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The Establishment and Assessment of Kuosheng (BWR/6) NPP Dry-storage System TRACE/SNAP Model

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ABSTRACT

The dry-storage systems of nuclear power plants (NPPs) in Taiwan have become one of the major safety concerns. This research focuses on the development of Kuosheng NPP (BWR/6) dry-storage system TRACE/SNAP model. There are two steps in this research. The first step is the verification of TRACE/SNAP dry-storage model by using VSC-17 experimental data. By using VSC-17 data, VSC-17 dry-storage system was established by TRACE/SNAP. Then, the analysis results of TRACE were compared with VSC-17 data. The results of TRACE were similar to VSC-17 data. It indicates that TRACE has the respectable accuracy in the simulation and analysis of the dry-storage systems. The next step is the application of TRACE in the dry-storage system of Kuosheng NPP. Kuosheng NPP is the second BWR NPP of Taiwan Power Company. In order to solve the storage of the spent fuels, Taiwan Power Company developed the new dry-storage system for Kuosheng NPP. In this step, the dry-storage system model of Kuosheng NPP was established by TRACE/SNAP. Then, the steady state simulation of this model was performed and the results of TRACE were compared with Kuosheng NPP data. The results of TRACE in the steady state calculation were consistent with Kuosheng NPP data. Finally, this model was used to perform the safety analysis of Kuosheng NPP dry-storage system. Besides, FRAPTRAN code was used to calculate the transient performance of fuel rods.

FOREWORD

The US NRC (United States Nuclear Regulatory Commission) is developing an advanced thermal hydraulic code named TRACE for nuclear power plant safety analysis. The development of TRACE is based on TRAC, integrating RELAP5 and other programs. NRC has determined that in the future, TRACE will be the main code used in thermal hydraulic safety analysis, and no further development of other thermal hydraulic codes such as RELAP5 and TRAC will be continued. A graphic user interface program, SNAP (Symbolic Nuclear Analysis Program) which processes inputs and outputs for TRACE is also under development. One of the features of TRACE is its capacity to model the reactor vessel with 3-D geometry. It can support a more accurate and detailed safety analysis of nuclear power plants. TRACE usually used in the nuclear power plants analysis. This report showed TRACE can also do the calculation of small system such as dry-storage cask.

Taiwan and the United States have signed an agreement on CAMP (Code Applications and Maintenance Program) which includes the development and maintenance of TRACE. INER (Institute of Nuclear Energy Research, Atomic Energy Council, R.O.C.) is the organization in Taiwan responsible for the application of TRACE in thermal hydraulic safety analysis, for recording user's experiences of it, and providing suggestions for its development. To meet this responsibility, TRACE/SNAP dry-storage model of Kuosheng NPP has been built. In this report, this study uses the analysis results of SAR to assess the Kuosheng NPP dry-storage TRACE/SNAP model.

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EXECUTIVE SUMMARY

An agreement in 2004 which includes the development and maintenance of TRACE has been signed between Taiwan and USA on CAMP. INER is the organization in Taiwan responsible for applying TRACE to thermal hydraulic safety analysis in order to provide users' experiences and development suggestions. To fulfill this responsibility, the TRACE/SNAP model of Kuosheng NPP dry-storage system is developed by INER.

According to the user manual, TRACE is the product of a long term effort to combine the capabilities of the NRC's four main systems codes (TRAC-P, TRAC-B, RELAP5 and RAMONA) into one modernized computational tool. NRC has ensured that TRACE will be the main code used in thermal hydraulic safety analysis in the future without further development of other thermal hydraulic codes, such as RELAP5 and TRAC. Besides, the 3-D geometry model of reactor vessel, which is one of the representative features of TRACE, can support a more accurate and detailed safety analysis. TRACE usually used in the nuclear power plants analysis but it can also do the calculation of small system such as dry-storage cask.

Taiwan has four NPPs and for now all the spent fuels were set in the spent fuel pool inside each NPP. Someday the spent fuel pool will not be able to handle all the fuels, so Taiwan Power Company is now working on the plan that build up a dry-storage system of Kuosheng NPP. This dry-storage system is designed by the NAC Co. and it can store 87 bundles of spent nuclear fuels. In the SAR, many new analysis models and methodologies have been employed to evaluate the thermal-hydraulic behaviors and cooling ability in the dry-storage system. The previous analysis of Kuosheng NPP dry-storage system was done by CFD code [1].

In this study, SNAP 2.2.7 and TRACE v5.0p4 were used. By using VSC-17 data and TRACE/SNAP, the model of VSC-17 dry-storage system was established. Then, the analysis results of TRACE were compared with VSC-17 data. The results of TRACE were similar to VSC-17 data. It indicates that TRACE has the respectable accuracy in the simulation and analysis of the dry-storage systems.

Kuosheng NPP is the second BWR NPP of Taiwan Power Company. In order to solve the storage of the spent fuels, Taiwan Power Company developed the new dry-storage system for Kuosheng NPP. In this step, the dry-storage system model of Kuosheng NPP was established by TRACE/SNAP. Then, the steady state simulation of this model was performed and the results of TRACE were compared with Kuosheng NPP data. The results of TRACE in the steady state calculation were consistent with Kuosheng NPP data. Finally, this model was used to perform the safety analysis of Kuosheng NPP dry-storage system. The fuel rods integrity analysis of FRAPTRAN was also performed under the above conditions.

There were two parts of Kuosheng dry-storage safety analysis: fully-blockage and fully-overed. In this research, TRACE's results implied that Kuosheng NPP dry-storage system was safe in fully-blockage case and took 19.2 days to reach the safety criteria of cladding in fully-covered case.

ABBREVIATIONS

BWR	Boiling Water Reactor
CAMP	Code Applications and Maintenance Program
SAR	Safety Analysis Report
INER	Institute of Nuclear Energy Research Atomic Energy Council, R.O.C.
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
SNAP	Symbolic Nuclear Analysis Package
TRACE	TRAC/RELAP Advanced Computational Engine
VSC	Ventilated Storage Cask

1. INTRODUCTION

Taiwan has four NPPs and for now all the spent fuels were set in the spent fuel pool inside each NPP. Someday the spent fuel pool will not be able to handle all the fuels, so Taiwan Power Company is now working on the plan that build up a dry-storage system of Kuosheng NPP. This dry-storage system is designed by NAC Co. and it can store 87 bundles of spent nuclear fuels. In the SAR, many new analysis models and methodologies have been employed to evaluate the thermal-hydraulic behaviors and cooling ability in the dry-storage system. The previous analysis of Kuosheng NPP dry-storage system was done by CFD code [1].

In this study, SNAP 2.2.7 and TRACE v5.0p4 were used. According to the user manual [2], TRACE is the product of a long term effort to combine the capabilities of NRC's four main systems codes (TRAC-P, TRAC-B, RELAP5 and RAMONA) into one modernized computational tool. The development of TRACE is based on TRAC, combining with the capabilities of RELAP5 and other programs. One of the features of TRACE is its capacity to model the reactor vessel with 3-D geometry. It could support a more accurate and detailed safety analysis for nuclear power plants. SNAP, a graphic user interface program that processes the inputs and outputs of TRACE, has also been developing. FRAPTRAN is a Fortran language computer code that calculates the transient performance of light-water reactor fuel rods during reactor transients and hypothetical accidents such as loss-of-coolant accidents, anticipated transients without scram, and reactivity-initiated accidents [6].

In the dry-storage system, one of the main methods of heat removal is nature circulation by air. In the study from 2013 fall CAMP meeting done by ENEA [3], their team showed that TRACE calculated a nature circulation inside a heated pipe. The applications of TRACE in NPPs before were always focus on the working fluid as water. In the dry-storage cases, main working fluids are He and air. So this study can also proof that TRACE can calculate the thermal-hydraulic properties well even the working fluid is He and air.

Then a dry-storage system model of Kuosheng NPP was built and this 3-D TRACE model was validated using data from a ventilated storage cask (VSC-17) collected by Idaho National Laboratory. By comparing the calculations of this TRACE model and the experimental data, the feasibility of TRACE dry-storage model can be verified. After this, Kuosheng NPP dry-storage model can be used on the safety analyses. The safety analyses always concern about the series accident such as big earthquake, so a fully-blockage and a fully-covered case were calculated in this study. The final step is the fuel rods integrity analysis of FRAPTRAN under the above conditions. TRACE's analysis results (ex: power and coolant conditions) were used in FRAPTRAN's input files. FRAPTRAN can calculate the cladding temperature, hoop stress/strain, and oxide thickness.

