Thermal-hydraulic Code prediction of primary loop leakage in NPP

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Abstract : The leak flow estimation through a narrow channel is important for ascertaining safe designs of piping system in nuclear power plants. RELAP is a popular code for predicting the thermal-hydraulic behavior of leakage flow during loss of coolant accidents. In this paper leak flow through narrow slits created on a reactor grade pipe has been simulated and code predictions have been analyzed. Pressurized subcooled light water was used to simulate standard conditions of pressurized water reactors with a maximum pressure of 90 Bar. For various stagnation conditions and pipe geometries, experimental results from literature have been compared with code predictions. Leak Flow behavior has been studied for varying slit opening geometries and maximum temperature conditions.

***IndexTerms* - Narrow slit, LWR, choked flow, RELAP5, LOCA.**

I. INTRODUCTION

Leak-before-break analysis is crucial for primary loop coolant channels of a pressurized water reactor (PWR) to avoid radioactive hazards economically and mechanistically. The critical flow is an allied phenomenon of interest during a loss of coolant accident (LOCA) where subcooled coolant undergoes severe depressurization through unknown crack dimensions and friction magnitudes. However for through wall cracks the effect of friction decreases due to very low opening channel length (close to pipe thickness). Therefore, ability to predict the two-phase maximum flow rate for a known geometry and boundary condition is of great importance for further assessment of unknown crack flow rates. The light water reactor (LWR) transient analysis code RELAP was developed at the Idaho National Engineering Laboratory to estimate transient simulations of coolant systems during both large-break and small-break loss-of-coolant accidents. However experimental validation at reactor condition is important for the popular thermal hydraulic codes like RELAP5 for their acceptability with respect to various crack geometries. In the present work RELAP5 Mod 3.2 has been used to simulate leak flow through narrow circumferential slits of known opening dimensions. Circumferential slits simulates through wall cracks while avoiding uncertainties of crack morphology. Slits with sizes under study were 200-300 μm with aspect ratio 100-200 on 100 mm NB SS-304L pipes of 8mm thickness. The effective leak flow channel was hereby taken as 8 mm for RELAP input files. Pressurized sub-cooled light water was selected to simulate standard conditions of PWRs or PHWRs with stagnation pressures and temperatures in the range of 6 to 9 MPa and 230 to 250˚C respectively. The extensive experimental outputs along with thermal hydraulic analysis have been reported by Ghosh S. et al. (2011). The objective of the present study is to analyze the RELAP prediction of subcooled water through circumferential slit for several high pressure high temperature upstream stagnation conditions

II. LITERATURE SURVEY

Critical two phase flow from initially subcooled condition has been experimentally investigated by many researchers namely Zimmer .G. A. et al. (1979), Collier R. P. (1980), Amos & Shrock (1984) and was reviewed by Hall (1980), Abdollahian D. (1980). Few researchers also applied RELAP5 for several accident analysis programs for NPPs like Tabadar Z et al. (2012). Earlier, Ransom et al. (1980) applied the RELAP 5 choked flow model for calculating choked discharge rate for a large number of flow tests under Marviken III Test 4. Borges R. C. et al. (2000) did a Relap5/Mod3.2 analysis of a small break LOCA test for Pressurized Water Reactor (PWR) safety and found under prediction of break mass flow rate which was not properly explained. Roux V. J (2001) studied RELAP 5 core modeling capability in comparison with CFD code fluent and noted the drawback of the code about three dimensionality of flow, leading to under prediction or late prediction of flow parameters around core. Takeda T. et al. (2012) reported an under predicted primary loop mass flow rate using RELAP5 code in their ROSA facility for PWR simulation. USNRC report by Sokolowski L. et al. (2012) depicted the mass flow rate dependence on length-to-diameter L/D ratio of flow channel using critical flow models by Henry & Fauske (1971) and Ransom &Trapp (1980) under RELAP5 Mod3. But proper accuracy of correlation was not observed by the code run. Low pressure subcooled boiling flow instability was consistently under-predicted by RELAP5 Mod3.2 as studied by Dilla E. M. et al. (2006). Although many experiments were done using nozzles, orifices or short tubes, experimental validation of RELAP using real crack or slit is rare. Amos & Shorck (1983) did a number of experiments using a rectangular slit of uniform area which was basically a gap between two steel blocks. Revankar S. T. et al (2013) analyzed Amos & Shrock's data (1983) and showed that Henry Fauske model predicts the leak flow better than Ransom-Trap model. Ghosh S. et al. (2011) presented the experimental observation of critical leak flow rate through narrow circumferential slits of rectangular projection. However the experimental validation of RELAP5 critical flow prediction for practical circumferential slits on pipe, at reactor operating condition is rare in literature.

