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Steam Explosion Module Development for the MELCOR Code Using TEXAS-V

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Abstract

A steam explosion module, STX, has been developed using the mechanistic steam explosion analysis code, TEXAS-V, in order to estimate the dynamic load with steam explosion by implementing the module to the integrated safety analysis code, MELCOR. One of the difficulties in using mechanistic steam explosion codes is that they do not have any obvious criteria for defining some uncertain parameters such as triggering timing, triggering magnitude, mesh axial length and mesh cross-sectional area. These parameters have been user decision parts in the past. Steam explosion sample calculations and sensitivity studies on uncertain parameters were conducted to investigate those uncertain parameters. The TEXAS-V simulations were summarized in the format of a look-up table and a linear interpolation technique was adopted to calculate the steam explosion load between the data points in the table. The STX-module merged with MELCOR showed the same results as the original MELCOR and additionally it could estimate the steam explosion load in the reactor cavity.

Key Words : steam explosion, TEXAS-V, MELCOR, STX-module

1. Introduction

MELCOR[1, 2] is one of the representative integral computational codes used for severe accident modeling and safety analysis. MELCOR can simulate radioactive material behavior as well as thermal-hydraulic behavior in the reactor coolant system, cavity, and containment and engineered safety systems during severe accidents. MELCOR has a merit as a sensitivity study, uncertainty analysis, and for model improvement. Even though MELCOR contains mostly physics related with reactor severe accidents, some phenomena were omitted or modeled in a very simple way. Especially, steam explosion behaviors are completely omitted in the MELCOR due to its complicated phenomena and uncertainty.

In order to solve steam explosion hazards, many experimental and analytical works have been conducted during the last 20 years. Those works contribute to the understanding of steam explosion physics and the estimation of the steam explosion potential. One of the most successful results from the steam explosion research works was to induce consensus among steam explosion experts that the possibility that ALPHA-mode failure would be very low under the assumption that any strong external triggering would not exist in the reactor vessel. But, it was reserved for judging the steam explosion effects in the reactor cavity due to the limited experimental data at ex-vessel situation. As the IVR strategy is considered for the APR1400, the reactor cavity will be filled with highly subcooled water during the reactor core melting accident. This strategy might induce a strong ex-vessel steam explosion considering the steam explosion characteristics that highly subcooled water under a low pressure is prone to a strong steam explosion. Thus, steam explosion behaviors in the reactor cavity should be further investigated through experiments and using analytical tools.

In addition, it could be of value to study the integral effects by introducing the steam explosion model into the integral safety analysis codes such as MELCOR. Like SCRAP/ RELAP5/ MOD3.3 [3], merging a mechanistic model into an integral code is a good methodology for estimating steam explosion work with various accident sequences. Considering convergence and running time problems, it would be more desirable to use performing sensitivity studies and PSA work to use the integral codes with the results from the best estimated FCI codes. TEXAS-V[4, 5, 6] among the mechanistic FCI codes could be used for this purpose because it has been applied in reactor safety analyses.

In this study, a steam explosion module was developed using TEXAS-V. First, the sample steam explosion calculations for the prototype PWR cavity were conducted to settle the methodology of the ex-vessel steam explosion simulation. The sensitivity studies on several parameters such as mesh cross-sectional area, mesh axial length, triggering timing, and triggering magnitude were performed for the next consistent steam explosion work evaluation. Then, a look-up table was developed using TEXAS-V calculations based upon various fuel/coolant conditions. Finally, a steam explosion module was developed using the look-up table with linear interpolation, and the module was merged into the MELCOR code.

2. Sample Steam Explosion Calculations at the Reactor Cavity Using TEXAS-V

In this chapter, a base calculation is discussed. Then, the sensitivity studies on the uncertain parameters such as triggering timing, triggering magnitude, mesh cross-sectional area, and mesh axial length were conducted to choose proper values for those parameters. The fixed values of those parameters were consistently used to generate a look-up table.

2.1. Base Calculation

An ex-vessel explosion concept is represented in Fig. 1. The fuel melt congregated in the reactor lower vessel was poured into the reactor cavity when the reactor vessel failed. A fuel coolant interaction could create a steam explosion when a triggering event occurs at a certain location. The thermal-hydraulic conditions of fuel melt and cavity coolant become primary factors determining the steam explosion behaviors in the cavity.

The fuel and coolant conditions and four uncertain parameters are presented in Table 1. It was assumed that the triggering occurred at the bottom with its magnitude of 0.5 MPa. The mesh cross-sectional area was evaluated assuming that the interaction area of the mixture is the same as the FARO-L14 test [7, 8], in which the diameter ratio of the fuel jet and interaction chamber was 1:7. The mesh axial length of 0.1 m was used.