2. MODEL OF KUOSHENG NPP DRY-STORAGE SYSTEM

This dry-storage system was developed for BWR and it had 87 square-shaped fuel tubes for the spent fuels (shown in Figure 1(a)). The total power was about 17 kW. The tubes were put in a sealed steel canister filled with helium. Figure 1(b) shows the concrete-shielded and the heat was remove by the air channel between steel canister and concrete-shielded. Figure 1(c) is the bottom of this dry-storage system, it was made by steel and in these cases the bottom was set to be adiabatic. Figure 1~2 and Table 1 shows the TRACE model of Kuosheng NPP dry-storage system developed based on the relevant document [1][5].

There were three parts in this model: fuel, steel canister and concrete-shielded. First is the part of fuel, there were totally 87 fuel tubes and each of them can storage a bundle of BWR spent fuel. The fuel tubes were about 4 m long. The power distribution and axial power shape were just like the fuel removed from the spent fuel pool. In this model, all fuels were lumped together as one big fuel CHANNEL. The CANNEL component had 25 axial cells and connected to ring 1 of VESSEL 1 in Figure 2.

Second part is the steel canister; it was a VESSEL with a heat structure about 4.5 m high and the inner radius was 0.9m. VESSEL 1 has 31 axial cells and the 25 cells at the middle had same level as the 25 cells of fuel. The thickness of heat structure which used to model the steel wall was 0.0127m. This steel canister were fully sealed and the gas inside was He due to it has a higher heat transfer coefficient. The heat created by the fuel transferred to He and went to the steel canister. By connecting the flux of the inside canister wall and the second vessel (Left hand side of Figure 2), the heat generated by the fuel will transfer to the VESSEL 2, the air path and the concrete-shielded.

The left hand side of Figure 2 is the concrete-shielded and the air path. The valves were using to control the size of air channel entrance and exit. The thickness of the air path via the steel was 0.092 m. Also, there was a heat structure connected air channel and the outside temperature. This heat structure was using for modeling the concrete-shielded which thickness was about 0.67 m. The air channel was connected to a big PIPE component (the square one inside Figure 2). This PIPE was used to model the open area with atmospheric pressure and normal temperature 300K. With this connection, TRACE can calculate a nature circulation air flow rate by its self.

The initial condition was set to be some numbers that make sense in this situation. Then TRACE calculated the normal storage case into a steady state. The initial pressure of He inside the steel canister was from the report [1][5]. A standard filled He density was about 0.744 kg/m^3 and which equal to the pressure about 0.514 MPa (74.53 psi) at initial temperature. Finally, the animation of SNAP was also established in this study (see Figure 3).

After TRACE analysis, FRAPTRAN input deck was established by TRACE's results (ex: power, coolant conditions, heat transfer coefficients history data) and fuel rod geometry data. Figure 4 shows the fuel rod model of FRAPTRAN. The fuel rod was divided into 12 nodes from bottom to top.

Table 1 Geometric detail of Kuosheng NPP dry-storage system

System	Component	Characteristic dimension	
Steel canister		Diameter	1.83m
		Length	4.87m
		Thickness	0.013m
Fuel tubes		Length	4.56m
		Diameter	1.79m
		Number	87
Concrete-shielded	Lining	Thickness	0.044m
		Outer diameter	2.1m
	Air entrance,exit	Length	0.05m
		Width	3.45m
	Concrete	Thickness	0.67m

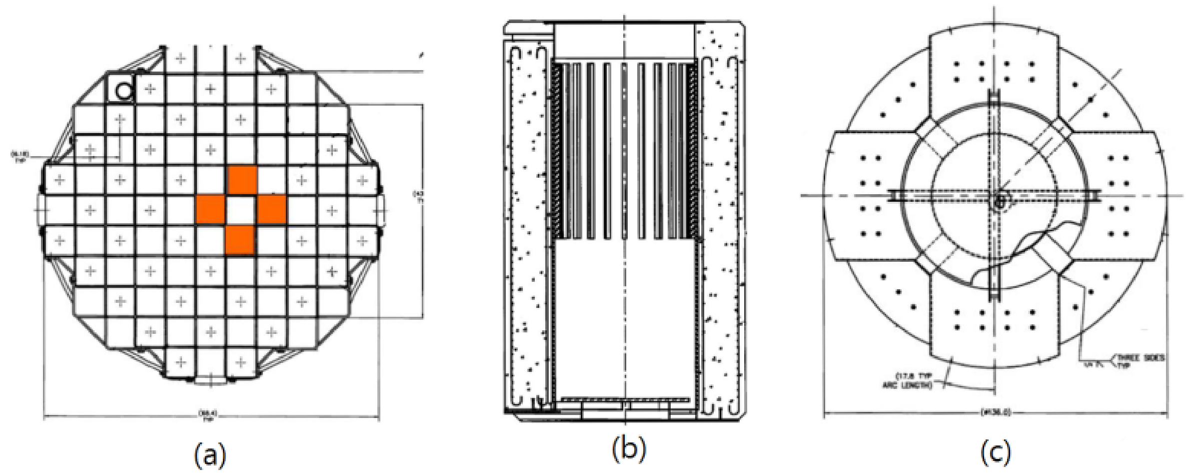


Figure 1 (a) Fuel (b) Concrete-shielded (c) Bottom of Kuosheng NPP dry-storage system