III. THERMAL HYDRAULIC MODEL FOR SUBCOOLED COOLANTS

The RELAP5/MOD3 code is based on a one-dimensional two-fluid nonhomogeneous and equilibrium model solved by a fast, partially implicit numerical scheme. The thermal-hydraulic model solves eight field equations for eight primary dependent variables like pressure, phasic specific internal energies, vapor, volume fraction (void fraction), phasic velocities, noncondensable quality where the independent variables are time and distance (Code Manual, NUREG/CR-4312, 1987). The primary choking model calculates the maximum flow rate through any geometry using time dependent differential equations. It is a homogenous, thermal equilibrium, mechanical non-equilibrium (slip) model. The characteristic equation obtained by solving the mass, momentum and entropy conservation equations where the entropy and density of each phase is assumed to change with pressure. A virtual mass coefficient is used to ensure a smooth transition between the phases. Boundary conditions are established by invoking the Mach number as a function of void fraction, specific volume and virtual mass. The thermal equilibrium assumption results in a speed of sound variation in water with the changes in vapor fraction. The hydrodynamic boundaries of a system are modeled using time-dependent volumes and junctions in RELAP. Nodalization was done in the simplest possible manner involving only the major sections of the setup. Focus was to find the prime thermal hydraulic predictions of RELAP in least complications. The flow channel volume 110 was divided into ten components to model the slit channel as a variable flow area domain with uniform area change from internal to external slit opening area throughout its length. Table 1 shows the description of volumes and junctions used in RELAP simulation. The nodalization scheme is represented in Fig. 1. Importantly the discharge coefficients were set to 1 to observe the raw prediction of the code. However experimentally fitted discharge coefficients always have the scope to improve the results. At the junction of slit exit to atmosphere the abrupt area change option was considered to account pressure fluctuations caused by the flow discharge into open atmosphere from a narrow channel of a very small effective length.

Table 1 shows the description of volumes and junctions

Component Name	Component Type	Component no.
SO(Source)	TDV (Time Dependent Volume)	100
TP (TEST PIPE)	Snglvol (single volume)	105
PKG (flow path through the pipe thickness)	Pipe	110
AIR-ATM	TDV (Time Dependent Volume)	109
SO_TP	sngljun (single junction)	200
TP_PKG	sngljun (single junction)	201
P-ATM	sngljun (single junction)	202