Initially the fuel melt of a 0.1 m diameter jet was

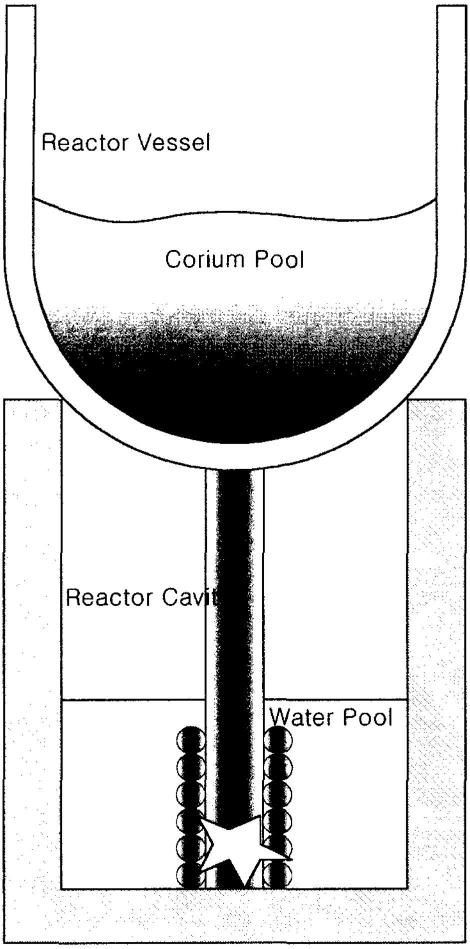

Fig. 1. Steam Explosion Concept at Wet PWR Cavity

poured into coolant at the speed of 7 m/sec. The mixing calculation stopped 0.58 sec after the fuel started to be poured. The fuel of 253 kg was poured and 73 kg, 28 % of total poured fuel, was broken into droplets. The fuel jet front and fuel front coincidently proceeded with almost constant speed before the fuel jet front arrived at the coolant surface (Fig. 2). After 0.4sec, the fuel jet front stopped proceeding due to front fragmentation near the surface of the coolant, while the fuel leading edge continuously proceeded until it arrived at the bottom of the cavity.

Table 1. Initial Condition for Basic Sample Calculation

Component	Property	Results
Melt (UO2/ZrO2, 80w/o, 20w/o)	Jet diameter(m)	0.1
	Jet velocity(m/s)	7.0
	Temperature(K)	2700.
	Melting temperature(K)	2500.
	Density(kg/m3)	8000.
	Specific heat(J/kgK)	565.
Water	Pressure(MPa)	0.1
	Temperature(K)	323
	Depth(m)	1.2
	Free fall(m)	2.8
Uncertain parameters	Diameter(m)	0.7
	Triggering timing	Bottom
	Mesh axial length(m)	0.1
	Triggering magnitude(MPa)	0.5

At 0.58 sec when the fuel front arrived at the bottom, the triggering event occurred. Fig. 3 shows time dependent explosion pressures at six locations (P1 ~ P6), which were located at 0.1 m ~ 0.6 m with a distance of 0.1 m from the bottom. The explosion peak pressure and propagation speed were about 115 MPa and

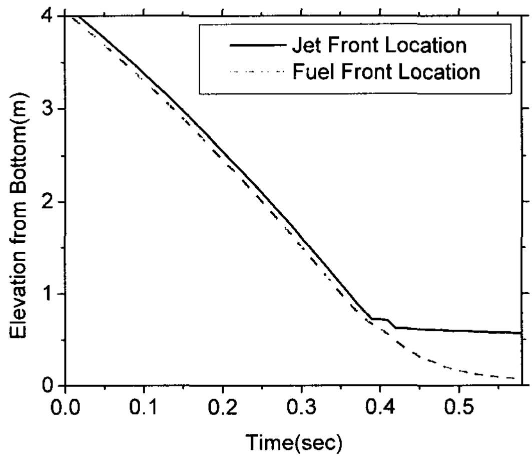

Fig. 2. Time-dependent Fuel Leading Edge Location

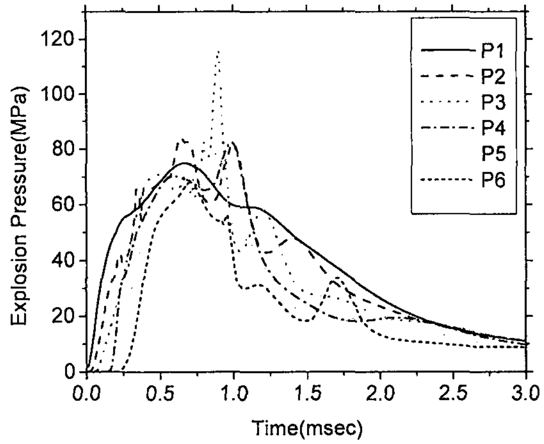

Fig. 3. Time-dependent Explosion Pressure Behavior at 6 Locations

1500m/s, respectively. The duration time of the explosion pressure was about 3 msec. The coolant kinetic energy increased for 2 msec after the triggering event occurred. At that time, the explosion pressure wave seemed to be propagating through the whole mixture. The coolant kinetic energy started to decay after 4 msec, at which time the pressure wave was already propagated through whole coolant. The fuel thermal energy was 431 MJ, and the peak value of the coolant kinetic energy was 1.64 MJ. The peak value of the conversion ratio, which was evaluated by dividing the fuel thermal energy by the coolant kinetic energy, was calculated as 0.4 %.