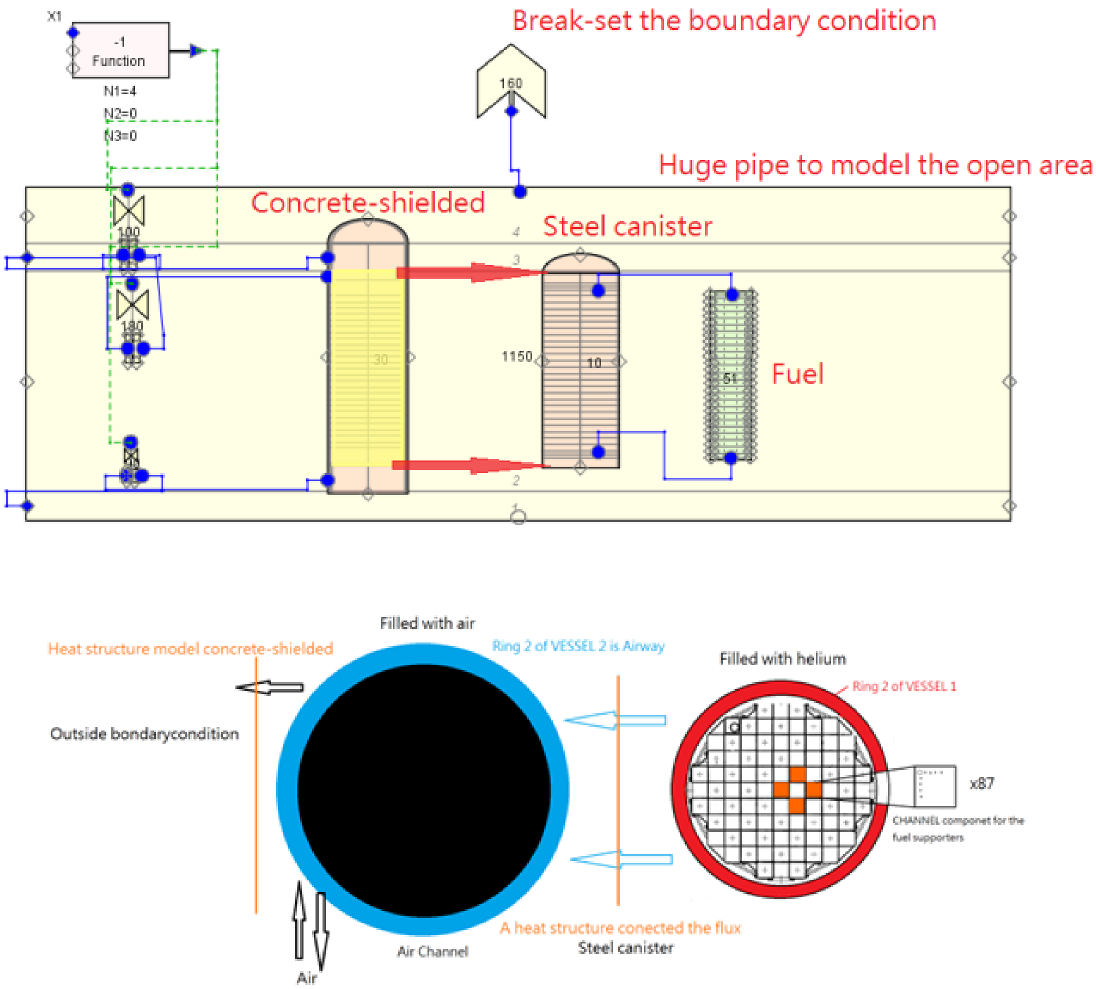


Figure 2　TRACE model of Kuosheng NPP dry-storage system

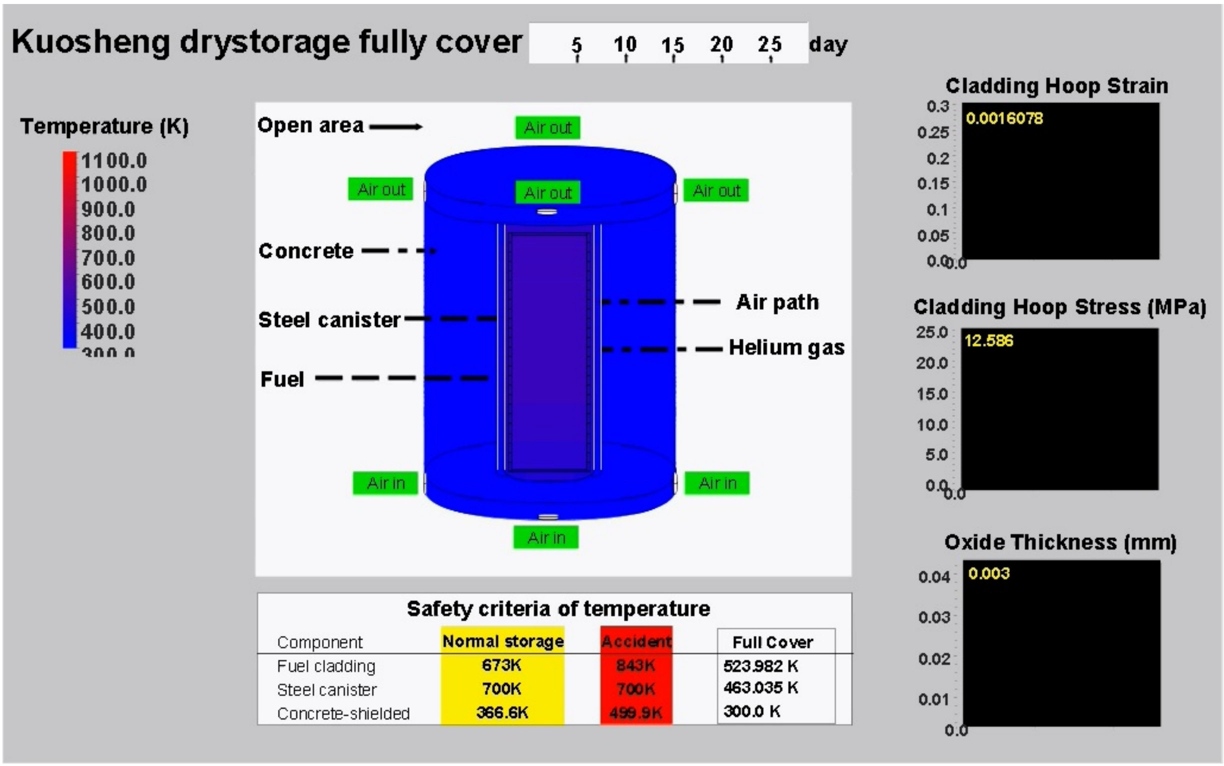


Figure 3 The animation model of Kuosheng NPP dry-storage system

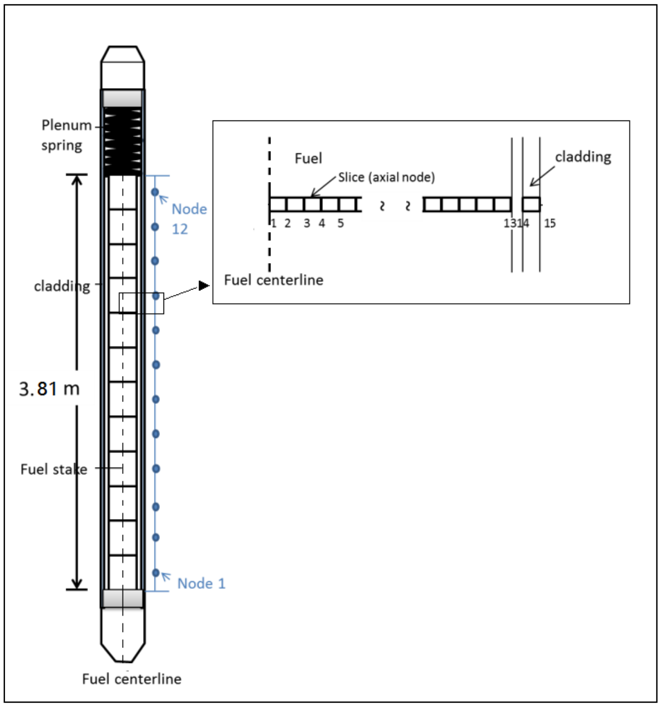


Figure 4 FRAPTRAN model of Kuosheng NPP dry-storage system

3. MODEL OF VSC-17 DRY-STORAGE SYSTEM

VSC-17 was an experimental dry-storage system [4]. A TRACE model of VSC-17 was built to check the ability of TRACE to calculate the dry-storage cases (Figure 5). The validation model was very similar to Kuosheng NPP model. The only difference was the power and the geometric. Figure 6 shows the fuel tubes of VSC-17. The power shape was set from VSC-17 report data and it was separated to 6 parts in the power table of TRACE model. The fuel tubes in VSC-17 model were also lumped together. The air flow value was from the CFD calculation due to the static pressure difference of the entrance and exit. It was about 0.65 kg/sec.

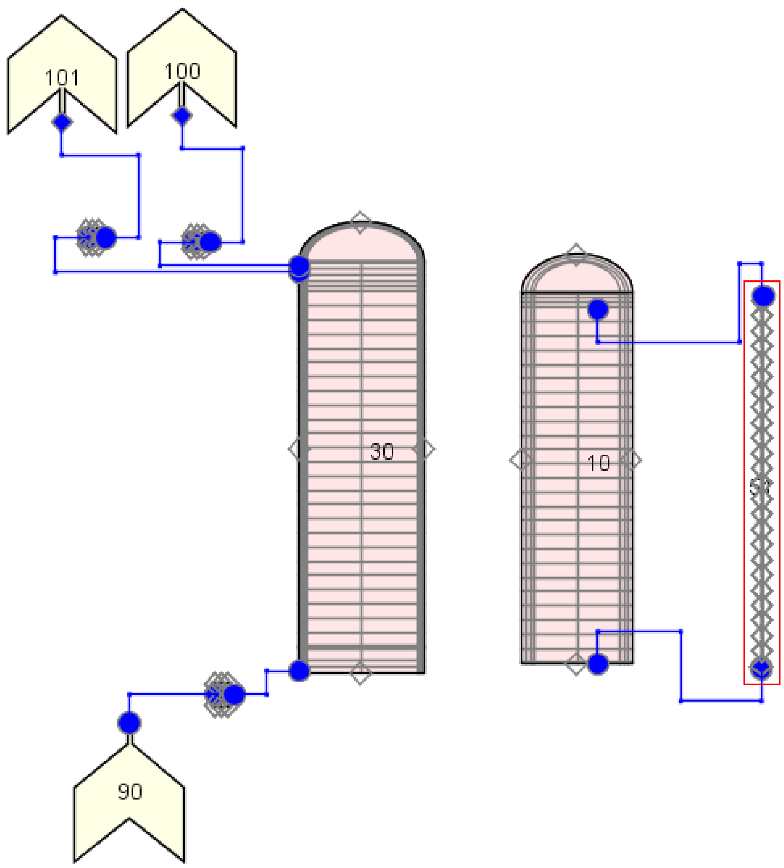
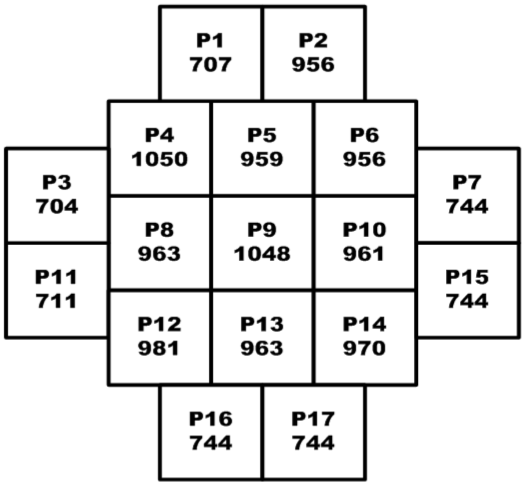


