JAEA-Research
2007-070

JAEA-Research

Application of Tritium Behavior Simulation Code (TBEHAVIOR) to an Actual-Scale Tritium Handling Room

Yasunori IWAI, Takumi HAYASHI
Kazuhiro KOBAYASHI and Toshihiko YAMANISHI

Tritium Technology Group
Fusion Research and Development Directorate

November 2007

Japan Atomic Energy Agency

日本原子力研究開発機構

JAEA-Research 2007-070

Application of Tritium Behavior Simulation Code (TBEHAVIOR) to an Actual-Scale Tritium Handling Room

Yasunori IWAI, Takumi HAYASHI, Kazuhiro KOBAYASHI and Toshihiko YAMANISHI

Division of Fusion Energy Technology,
Fusion Research and Development Directorate,
Japan Atomic Energy Agency
Tokai-mura, Naka-gun, Ibaraki-ken

（Received July 25, 2007）

It is essential from the viewpoint of fusion safety to confine and remove tritium in a room since tritium handling room is placed as ‘final barrier’ of fusion plant to prevent the environmental discharge of tritium. At the Tritium Process Laboratory (TPL) of Japan Atomic Energy Agency (JAEA), the application of our original three-dimensional TBEHAVIOR code to the tritium behavior in a room of 3000 m^3 was verified. The Renormalization Group Theory (RNG) model was selected as Low-Reynolds model for practical calculation time as well as to reasonable precision in evaluation of velocity from the engineering viewpoint. A series of evaluated results indicated that a flow adjacent to a wall surface plays an important role for tritium transport in a ventilated room. Evaluation of attenuating behavior is further important since the ventilation is normally stopped for the tritium confinement in the case of tritium leakage. We demonstrated that an attenuating behavior can also be evaluated well by the TBEHAVIOR code. Even an attenuating or stagnant flow of less than 10mm/s in a room mixed tritium concentration uniform promptly. The presence of apparatuses in a room did not generally affect tritium behavior. Although the effect of buoyancy was limited to the initial period after the leak, the spread of tritium was promoted by buoyancy. It led to the shortening of elapsed time until the concentration became uniform.

Keywords: Fusion, Tritium, Safety, Confinement, Final Barrier, Simulation

JAEA-Research　2007-070

トリチウム挙動シミュレーションコード（TBEHAVIOR）の実規模トリチウムハンドリング建屋への適用性

日本原子力研究開発機構　核融合研究開発部門
核融合エネルギー工学研究開発ユニット
岩井 保則、林 巧、小林 和容、山西 敏彦

（2007年7月25日 受理）

核融合プラントにおいてトリチウムハンドリング建屋はトリチウムの環境放出を防ぐ最終障壁となる。核融合安全性の見地からは建屋内にトリチウム閉じ込め、除去することは不可欠となる。日本原子力研究開発機構トリチウム工学研究グループは開発を進めてきた三次元トリチウム挙動シミュレーションコード（TBEHAVIOR）の3000㎥の実規模トリチウムハンドリング建屋への適用性の実証を行った。評価精度と計算時間短縮の両立性を模索した結果、低レイノルズモデルとして繰り込み群モデルを選択した。実験との比較から換気された建屋内のトリチウム輸送には壁近傍の流れが重要な役割をしていることを見いだした。またトリチウム漏洩時には閉じ込めのため建屋換気を停止した場合の建屋内の減衰流れによるトリチウム輸送評価も重要となる。実験との比較からTBEHAVIORコードは減衰流れの評価にも有効であることを示し、10mm/s程度の流れにてトリチウムはすみやかに輸送されることを見いだした。また建屋内の機器群はその存在を詳細に反映せずとも実用的な挙動概略の把握はできることを示した。大量漏洩時の浮力効果は主に漏洩初期に限定されるが、濃度が均一となるまでの時間を短縮する効果があることを示した。

原子力科学研究所（駐在）：〒319-1195　茨城県那珂郡東海村白方白根2-4

Contents

目次

Table Lists

Figure Lists

1. **Introduction**

A feature of fusion site is that fusion tritium fuel will be handled in a broad area of the site. The site inventory of tritium will reach a few kilograms. Radiological safety for workers and for surroundings is thus the most important matter for consideration. Only a small number of tritium research facilities for fusion fuel handling are dotted in the world. In the facilities, tritium has been handled safely with the common multiple confinement concept. In the concept, each confinement barrier has individual confinement and detritiation system to confine and remove tritium efficiently in case of an accidental tritium leakage. There are some limited data on tritium confinement and detritiation up to secondary confinement such as gloveboxes and hoods 1)-3). Only a little fragmentary data on tritium confinement and detritiation in final confinement such as tritium handling rooms is reported as incidents though such an accident has not experienced in Japan 4). It is needless to say that the soundness of the confinement and detritiation system for final confinement is an important key for site licensing. Understanding of three-dimensional tritium behavior in a room of a few thousand m^3 or more is thus inevitable matter for the suitable design of the confinement and detritiation system considering an arrangement of tritium monitors and ducts.

From this background, the systematic numerical study on tritium behavior in a room has been conducted at the Tritium Process Laboratory (TPL) of Japan Atomic Energy Agency (JAEA), At the TPL, the Caisson Assembly for Tritium Safety study (CATS) with a $12m^3$ airtight vessel called "Caisson" was also installed to acquire the actual data on tritium behavior in a simulated room5)-10). Our original three-dimensional 'TBEHAVIOR' code has been developed and improved based on the observed data in the Caisson with integrating a lot of tritium related phenomena into the code 11) 12). Tritium behavior in the Caisson has been explainable by the 'TBEHAVIOR' code. A remaining matter for consideration is whether the code is applicable to the tritium behavior even in an actual-scale room of a few thousand m^3 or more.