2.2. The Sensitivity Studies on the Uncertain Parameters

The explosion peak pressure was used as criterion for a sensitivity analysis because the explosion potential is expected to be proportional to the peak pressure. The triggering timing, triggering magnitude, mesh axial length, and mesh cross-sectional area are discussed and proper values are suggested for each item.

The sensitivity results are briefly summarized in Table 2 and these results will be consistently used for arranging the look-up table.

Triggering timing would govern the mixture conditions such as volume fractions of each phase, and fuel particle distribution, which are essential to determine the steam explosion work. Due to the lack of understanding of the triggering mechanism, available steam explosion computer codes could not estimate the triggering timing and its magnitude. These triggering parts remain under the responsibility of the code user.

We could consider the configuration of three kinds of triggering timing as in Fig. 4. When the earlier triggering timing is used, the mixture is rarely voided but it does not have enough fuel droplets. When the later triggering timing is used, the mixture includes enough fuel droplets but it is too much voided. It could be explained that too late triggering and too early triggering would not cause strong steam explosions due to the highly voided mixture and the lack of fuel droplets, respectively. The explosion pressure is the highest at 139 MPa when the triggering location was in the middle at 1.1 m. With the earlier triggering (1.7 m) or the later triggering (1.0 m), the explosion pressure is low at about 30 MPa.

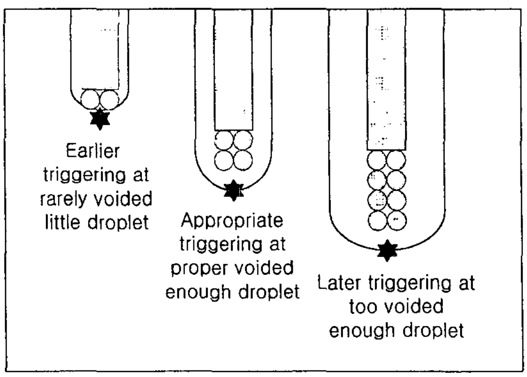

Fig. 4. Configurations of the Various Triggering Timing

A reasonable method to determine the triggering timing should be developed in order to obtain steam explosion results not far from the potential value under various initial conditions. Two types of triggering timing logic could be induced by a concept maintaining the mixture length as long as possible and the vapor fraction of the triggering mesh under a user-defined value(Fig. 5). It was assumed that the triggering event occurred at the fuel front. The two types are:

1) When the vapor fraction of the certain mesh becomes greater than the user defined value (IBOTTOM1).
2) When the fuel front arrives at the bottom (IBOTTOM2).

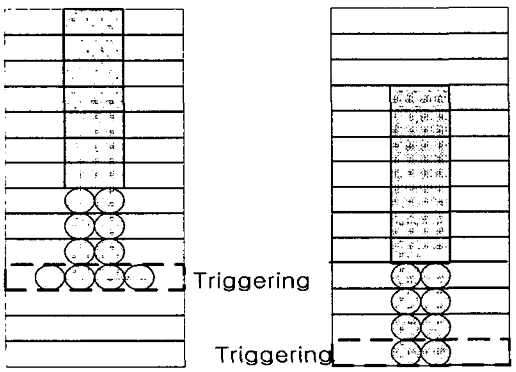

Fig. 5. Two Types of the Triggering Logic

With IBOTTOM1, the user-defined vapor fractions of the triggering mesh were used from 0.05 to 0.3. When the vapor fraction of the triggering mesh increases from 0.2 to 0.3, the explosion weakens compared to the explosion pressure (from 94 MPa to 66 MPa). When the vapor fraction of the triggering cell is low, from 0.05 to 0.1, the explosion is relatively strong considering the explosion pressure of 115 ~ 124

Table 2. Sensitivity Study on the Several Uncertain Parameters

Triggering Location (m)	1.7	1.1	1.0	-
Peak pressure (MPa)	25.5	139.5	30.1	-
Void fraction of trigger mesh	0.05	0.1	0.2	0.3
Peak pressure (MPa)	124.7	115.2	95.3	66.4
Triggering Force (MPa)	0.3	0.5	1.0	1.5
Peak pressure (MPa)	104.3	115.2	116.9	117.2
Mesh axial Length (m)	0.05	0.1	0.15	0.2
Peak pressure (MPa)	127.5	115.2	129.7	164.3
Mesh area (m^2) Diameter(m)	.188 0.49	.384 0.7	.650 0.91	.985 1.12
Peak pressure (MPa)	147.1	115.2	48.1	33.6

MPa. With IBOTTOM2, the fuel mass in the triggering mesh is enough, but the explosion is weak because the vapor fraction of the triggering mesh is relatively high at 0.3. The explosion behaviors with IBOTTOM2 are similar to the results with the user-defined vapor fractions of 0.3.