Figure 5 TRACE model of VSC-17 dry-storage system



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P3 704w
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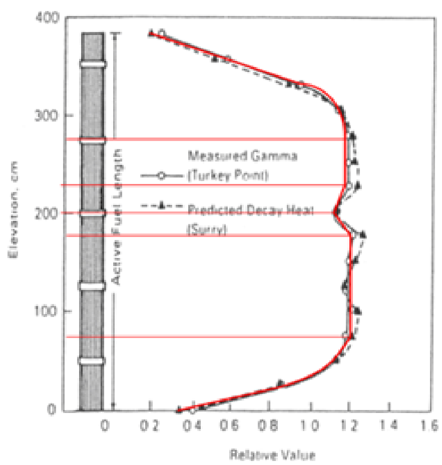

- Section 1: Polynomial
- Section 2: Constant
- Section 3: Linear
- Section 4 : Linear
- Section 5: Constant
- Section 6: Polynomial

Figure 6 Fuel tubes and Power distribution of VSC-17

4. RESULTS

The dry-storage analysis by using TRACE/SNAP model was described above. This analysis was divided into four parts: The VSC-17 TRACE model validation by comparing TRACE results to the experimental data, and the three cases of Kuosheng NPP dry-storage system: steady state, fully-blockage and fully-covered.

4.1 VSC-17 Analysis

This VSC-17 analysis was used to check the model of TRACE in the dry-storage system. Figure 7 is the fuel cladding temperature at different altitudes, the points are the temperature from VSC-17 experiments for each rod and the blue line is the output of TRACE. Since the fuel of TRACE model were lumped together, the TRACE outputs just had one temperature at each altitude. And it was a kind of average rods here. The number of fuel is shown in Figure 6. Fuel P09 and P10 were closer to the center so they had a higher temperature output. Figure 8 shows the temperature of steel canister surface. Their results were similar. The above comparison results indicate that TRACE has the respectable accuracy in the simulation and analysis of the dry-storage systems.

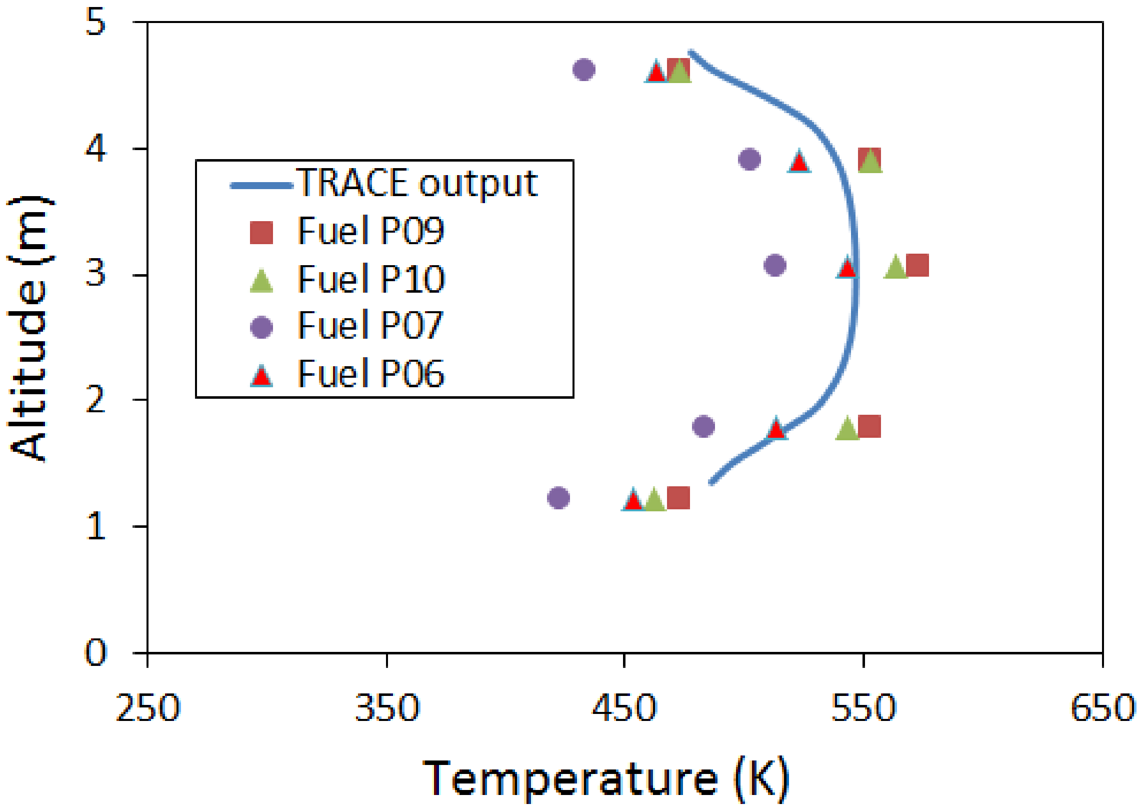

Figure 7 TRACE result : Temperature distribution of cladding of VSC-17

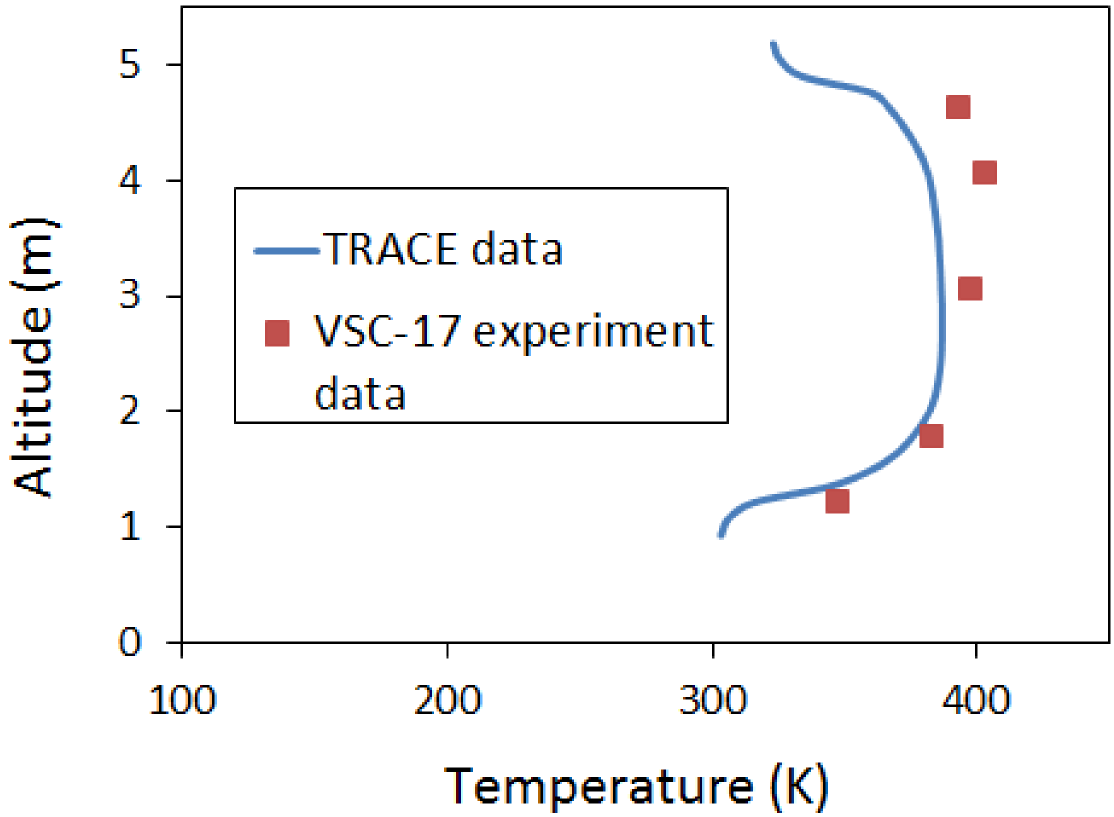

Figure 8 TRACE result : Temperature distribution of steel canister surface of VSC-17

4.2 Kuosheng NPP Dry-storage System Analysis (Steady-state)

There are three parts in the analysis of Kuosheng NPP dry-storage system analysis: steady state (normal storage), fully-blockage and full-covered. First, the steady state analysis can help us check that the cask can do a long term heat removal in the normal situation. Then it comes to the safety analysis. Fully-blockage case is that when the air entrance and exit were blocked, no air comes in and out, but the concrete-shielded still removed the heat by thermal conduction. In this kind of accident, the heat removal was worse than normal situation but it still had a steady state that the temperature of cladding went into constant. But the fully-covered case was not the same. The cask was cover by the mudflows or anything else generated by some natural disaster. The concrete did not remove the heat by conduction, so the fuel temperature kept rising till the cladding failed. These analyses focus on the max temperature and the pressure limit at each component. Table 2 shows the safety criteria of dry-storage system in different cases. The next 3 parts compare the results to the safety criteria.