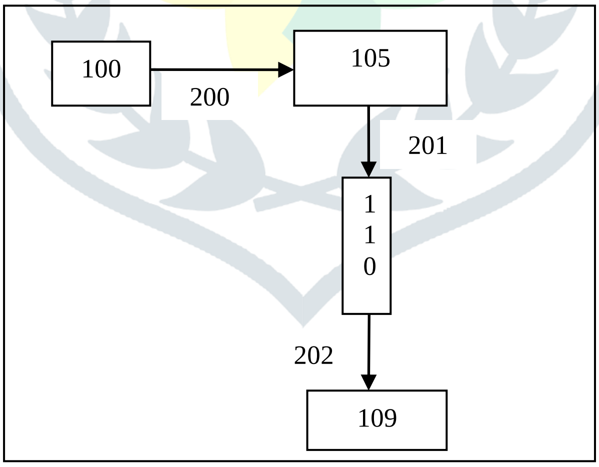

Fig. 1 Nodalization Scheme for the setup

IV. SIMULATION RESULT AND DISCUSSION

RELAP validation of leak flow thermal hydraulics was done on an average internal slit opening area calculated from the initial and final slit opening dimensions. Slit dimensions used in this analysis are depicted in Table 2. Results of RELAP5 code run are compared with experimental findings in the following tables. For the smaller slit sizes huge under-prediction at the order of 15-24% was found. For both the cases prediction seemed to improve for higher pressure data. For little higher area however better RELAP5 prediction was envisioned at higher stagnation pressures. On average it was found that the choked flow model of RELAP5 using modified Bernoulli's equation by Ransom & Trap under-predicts the leakage flow rates at around 10-25% of that found in experiments.

Table 2 Slit Dimensions for RELAP validation

Slit No	Slit Length×10^{-2} (m)		Slit width ×10^{-2} (m)
	Inner	Outer	
1	1.75	5.21	0.023945
2	1.98	5.35	0.026405
3	2.14	5.51	0.029018
4	1.77	4.92	0.033393
5	2.17	5.15	0.037108
6	2.21	5.12	0.031760

The following plots (Fig. 3 to Fig. 6) shows critical flow behavior for distinguished slit opening geometries. At 53˚ subcooling RELAP prediction for the smallest slit shows very similar trends as found in test, both showing higher flow rates at higher pressures. Similar outputs at Fig. 4, 5 and 6 at subcooling of 49˚, 57˚ and 48˚ confirms this fact for other slit openings too. LOCA has been simulated by RELAP5 in many literatures mostly to study the transient behavior of the critical mass flow rate. However present steady state observations at a constant degree of subcooling expresses that at higher pressures RELAP prediction was relatively better for many cases.

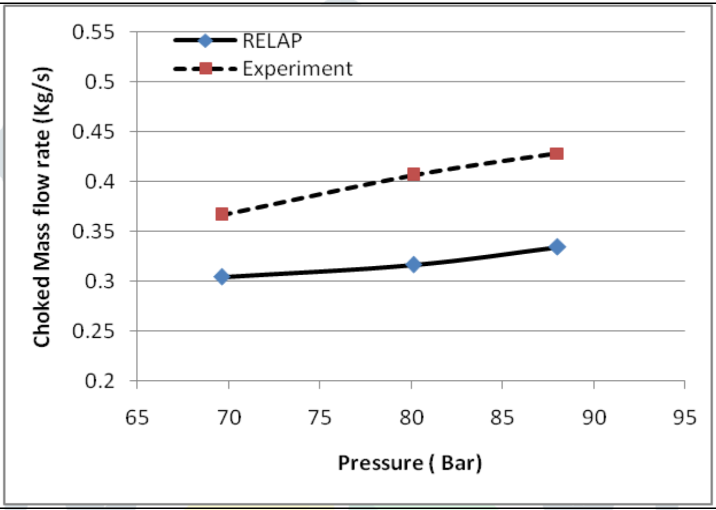

Fig. 3 RELAP prediction compared to experiment at 53 degree subcooling, SOA = 4.19×10^{-4}m^2