The vapor fraction could be the criterion for triggering timing together with the fuel arrival time at the bottom. The vapor fraction of 0.1 is recommended as the criterion for void fraction because the above calculations showed that the explosion was strong enough with the vapor fraction of 0.05 ~ 0.1 and 0.1 to ensure enough fuel at the triggering mesh rather than 0.05. If the coolant pool is deep enough or the coolant subcooling is low, the triggering timing will be determined by IBOTTOM1. When the coolant pool is shallow or/and the coolant subcooling is high, IBOTTOM2 will be used for the triggering timing. In the actual reactor case, IBOTTOM1 could become a primary triggering timing criterion because the coolant subcooling is expected to be relatively small less than 10K, and also in a special situation like the IVR strategy, the coolant pool is very deep though the coolant subcooling is very high.

When the ambient pressure is 0.1 MPa, TEXAS-V developers suggested the fragmentation threshold pressure and the initial triggering pressure should be 0.2 MPa and 0.5 MPa, respectively. When the triggering pressure of 0.3 ~ 1.5 MPa was used, the explosion results seemed to have little different. Even though the triggering pressure is raised to 1.5 MPa, the explosion pressure was 117 MPa, which was similar to the case for the triggering pressure of 0.5 MPa. It would be generally accepted that the triggering magnitude does not affect the explosion results if the triggering event triggers the steam explosion. The fragmentation threshold pressure and the triggering pressure could be set to 0.2 MPa and 0.5 MPa above the ambient pressure, respectively. It is understood to be reasonable that the mesh axial length is greater than the diameter of the Lagrangian particles when the Lagrangian particles are included in the Eulerian domain. If the mesh axial length is larger than the diameter of the initial fuel diameter (0.1 m), the explosion pressure is not affected by the mesh axial length. The explosion pressure had the same order of magnitude as 115 ~ 164 MPa when the mesh axial length of 0.05 ~ 0.2 m was used. It must be noted that the convergence becomes very poor if the mesh axial length becomes too small compared to initial fuel diameter.

Even though the fuel jet is poured into the coolant of the large cross-sectional area, the fuel-coolant interaction zone is limited to the fuel jet. The coolant far from the fuel jet will not interact with the fuel in the real condition, while all coolant in the mesh interacts with the fuel in the one-dimensional code. Thus, the proper mesh area or the mesh radial diameter should be defined to simulate FCI using a one-dimensional code like TEXAS-V. Four interaction zones with diameters of 0.49 ~ 1.12 m were used to investigate the mesh area effect on the explosion. The explosion pressures become as low as 33 ~ 50 MPa when the diameter of the mesh was beyond 0.9 m with the fuel diameter of 0.1 m.

The interaction area might be related with a jet diameter. In the KROTOS test [9, 10], the diameter ratio of the fuel to water chamber was 1:3 and the fuel-coolant mixture seemed to be fully developed over the entire water chamber. In the FARO test, the diameter ratio was 1:7, but the mixture behaviors could not be measured. In the recent TROI test using ZrO2 [11], the fuel and coolant mixture configuration was obtained using a high speed video camera. The fuel and coolant mixture in the TROI test was limited to 20 cm because the mesh size of that photo was 10 cm and the relatively white region was the mixture of fuel and coolant (Fig. 6). The diameter ratio could

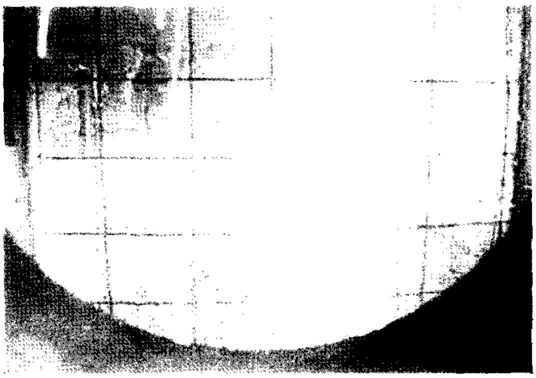

Fig. 6. A High Speed Photo Image of the ZrO_2/Water Mixing Behaviors at TROI Test

be around 1:7 considering that the fuel jet diameter was over 3 cm. Based on Table 2 and the above experimental results, the diameter ratio could be set at 1:7. One substitution to determine this interaction area is the two-dimensional analysis on several kind of jet diameter using a reliable two-dimensional code.

3. STX Steam Explosion Module Development

The above sample calculations reveal that the steam explosion work estimation could be affected by triggering timing and the mesh cross-sectional area, while the triggering magnitude and the mesh axial length have little effect on the steam explosion results. The triggering timing logic based upon the void fraction of the local cell and the 1:7 diameter ratio of jet to reaction zone, were suggested. These will be consistently used for developing the look-up table.