The steady state analysis of Kuosheng NPP dry-storage system is just like the VSC-17 case. When the dry-storage cask was in the normal heat removal condition, TRACE calculated it for some times and gave a temperature outputs.

Table 3 shows TRACE outputs and SAR [4] data of the max temperature in different components. The max temperature of fuel cladding was about 523.85K and the max temperature of steel canister was 452K in this case. The results calculated by TRACE were very close to SAR data. The temperatures of fuel, steel and concrete were all lower than the safety criteria. The steady state temperatures were used to be the initial temperature of fully-blockage and fully-covered cases.

Figure 9 shows the radial temperature distribution of the steady state analysis. There are 4 parts shown in this picture: fuel, steel canister, air channel and concrete. The axial nodes chosen in this picture were the nodes in the middle. The design pressure limit of steel canister in the normal storage situation is 110 psig (0.758 MPa) and the TRACE calculation was 0.447 MPa. It was far lower than the design limit.

Table 2 Safety criteria of temperature in dry-storage system

Component	Normal storage	Accident
Fuel cladding	673 K	843 K
Steel canister	700 K	700 K
Concrete-shielded	366.6 K	499.9 K

Table 3 Max temperature of steady state analysis

Component	TRACE (K)	SAR (K)
Fuel rods	530.14	524
Fuel tubes	529.26	
Steel canister	474	437
Concrete-shielded	324	336

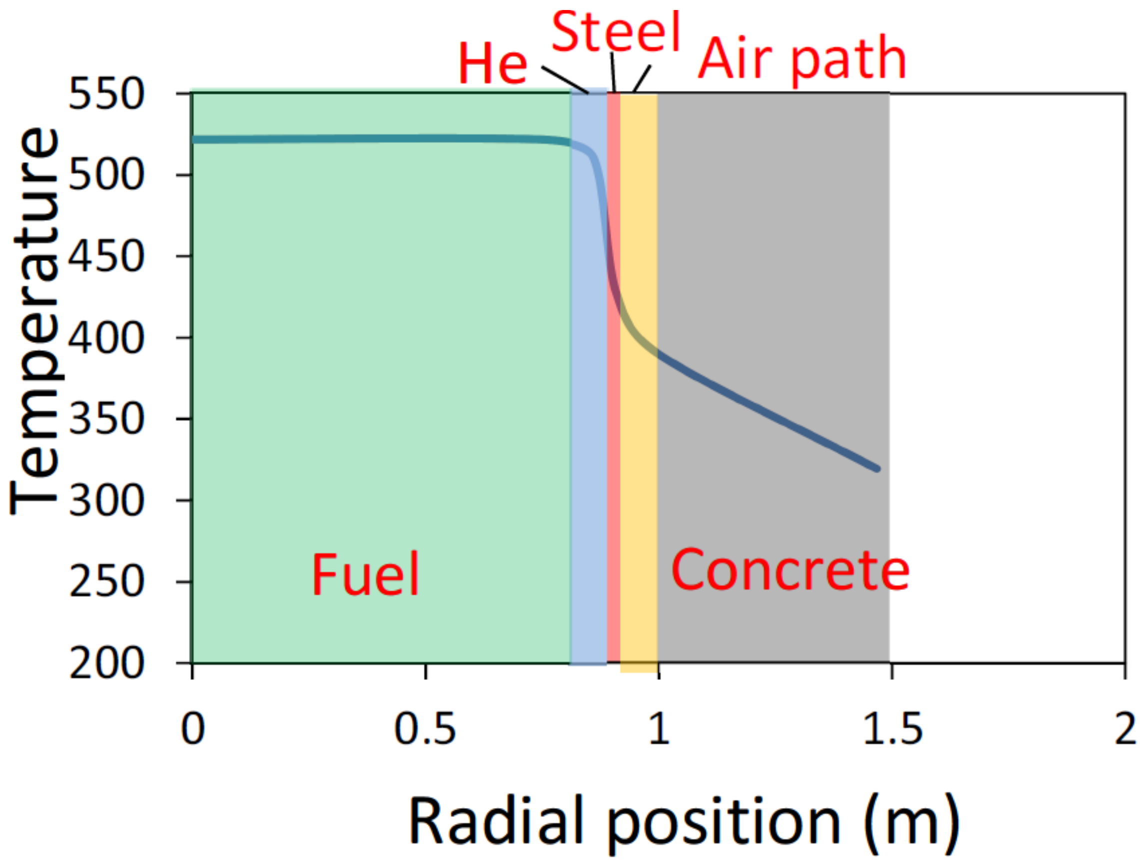

Figure 9 TRACE result : Radial temperature distribution of normal storage

4.3 Kuosheng NPP Dry-storage System Analysis (fully-blockage)

The fully-blockage case was the dry storage system model with the entrance and exit closed. The first 10 hours was the steady state. Then the air flow was closed by valves. The max hot node temperature calculated by TRACE is shown in Figure 10 and 11. Figure 12 shows the radial temperature distribution of this analysis.

The max temperature of fuel cladding was 609K and for steel canister was 517K. In the fully-blockage case, the fuel cladding temperature rose to 609K and went in a constant value. The temperature calculated by TRACE was a little lower than SAR data. It was because TRACE was an average rod model in this study and also we did not have some material details, conductive setting details of SAR model.

Although the fully-blockage temperatures were higher than the steady state case, but it was still lower than the safety criteria. So in this case the dry storage system was safe.

The design limit of steel canister pressure is 1.723 MPa in un-normal cases. The max pressure in this fully-blockage case was 0.5226 MPa. The pressure was still lower than design limit. Table 4 shows the max temperature results of fully-blockage analysis. After the TRACE analysis, FRAPTRAN input deck is established by the TRACE's results (ex: power, coolant conditions, heat transfer coefficients history data) and fuel rod geometry data. Figure 13 shows the results of FRAPTRAN in this case. When the cladding temperature increased, the hoop strain and stress of cladding also went up.

Table 4 Max temperature of fully-blockage analysis

Component	TRACE (K)	SAR (K)
Fuel rods	605.8	675
Fuel tubes	604.86	
Steel canister	543.69	544
Concrete-shielded	416.4	395