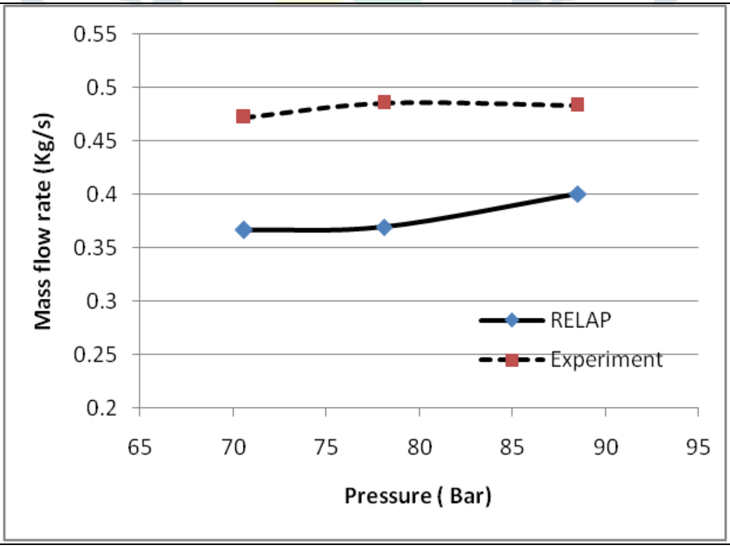

Fig. 4 RELAP prediction compared to experiment at 49 degree subcooling, SOA 5.22×10^{-4}m^2

The trend of increase in flow rates with stagnation pressure is the same for both the theoretical and practical scenarios. The nature of observed flow is analogous to the standard two phase critical flow theory and also resembles with experimental results with rectangular slits by Amos & Shrock (1983).

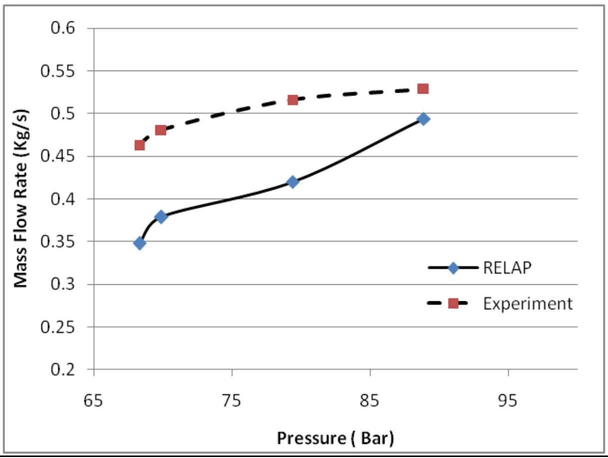

Fig 5. RELAP prediction compared to experiment at 57 degree subcooling, SOA $6.209\times10^{-4}m^2$

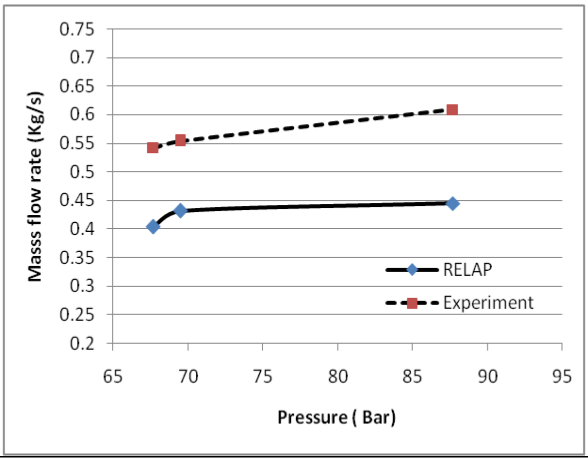

Fig 6. RELAP prediction compared to experiment at 48 degree subcooling, SOA $7.018\times10^{-4}m^2$

For fixed upstream pressure, flow prediction shows almost similar fashion of low predictions. However for higher upstream pressure like 90 Bar almost all the predictions are lower than experiments. Another study of relative choked flow behavior has been harnessed for several pressure domains in Figure 7. At the level of 70 bar predicted results hardly adhere to that of the experiments. However this trend of diversion was found to decrease with the increase of stagnation pressure. A higher pressure involves more subcooled states. Higher the subcooling more the boiling delay and at high velocity lesser the chances of water to get vaporized before reaching the exit of the slit length. Thus a comparatively large subcooling may result in single phase flow with much less non-equilibrium effects. In those cases the nonhomogeneous Equilibrium choked flow model by Ransom-Trap provides better predictions.