3.1. Characteristics of STX Module

The explosion potential depends on the mixture conditions such as the mixture volume, volume fraction of each phase, and the fuel particle diameter distribution. The mixing, which determines the mixture condition, depends on the thermal-hydraulic conditions such as coolant pool depth, coolant temperature, coolant pressure, fuel jet diameter, fuel injection speed, and fuel temperature. We can create a function, in which the explosion work is calculated by adding the above thermal-hydraulic conditions. Thus, explosion work was evaluated using TEXAS-V for the various values of the above 6 initial parameters, and those results were arranged in the format of a look-up table.

The explosion peak pressure and impulse were calculated from the time-dependent pressure data

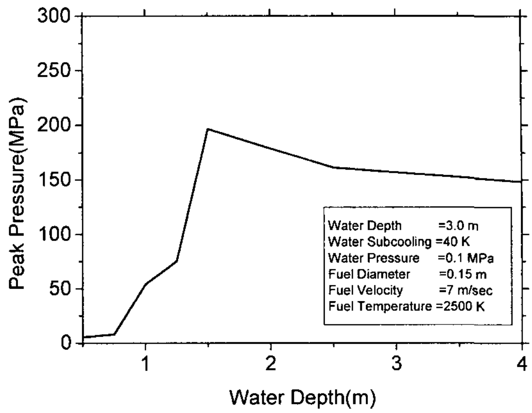

Fig. 7. Water Depth Effect

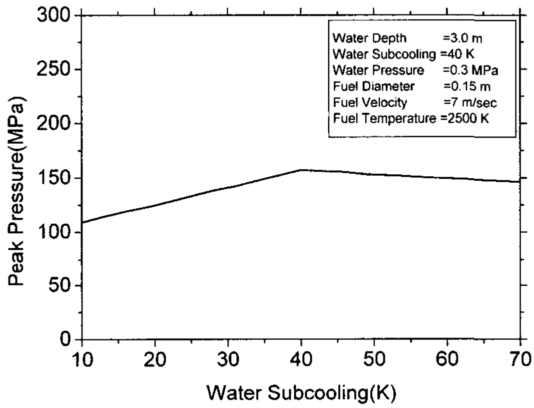

Fig. 8. Water Subcooling Effect

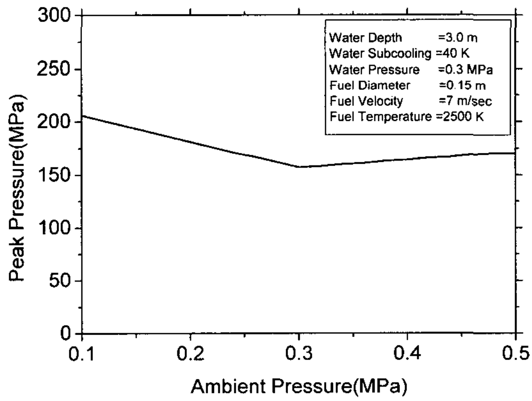

Fig. 9. Ambient Pressure Effect

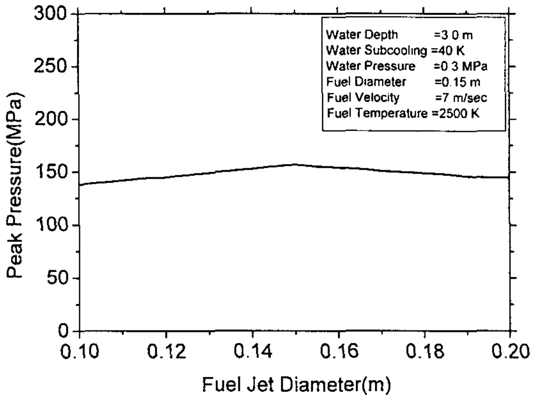

Fig. 10. Fuel Jet Diameter Effect

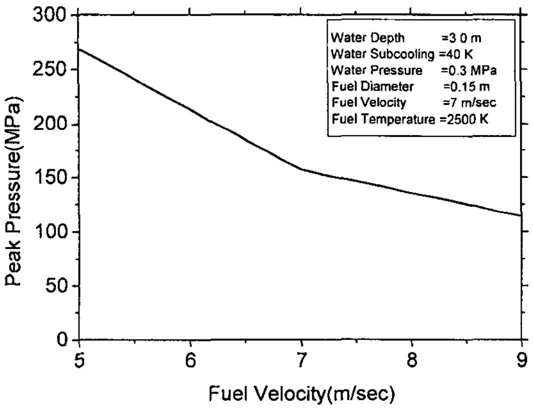

Fig. 11. Fuel Velocity Effect

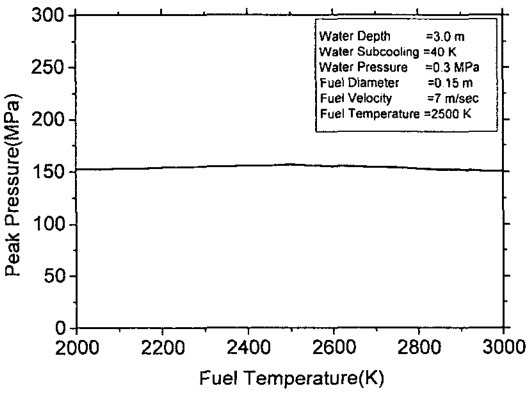

Fig. 12. Fuel Temperature Effect

obtained from the TEXAS-V calculations. 36 calculations were done, which is a combination of three points on each parameter: coolant depth (1, 2.5, 4 m), coolant subcooling (10, 40, 70 K), coolant pressure (0.1, 0.3, 0.5 MPa), fuel jet diameter (0.1, 0.15, 0.2 m), fuel jet speed (5, 7, 9 m/s) and fuel jet temperature(2000, 2500, 3000 K). The interpolation technique was introduced in order to extract the explosion results from the calculated data points.

In order to characterize the STX module, sensitivity studies on the 6 initial parameters such as depth, temperature, and pressure of water pool, fuel jet diameter, fuel jet velocity, and fuel temperature were conducted. Figs. 7 ~ 12 show the initial parameters' effects on the peak pressure. The base values of those calculations were: water depth of 3.0 m, water subcooling of 40 K, ambient pressure of 0.3 MPa, fuel diameter of 0.15 m, fuel velocity of 7 m/sec, and fuel temperature of 2500 K. The water depth and fuel velocity had significant effects on the explosion peak pressure, while the other parameters had small effects. Those results mean that the fuel breakup is the most important factor on the steam explosion.

The peak pressure increases from 50 MPa to 150 MPa as does the water depth from 1.0 to 2.5 m, because fuel mass participating in the steam explosion increases proportional to the water depth. However, the explosion peak pressure does not increase for the water pool deeper than 2.5 m, because the participated fuel mass does not increase any more (Fig. 7).

