing the unique capabilities of each of these software packages, RELAP5 for its capability of modeling the nuclear reactor and primary loop components, and LabVIEW for its advanced sensor and instrumentation capabilities. Thus allowing the use of the instrumentation software to interpret sensor data and model the remainder of the secondary loop, while at the same time receiving responsive feedback from the RELAP5 software as to how the primary side of the reactor would be responding. The transient simulations performed in this work have produced results for the peak cladding temperature that are within 0.6% of that produced by the RELAP5 program alone as well as differences in the pressurizer pressure around 0.55%. The percent difference plots also demonstrate that as the simulation time progressed the simulation methods diverged from each other. It is likely that this is due to error carried forward with very small variations in the calculated values to begin with beginning to be more evident as the simulation

progresses, these errors would take some time to work through but the simulations gradually converged toward the end.

Herein we have shown that various secondary loops can be modeled using LabVIEW, and with the proper plant or simulation data these models can accurately represent the physical conditions of the plant even in transient conditions. And with such models companies will have increased capabilities to model their system in combination with experimental apparatuses including replacement plant components, instrumentation systems, or in other cases in the future with a hybrid energy system without ever needing to physically connect to the reactor. This will also aid in the accident analysis of the plants that are to include these new components as shown with the transient simulations demonstrated.

The benefit of modeling the system this way is that with very simple modifications to the programming, we can monitor and visualize the response and performance of a plant based on these changes to the system. Possible changes to the plant system may include additional, replacement, or experimental components, and when coupled with RELAP5 the reactor performance can be analyzed in both steady state and transient conditions. This system will not only be capable of producing digital results but with the utilization of LabVIEW's designed purpose, the model will be capable of being directly linked to physical apparatus instrumentation and thus interpret that apparatus data which provides further flexibility in reactor performance analysis.

In future coupling applications a hybrid energy system could be modelled after a more complex secondary steam loop model has been designed and tested. This way the coupling will allow users to integrate the computational model to the experimental apparatus used for secondary steam loop feedback effects of primary and secondary steam cycles using an experimental apparatus representing some of the steam cycle components.



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