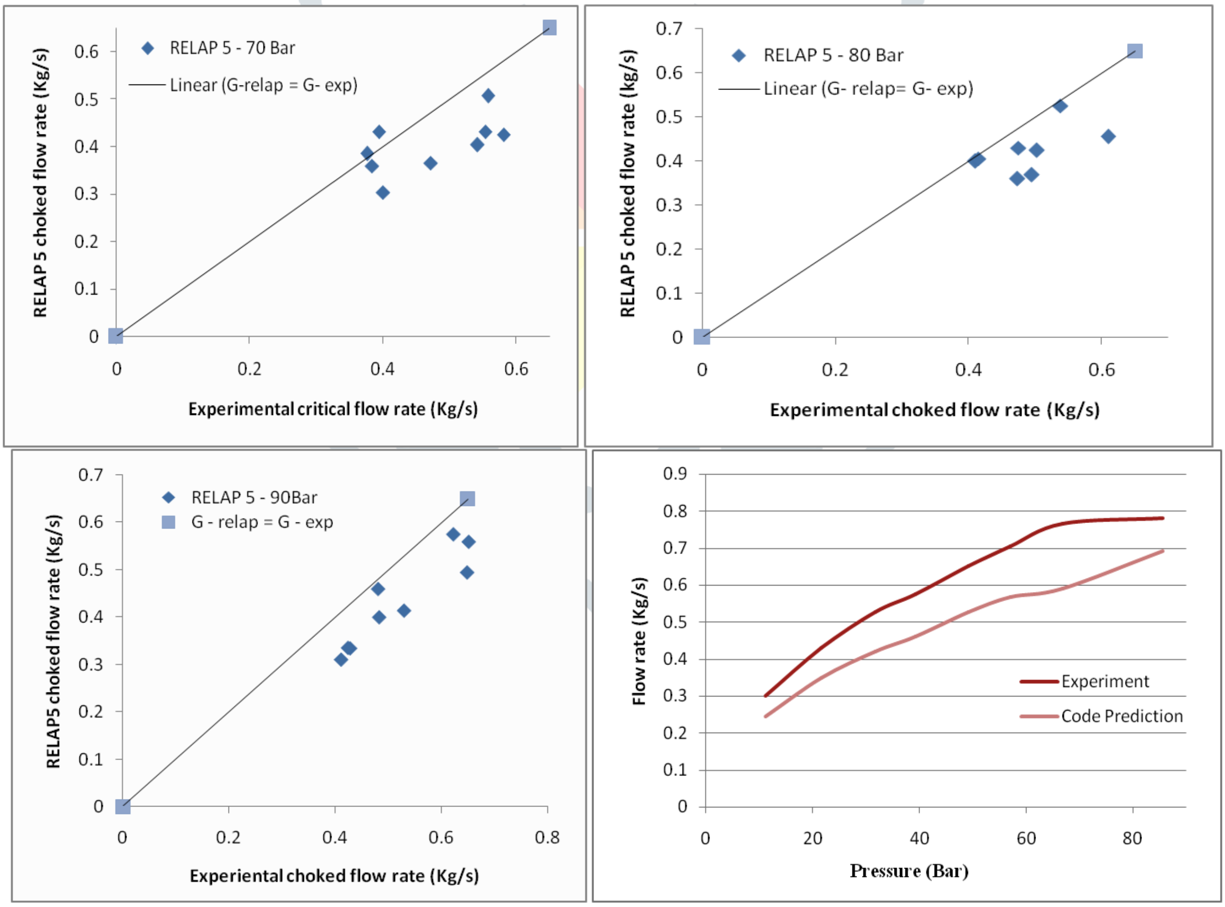

Fig. 7 RELAP5 choked flow prediction for several upstream stagnation pressures

Figure 8 shows comparative plot of leak flow data measured from experiments and code run for 4 different slit opening areas. Corresponding flow rates are under-predicted by RELAP mostly for lower slit opening areas with the effective flow length approximated as 8 mm at the maximum. More predictions were found in experimental range with the increase in slit size. Being a circumferential slit, experimental geometry tends to become a sharp edged orifice with channel length much lesser than 8mm which might be a reason for higher flow rates observed in experiments. Therefore RELAP5 choked flow model by Ransom Trap seems inadequate in predicting flow through very narrow circumferential openings.