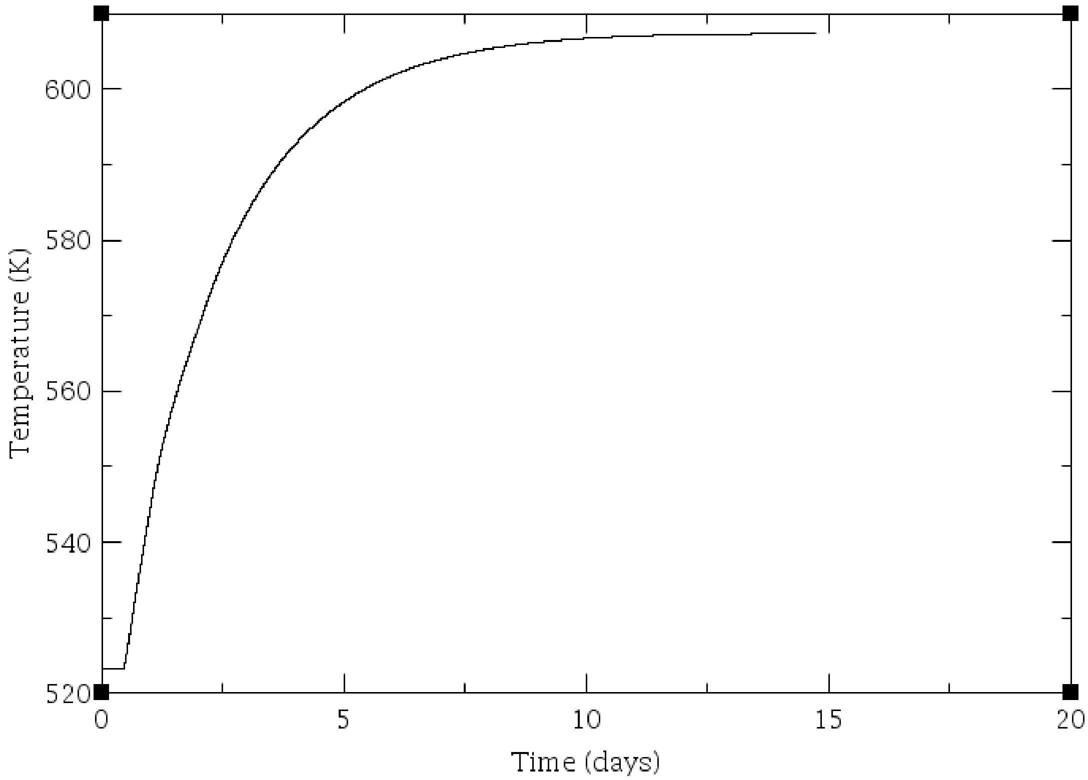

Figure 10 TRACE result : Max hot node temperature of fuel cladding

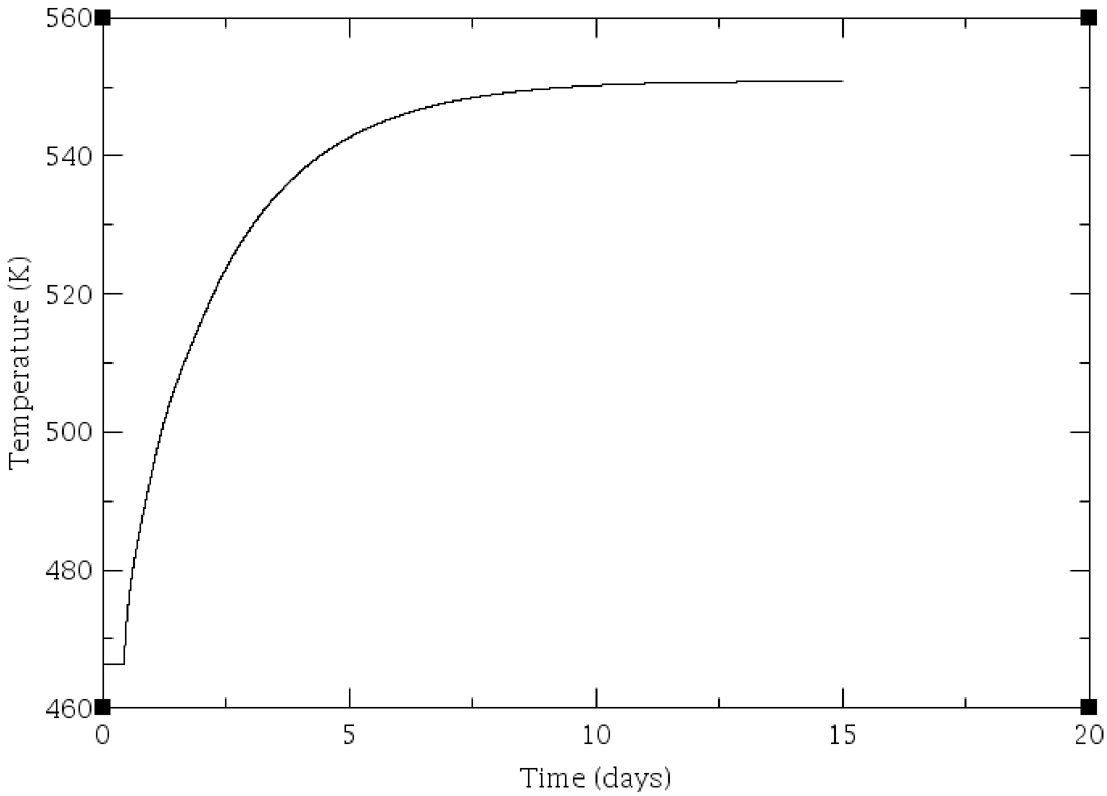

Figure 11 TRACE result : Max hot node temperature of steel canister

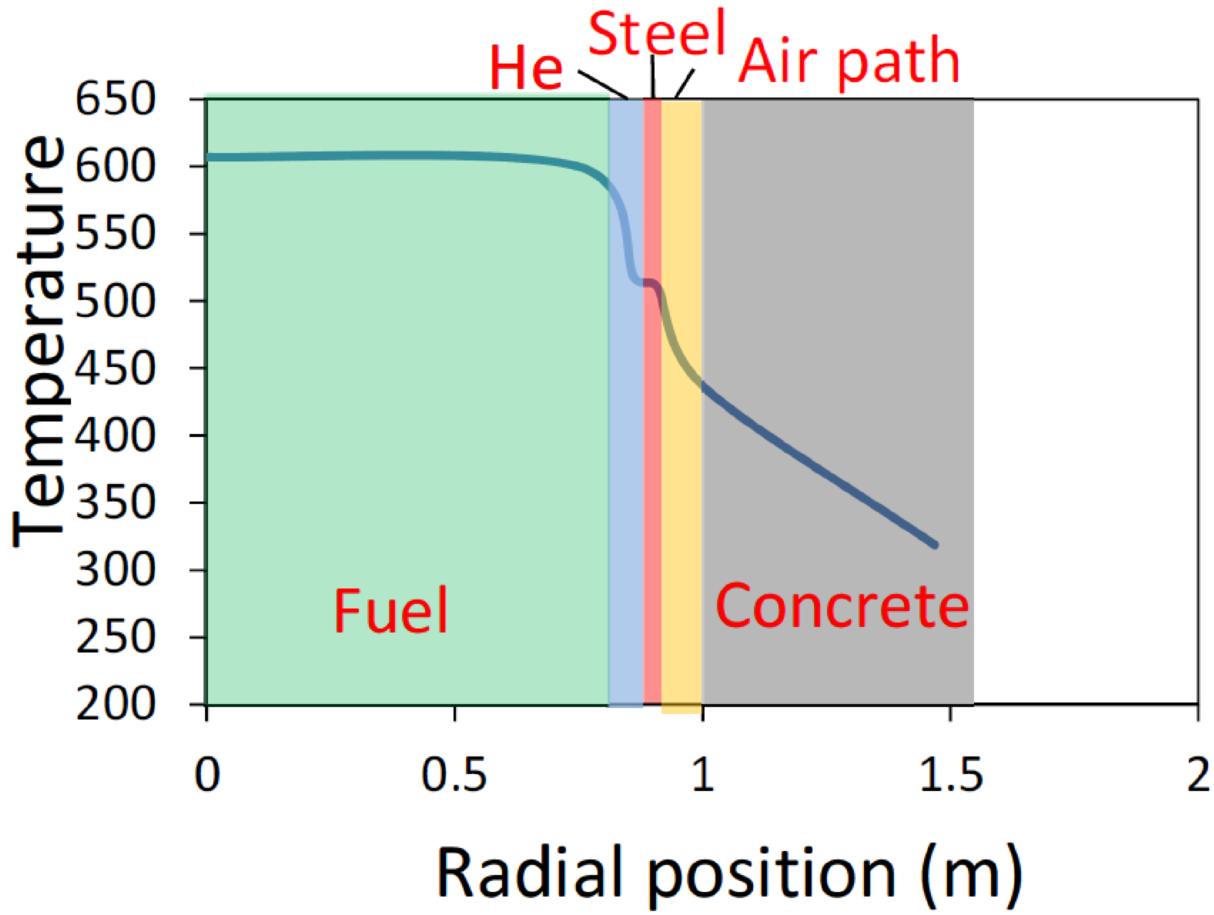

Figure 12 TRACE result : Radial temperature of fully-blockage

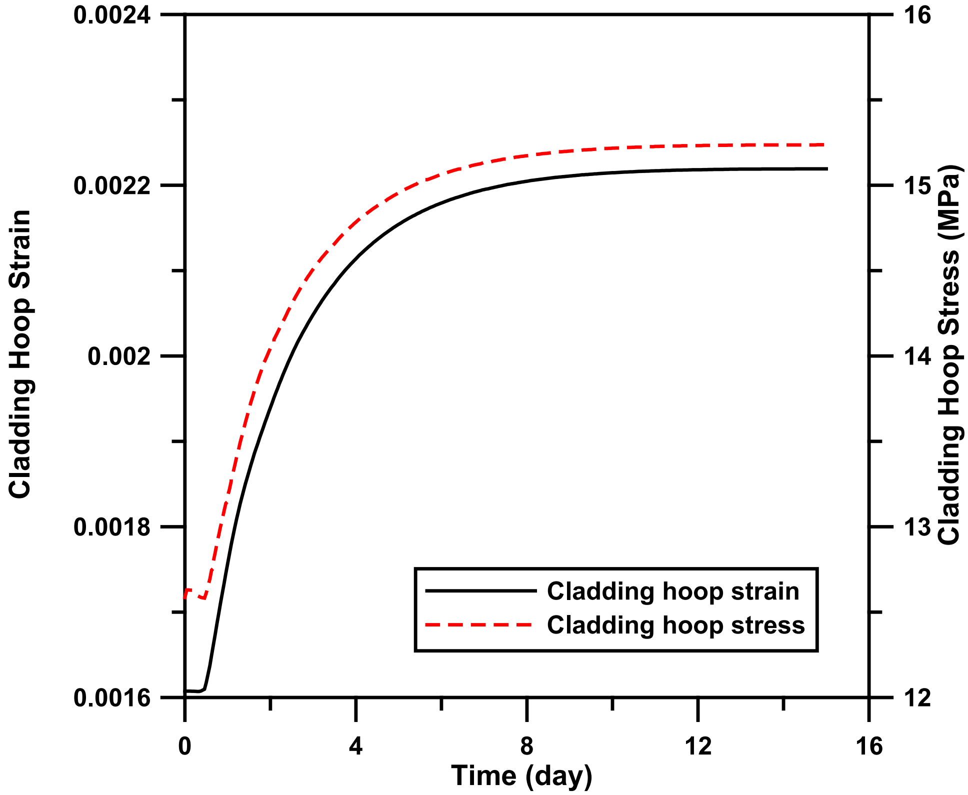

Figure 13 Cladding hoop strain and stress of fuel rod in fully-blockage case

4.4 Kuosheng NPP dry-storage system analysis (fully-covered)

Figure 14 shows the peak cladding temperature comparison of fully-covered and fully-blockage cases. The heat of the fully-covered case did not go out and so the cladding temperature kept rising. The comparison of the fully-blockage and fully-covered cases was very important. It can show that how the temperature went up when the worst situation happened. The cladding temperature of fully-blockage was 609K, it was lower than the safety criteria (843K). In Figure 14, the temperature of fully-covered case rose faster and it only took 4.5 days to reach the temperature of fully-blockage case (609K). Then the