The increase of water subcooling causes a strong explosion peak mainly due to the suppression of the vaporization. It is generally accepted that the large voided mixture is not apt to make a strong explosion. When the subcooling exceeds 40 K, the increase of subcooling causes the explosion peak pressure to be slightly lower because the vapor suppression effect is already enough and the water is difficult to vaporize as the subcooling of the water increases (Fig. 8).

The increase of ambient pressure induces a weaker steam explosion. The peak pressure decreases from 200 MPa to 150 MPa as the ambient pressure increases from 0.1 MPa to 0.3 MPa. This is because the higher ambient pressure makes vaporization easier due to the low latent heat. It must be pointed out that the water subcooling was used instead of the water temperature (Fig. 9).

The fuel jet diameter has little effect on the explosion peak pressure as shown in Fig. 10. But, considering that the cross sectional area of the water pool is 7 times that of the fuel jet diameter and that the explosion pressure decays in proportion to $\frac{1}{r^2}$, the larger fuel jet diameter could create stronger steam explosions.

The explosion peak pressure decreases against increasing fuel velocity. The explosion peak pressure decreases from 270 MPa to 120 MPa as the fuel velocity varies from 5 m/s to 9 m/s. The higher fuel velocity implies that the early fuel breakup becomes larger and the mixture becomes more voided. The highly voided mixture is difficult for making strong explosions (Fig. 11).

The fuel temperature does not affect the explosion peak pressure as in Fig. 12. It is because the fuel of 2000 K is high enough to make a strong explosion. It must be noted that only 5% of the fuel energy was used for the strong steam explosion.

3.2. Module Implementation into MELCOR

A fuel jet will be poured into the reactor cavity coolant when the reactor vessel fails during a severe accident. As MELCOR evaluates thermal-hydraulic conditions of the poured fuel jet and the cavity coolant, these conditions are to be transferred into the steam explosion module (STX module), which could extract the steam explosion result from the look-up table. Thus, the STX module was merged into MELCOR, to evaluate steam explosion work based upon the debris ejection conditions and cavity coolant data. The merging procedure of the STX module into MELCOR is represented in Fig. 13. The STX module would extract the fuel conditions from MELCOR subroutines such as FDIRN1.F, FDISRT.F, and FDICON.F. The coolant conditions are to be extracted from CAV2CV.F.

The MELCOR input for the Ulchin nuclear power plants, which are Korea Standard Nuclear Power Plants, was adopted for preparing the test input to evaluate the STX-merged MELCOR. The containment, reactor vessel, and cavity were only modeled in order to simplify the test input. It was assumed that the lower plenum of the reactor vessel was filled with debris of 40 tons and the reactor cavity was filled with water whose temperature was 311℃ and depth was 1 m.