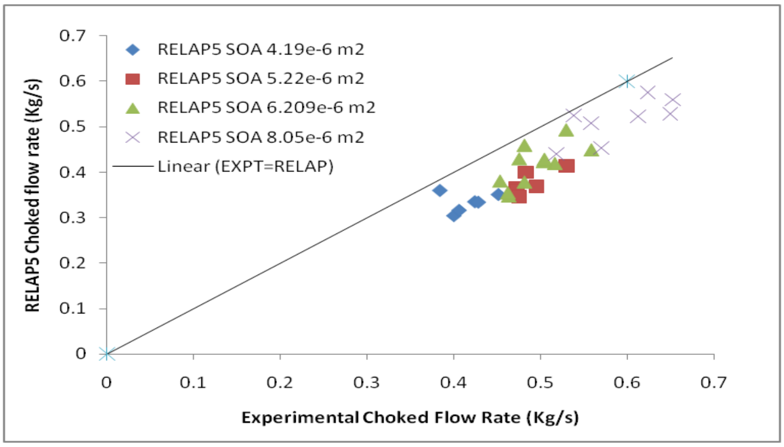

Fig. 8 Comparative study of RELAP prediction and experimental outputs for several slit opening

Although the abrupt area change effects have been included in the input deck for code run, results did not predict the flow rates satisfactorily. The same has been affirmed when slit flow data by Amos & Shrock (1983) and Revankar et. al. (2013) was compared with their respective RELAP5 prediction. The strong effect of L/D ratio of the flow channel was apparent in flow prediction while the flow length changed from 63.5 mm (Amos & Shrock, 1983) to 3.5 mm and 1.3 mm (Revankar et. al). It simply reproduces the fact that non equilibrium effects are more prominent when the transit time through leak geometry gets reduced. So the length of flow channel practically considered in present work being the pipe thickness a large under-prediction has been observed for almost all experimental data sets.

V. Conclusions

RELAP code has been applied to simulate the experimental findings for subcooled water leak flow through narrow circumferential slits. A large number of RELAP5 predictions for highly subcooled leakage flow appeared on average 10 to 20% less than their experimental counterparts. The least variance between the two was exhibited at higher slit opening area as well as higher stagnation pressures. In fact two phase flow initiated during choking at a large depressurization gradient through the narrow slits involve large nonequilibrium effects. A subsonic state in subcooled flow zone gets supersonic at the same choking velocity while transformed to a two phase mixture at downstream. Such flow is attributed with severe instabilities especially the metastable liquid presence due to flashing delay in low L/D_h ratio channels (<10 mm). Such effects are supported at lower channel length or hydraulic diameter where conventional critical flow model predictions are unacceptable. A leak through narrow circumferential opening may also behave like a sharp-edged orifice (or of very small length). The relative opening area for a given leak channel length is an important factor of consideration, as observed in this analysis. Choked flow model of RELAP5 although takes care of abrupt area changes, it underestimates the flow rate for a higher inlet stagnation pressure.

VI. Acknowledgment

Thanks to the collaborators of HPLAB projects at Jadavpur University for their valuable inputs to carry out the research work.