temperature kept rising to the safety criteria (843K) at 19.2 days.The pressure inside steel canister was 0.73 MPa at 19.2th day. It was much lower than the design limit of steel canister (1.723 MPa).

Figure 15 shows the results of FRAPTRAN in this case. When the cladding temperature increased, the hoop strain and stress of cladding also went up. However, the hoop strain increased and stress dropped sharply after about 23 days. Besides, the oxide thickness of cladding went up after 28 days in fully-covered case (see Figure 16) and kept constant in fully-blockage case. According to the above results of FRAPTRAN, it indicated that the integrity of cladding was not kept after 23 days for fully-covered case.

Figure 17 is the SNAP animation model of this dry-storage system. This model was built by combining TRACE and SNAP. The important temperature of each part can easily be seen in this model and it can help others to understand the analysis of dry-storage system.

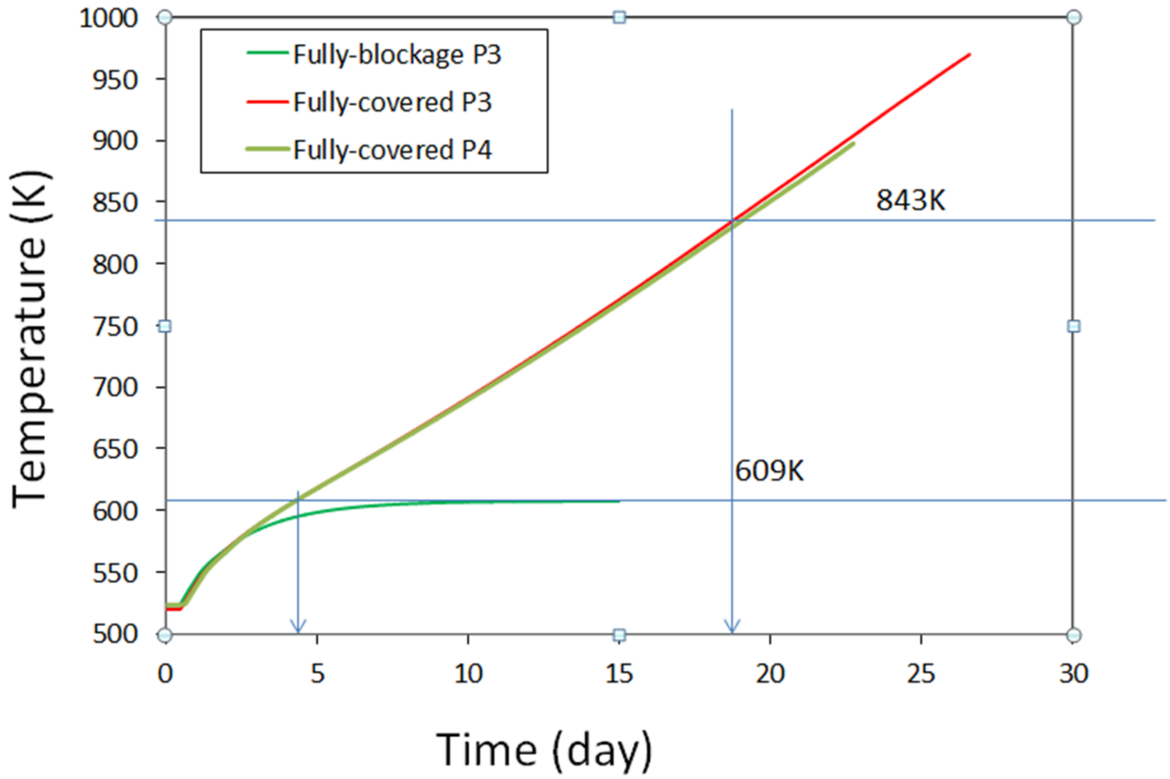

Figure 14 TRACE result : Max hot node temperature of fuel in fully-covered and fully-blockage cases