The calculation procedure was not changed from the original MELCOR. The debris was transferred from the pressure vessel to the cavity. The ejected debris was cooled and settled down onto the cavity bottom wall, and the STX module was independently operated with this original MELCOR procedure. As soon as the pressure vessel failed, the cavity coolant conditions were stored by STX_MEL.F of the STX module. During the debris ejection period, the time-dependent debris conditions were stored and the time-averaged debris conditions are calculated by STX_MEL.F of the STX module, too. After the required fuel and coolant conditions were obtained, the steam explosion work was evaluated by STX_IPL of the STX module.

The pressure vessel pressure varied from 0.2 MPa to 0.1 MPa and the debris ejection started from 10sec (Figs. 14 ~ 15). The original

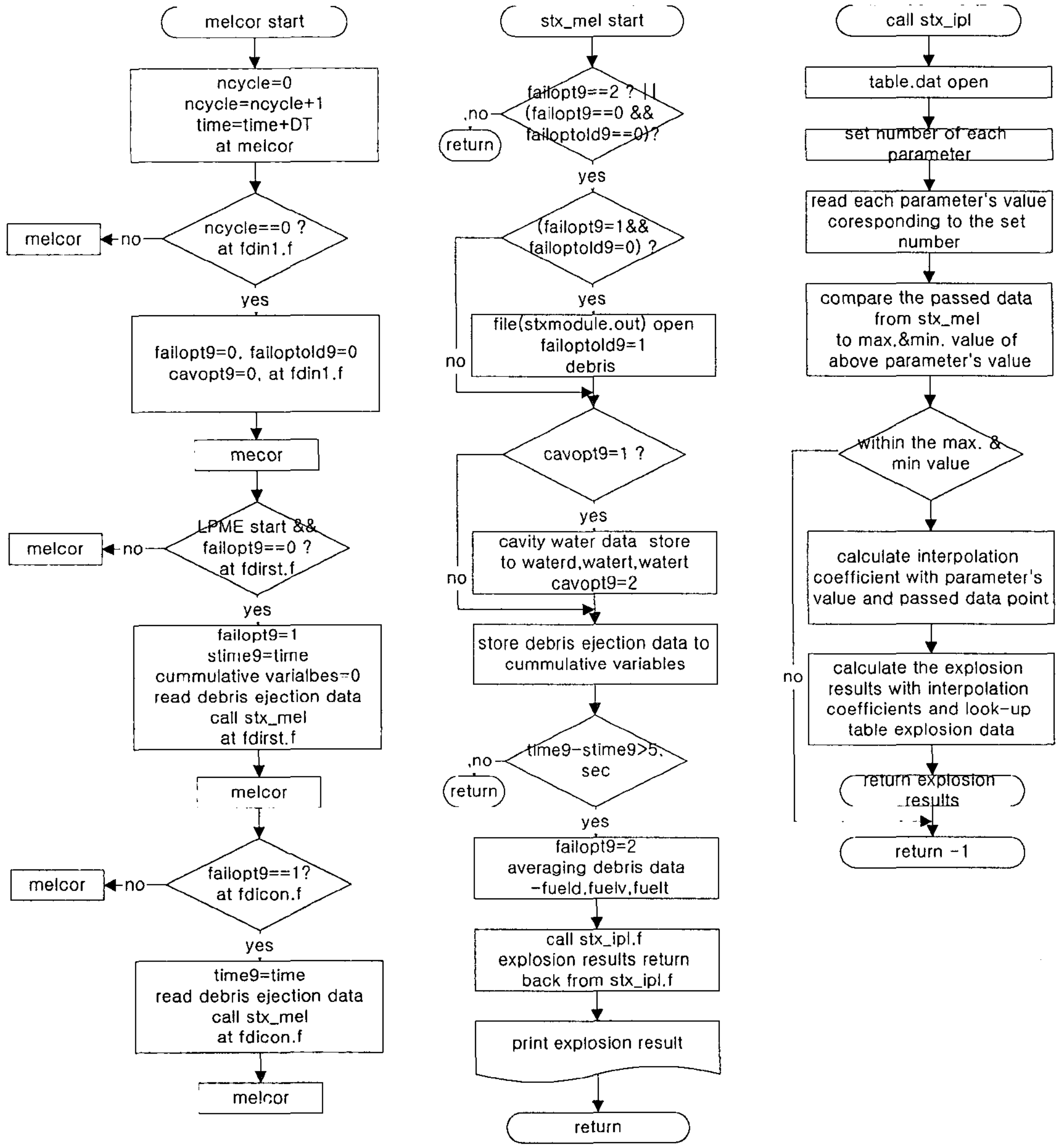

Fig. 13. Flow Chart of STX Module

MELCOR and the STX-merged MELCOR results could provide exactly the same results for a given condition. The STX-merged MELCOR, however, could give other results, as shown in Table 3, which presents the steam explosion calculation results. Those steam explosion results were obtained from the STX module merged into MELCOR.