References

[1] **Abdollahian D., Healzer J., Jansen E. and Amos C., Critical flow Data review and analysis, Part I, S. Levy Inc., SLI-7908-1, November 1980.**

[2] **Amos C.N. and Schrock V.E., Critical Discharge of Initially Subcooled Water through Slits, NUREG-CR-3475, USNRC, 1983.**

[3] **Amos C.N. and Schrock V.E., Two-Phase Critical Flow in Slits, Nucl. Sci. Eng.,1984, Vol 88, pp. 261-274.**

[4] **Borges R. C., Auria F. D., Alvim A. C. M., RELAP5/MOD3.2 Post Test Simulation And Accuracy Quantification Of Lobi Test A1-93, 2000 Relap5 International Users Seminar, Jackson Hole, Wyoming, USA – September 12-14, 2000.**

[5] **Collier R.P., Second status report on a study of critical two-phase flow through simulated cracks, BWR Piping integrity Analysis program review, Electrical Power Research Institute, May, 1980.**

[6] **Dilla. E. M., Yeoh. G. H., Tu J. Y., Numerical and Experimental Study of Subcooled Boiling Flows at Low Pressures, ANZIAM J. 46 (E), pp. C1336 -C1352, 2006.**

[7] **Ghosh B., Bandyopadhyay S. K., Gupta S. K., Kushwaha H. S., Venkat Raj V., Leak rates through cracks and slits in PHT pipes for LBB, Nuclear Engineering and Design 212 (2002) pp 85–97.**

[8] **Ghosh S., Mukhopadhyay D, Saha . S. K., An experimental analysis of subcooled leakage flow through slits from high pressure high temperature pipelines, International Journal of Pressure Vessels and Piping 88 (2011) pp 281-289.**

[9] **Hall. D. G., An Inventory of the Two Phase Critical Flow Database, Idaho National Engineering Laboratory, ECG-CAAP-5140, June 1980.**

[10] **Henry R. E., Fauske H. K., The two phase critical flow of one component mixture in nozzles, orifices and short tubes. *Trans. ASME J. Heat Transfer* 93 (1971), pp. 179–187.**

[11] **Ransom V. H. et al., RELAP5/MOD2 Code Manual, Volumes I and II, NUREG/CR-4312, EGG-2396, August and December, 1985, revised April 1987.**

[12] **Ransom V. H., Trapp J. A., The Relap5 Choked Flow Model And Application To A Large Scale Flow Test, The American Society of Mechanical Engineers Heat Transfer Division, Nuclear Reactor Thermal-Hydraulic, 1980 Topical Meeting, Saratoga, New York.**
[13] **Revankar S. T., Wolf B. and Vadlamani A, Assessment of Leak Rates through Steam Generator Tubes, School of Nuclear Engineering West Lafayette, Purdue University, IN 47906-1290, July 2013**
[14] **Roux V. J. P., Evaluation Of Relap5 Reactor Core Modeling Capability, Thesis for Master Of Science, University Of Florida, 2001.**
[15] **Sokolowski L. and Kozlowski T., Assessment of Two-Phase Critical Flow Models Performance in RELAP5 and TRACE Against Marviken Critical Flow Tests, Office of Nuclear Regulatory Research,U.S. Nuclear Regulatory Commission, Washington, DC, February 2012, NUREG/IA-0401.**
[16] **Tabadar Z. et al., Simulation of a control rod ejection accident in a VVER-1000/V446 using RELAP5/Mod3.2, Annals of Nuclear Energy, Volume 45, July 2012, pp. 106–114.**
[17] **Takeda T., Asaka A., Nakamura H.; RELAP5 Analysis of OECD/NEA ROSA Project Experiment Simulating a PWR Loss-of-Feedwater Transient with High-Power Natural Circulation; Hindawi Publishing Corporation, Science and Technology of Nuclear Installations, Volume 2012, Article ID 957285, 15 pages.**
[18] **The Relap5 Development Team, RELAP5/Mod3.2 Code Manual, NUREG/CR-5535 Report, vols. 1-5, Idaho National Engineering Laboratory, August 1995.**