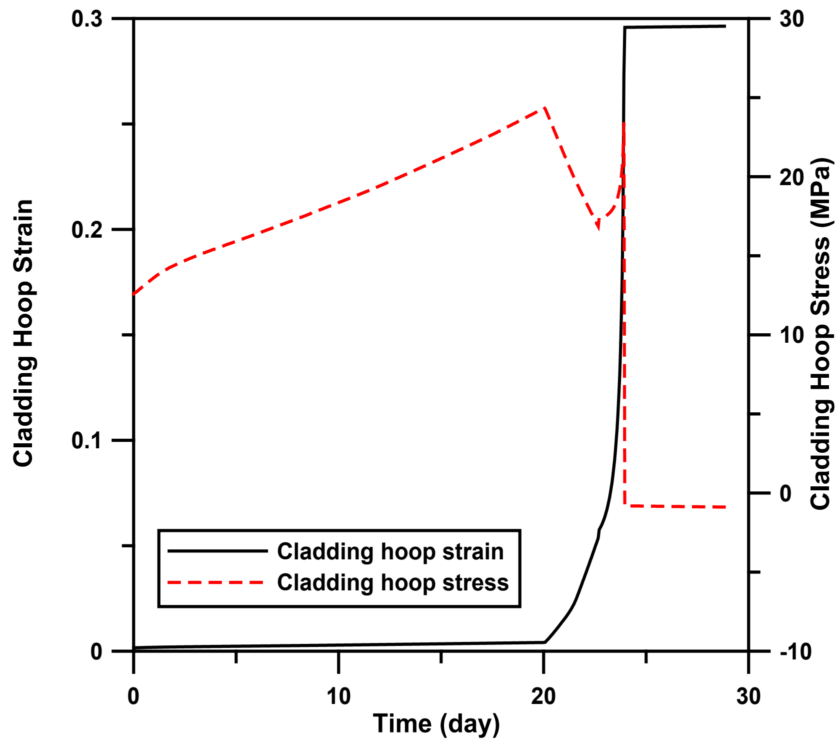

Figure 15 Cladding hoop strain and stress of fuel rod in fully-covered case

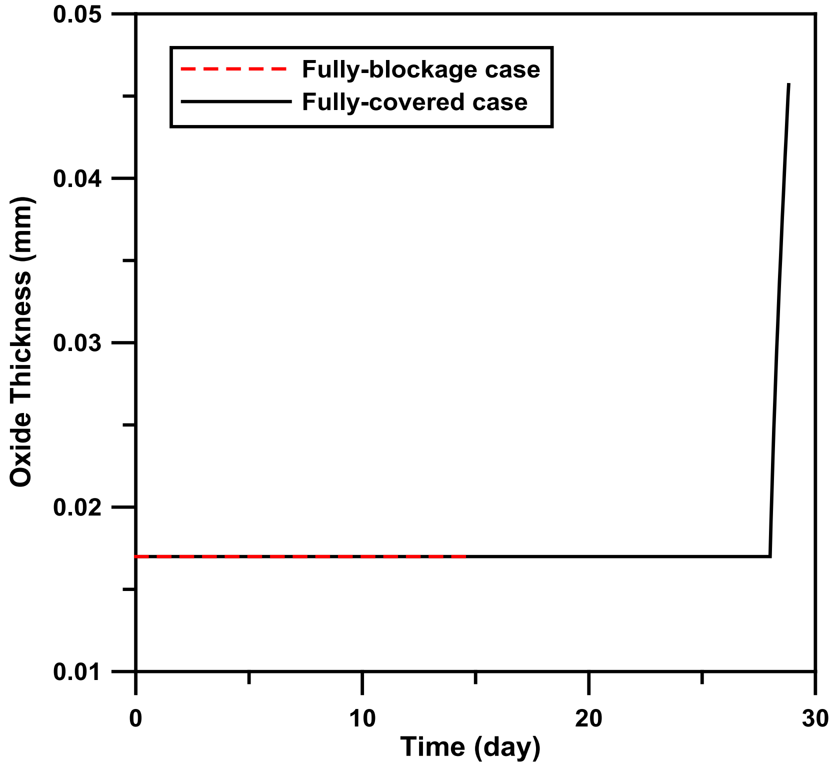

Figure 16 Oxide thickness of fuel rod in fully-covered and fully-blockage case

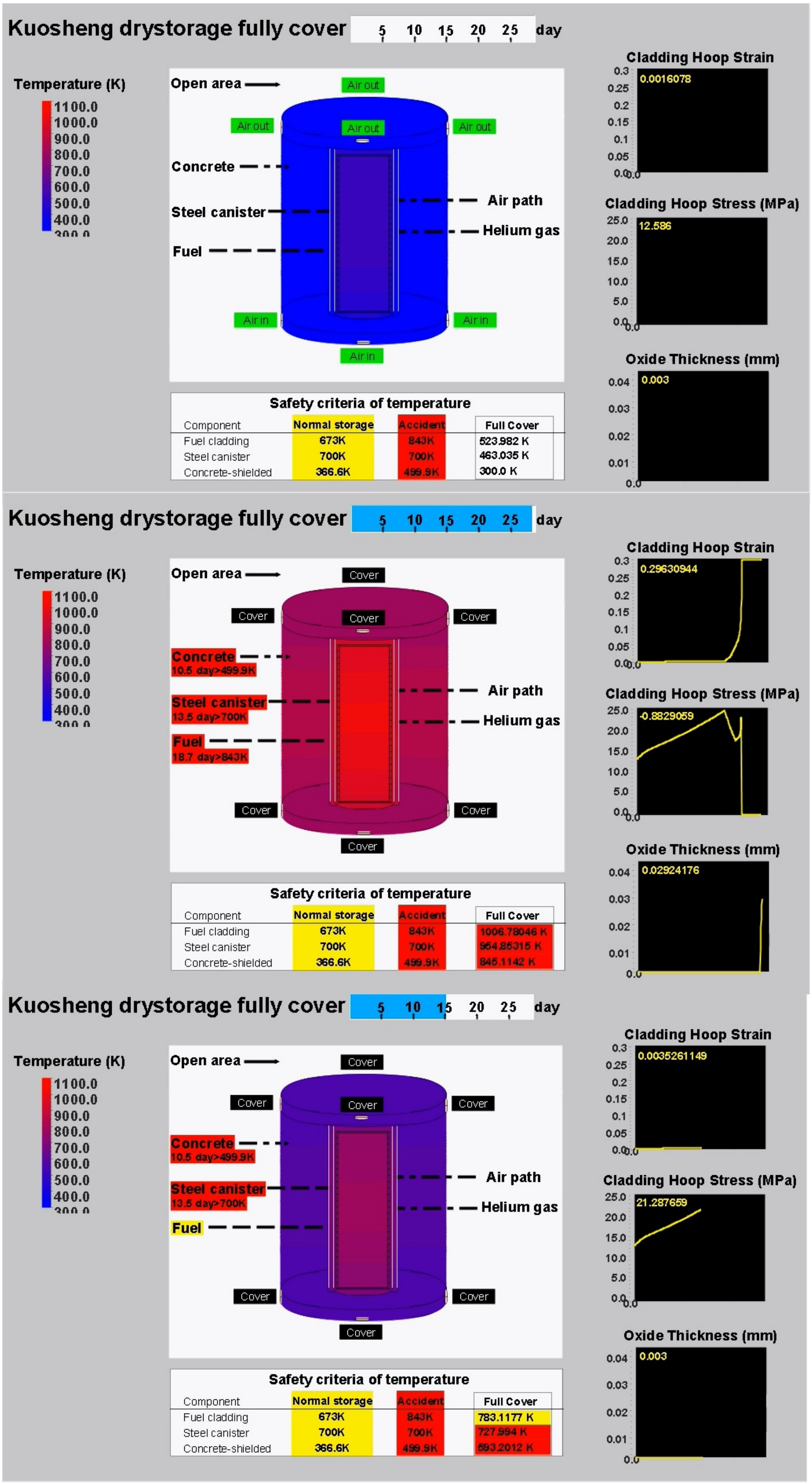

Figure 17 Animation model of Kuosheng NPP dry-storage system

5. CONCLUSIONS

By the calculation of TRACE/SNAP in the dry-storage system, this study gives several conclusions:

1. The methodology of TRACE/SNAP/FRAPTRAN for the analysis of dry-storage system was developed successfully in this research. SNAP 2.2.7 ,TRACE v5.0p4, and FRAPTRAN v1.4 were used in this methodology.
2. TRACE results were similar to VSC-17 data. It indicates that TRACE has the respectable accuracy in the simulation and analysis of the dry-storage systems
3. In the accident analysis of Kuosheng NPP dry-storage system, there are safety concerns only in the fully-covered case and the cladding temperature took 19.2 days to reach the safety criteria.
4. The pressures inside the steel canister were always lower than the design limit in the cases of this study.
5. According to the results of FRAPTRAN, it indicated that the integrity of cladding was not kept after 23 days for fully-covered case.

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10. SUPPLEMENTARY NOTES
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11. ABSTRACT (200 words or less)
The dry-storage systems of nuclear power plants (NPPs) in Taiwan have become one of the major safety concerns. This research focuses on the development of Kuosheng NPP (BWR/6) dry-storage system TRACE/SNAP model. There are two steps in this research. The first step is the verification of TRACE/SNAP dry-storage model by using VSC-17 experimental data. By using VSC-17 data, VSC-17 dry-storage system was established by TRACE/SNAP. Then, the analysis results of TRACE were compared with VSC-17 data. The results of TRACE were similar to VSC-17 data. It indicates that TRACE has the respectable accuracy in the simulation and analysis of the dry-storage systems. The next step is the application of TRACE in the dry-storage system of Kuosheng NPP. Kuosheng NPP is the second BWR NPP of Taiwan Power Company. In order to solve the storage of the spent fuels, Taiwan Power Company developed the new dry-storage system for Kuosheng NPP. In this step, the dry-storage system model of Kuosheng NPP was established by TRACE/SNAP. Then, the steady state simulation of this model was performed and the results of TRACE were compared with Kuosheng NPP data. The results of TRACE in the steady state calculation were consistent with Kuosheng NPP data. Finally, this model was used to perform the safety analysis of Kuosheng NPP dry-storage system. Besides, FRAPTRAN code was used to calculate the transient performance of fuel rods.

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