As shown on the line of STX_MEL3 in Table 3, the debris melt started being ejected from the

Table 3. Steam Explosion Work Obtained by STX Module Merged into MELCOR

STX_MEL1 :	**
STX_MEL2 :	*** EX-VESSEL FUEL-COOLANT INTERACTION
STX_MEL3 :	*** EJECTION STARTING & ENDING TIME= 0.85695E+01 0.13630E+02
STX_MEL4 :	**
STX_MEL5 :	WATER DEPTH,TEMP,PRES,JET DIA,VEL,TEMP=
STX_MEL6 :	1.82 M 311.00 K 0.10 MPA 0.18 M 8.35 M/S 2773.52 K
STX_IPL1 :	TRY TO OPEN TABLE.DAT(31)
STX_IPL2 :	THE NUMBER OF I,J,K,L,M,N DATA=
STX_IPL3 :	3 3 3 3 3 3
STX_IPL4 :	WATER DEPTH,TEMP,PRES,JET DIA,VEL,TEMP=
STX_IPL5 :	1.82 M 311.00 K 0.10 MPA 0.18 M 8.35 M/S 2773.52 K
STX_IPL6 :	TRY TO READ RAW DATA AND PROCESSING
STX_IPL7 :	CLOSE TABLE.DAT(31)
STX_MEL7 :	FROM SUBROUTINE STX_MEL:
STX_MEL8 :	EXPLOS. IMPULSE AND PRESSURE=
STX_MEL9 :	110.KPA*SEC 102 MPA

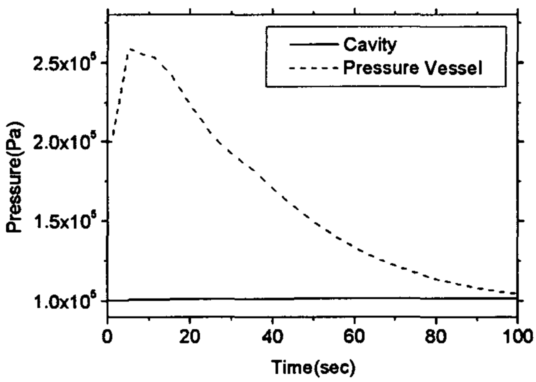

Fig. 14. Time-dependent Pressure Profile During Vessel Breach

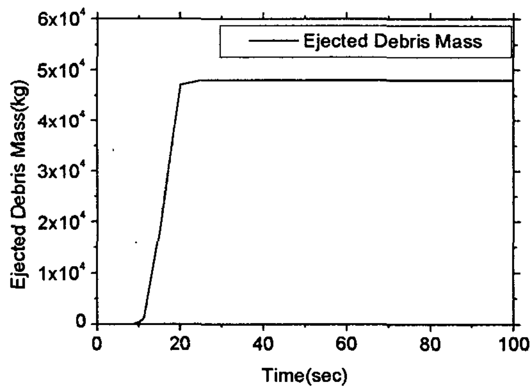

Fig. 15. Cumulative Ejected Debris Mass During Vessel Vreach

reactor vessel to the reactor cavity after 8.5 seconds and the ejection stopped at 13.6 seconds. At STX_MEL5 and STX_MEL6, the coolant depth, temperature, pressure, jet diameter, ejection speed, and jet temperature were 1.82 m, 311 K, 0.1 MPa, 0.18 m, 8.35 m/sec, and 2773.5 K. STX_MEL.F transfers the coolant and fuel conditions to STX_IPL.F. The evaluated steam explosion pressure and explosion load were calculated to be 102 MPa and 110 kPa sec, respectively, and they were shown at STX_MEL8 and STX_MEL9. Thus, the STX merged MELCOR code could evaluate the explosion work without any distortion of the original MELCOR calculation. The calculation time run by the STX module was very tiny because the STX module does not solve the equation for the steam explosion process but it extracts the pre-calculated steam explosion work from the Look-up table.

4. Conclusions

It might not be realistic to merge the mechanistic steam explosion code into integral safety analysis code mainly due to the difficulty of the convergence or huge running time of the mechanistic steam explosion codes. It must be noted that numerical stability and a short running time are required for the integral safety analysis code. In this work, the pre-calculated results using the mechanistic steam explosion code, TEXAS-V, are used for preparing the STX module, which was merged into the integral safety analysis code, MELCOR.

The sample calculations and the sensitivity studies on the several uncertain parameters were discussed in order to overview the TEXAS-V code characteristics and to conduct consistent calculations for preparing a look-up table. As the reaction area and the triggering timing could have a great effect on the TEXAS-V results, the 1:7 ratio for the jet, reaction diameter and the triggering timing logic based upon the void fraction were suggested.

A look-up table with a limited range of coolant and fuel conditions was generated. This look-up table and Lagrangian interpolation were merged into the MELCOR code. The effect of STX steam explosion module on MELCOR was verified using a simple input test, and it was confirmed that the STX module merged MELCOR was working properly with the steam explosion work estimation ability.

Currently, the STX module is limited by the look-up table boundary. It is actually caused by a difficulty in convergence in the mechanistic steam explosion code. Thus, it would be desirable to extend the range of the Look-up table.

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