To verify the application of code to the tritium behavior in an actual room, we confirmed the precision in velocity by the code under gentle ventilation first. A numerical three-dimensional velocity distribution in the ventilated Caisson was compared with corresponding experimental observations. What is further important is an attenuating behavior since the ventilation is stopped for the tritium confinement in the case of an accidental tritium leakage. A numerical attenuating behavior in the Caisson was compared with corresponding experimental observations. The eddy viscosity model was thus scrutinized. Application of the code was furthermore verified by comparison with the data on tritium behavior observed in the radiologically controlled room of 3000 m^3 at Tritium System Test Assembly (TSTA) at the Los Alamos National Laboratory (LANL) under the US - Japan collaboration 13) 14). Three cases of experiments were conducted. In the Case 1, the released point of tritium was a corner of the room to make clear the effect of surrounded apparatuses on the behavior. In the Case 2, tritium was released from almost center of the room where a flow is weak and stagnant. In the Case 3, plenty of deuterium-diluted tritium was released from the same point of Case 2 to investigate the effect of buoyancy on the behavior.

2. TBEHAVIOR Code and Simulated Tritium Handling Rooms

Figure 1 shows a mesh partition model of the Caisson for numerical evaluation 5) 11). Systematic study on tritium behavior in a ventilated Caisson has been conducted to simulate the tritium leakage in a ventilated room 5)-10). Caisson was ventilated by a single exhaust duct and a single supply duct through the ventilation system called air cleanup system (ACS). The ducts projected at 0.09m below the roof. Simulated emergency isolation valve is installed in the ACS line for the demonstration of tritium confinement. Six stationary ion chambers called TM0-TM5 and one movable ion chamber called TM6 were installed in Caisson for tritium concentration monitoring. Nitrogen-diluted tritium filled in the stainless container was remotely released and purged by nitrogen to ensure the tritium was swept from the container. As for the mesh partition shown in Figure 1, the Caisson was divided into 38 meshes in x direction, 43 meshes in y direction and 31 meshes in z direction. The coordinates of ducts and monitors were reported elsewhere11). How the tritium was released into Caisson affected tritium mixing behavior. It was strictly considered using the Residence Time Distribution function 12).

Figure 2 shows a mesh partition model of radiologically controlled 3000m^3 tritium handling room called ‘main cell’ at TSTA in LANL. The room composes of a space of 12.00 m^W, 29.00 m^D and 8.50 m^H and the hollows. It has 3000 m^3 of approximate volume in total. The room was ventilated by six supply ducts and six exhaust ducts. Nine ion chambers were installed in the room for tritium monitoring. In the intended tritium release experiments in the room, tritium was released immediately just after the stop of ventilation. Information on the ventilation condition is listed in **Table 1**. As for the mesh partition model shown in Figure 2, the room was divided into 26 meshes in x direction, 63 meshes in y direction and 30 meshes in z direction. The coordinates of ducts and monitors were listed in **Tables 2 and 3**. Apparatuses in the room were not taken into consideration in the model shown in Figure 2.

The TBEHAVIOR code is based on three-dimensional turbulent flow model 11). The basic equations of the TBEHAVIOR consist of the equations of eddy motions, the continuity equation and diffusive equation. As for the equations of eddy motions, Low-Reynolds model was incorporated in the k-ε equations in order to consider the effect of wall viscosity on the tritium behavior. Four different eddy viscosity models are incorporated in the TBEHAVIOR code, which are Standard [Launder-Spalding] model15), Launder-Sharma model16), Chien model 17) and Renormalization Group Theory (RNG) model18).

3. Results and Discussion

3.1 Precision in velocity evaluated by TBEHAVIOR code

Figure 3 shows a typical shot of tritium distribution in a ventilated Caisson in case of a tritium leakage. We see from a series of shots that leaked tritium forms a plume and it transfers especially along the flow adjacent to wall surface in a ventilated Caisson. Precision in velocity distribution adjacent to the wall surface is thus important in numerical analysis of tritium behavior. We need to incorporate the Low-Reynolds model in the k-ε equations for this reason. As for the Low-Reynolds model considering the wall viscosity, the adoption of wall functions in the k-ε equations is popular in academic study on turbulence. In this case, we need simultaneously to subdivide the mesh especially adjacent to the wall surface for the ‘wall functions’ to improve the precision of the evaluation. Accordingly, huge numbers of mesh volume were required to apply the model to a large-scale ventilated room and it led to the enormous calculation time to evaluate the tritium behavior in a long haul even though precision in velocity especially adjacent to the wall surface was satisfactory. From the viewpoint of engineering use of a code of this sort, we attach great importance to practical calculation time as well as to reasonable precision in evaluation. To manage both practical calculation time and reasonable precision in evaluation, the RNG model has thus been adopted for eddy viscosity model in our numerical study on the evaluation of tritium behavior since ‘wall functions’ are not incorporated in the RNG model.

As for the validity of RNG model especially for the evaluation of velocity adjacent to the wall surface, **Figure 4** shows a typical observed velocity distribution along x direction in the Caisson under 50m^3/h of ventilation flow rate and the corresponding evaluated results. The velocity distribution was measured by hot-wire anemometers. The velocity distribution, especially adjacent to the wall surface, evaluated by RNG model was consistent well with the experimental observations. The validity of RNG model especially for the evaluation of velocity adjacent to the wall surface was thus verified through a series of comparative study between experimental and numerical11).

As for the evaluation of dynamic behavior of velocity using RNG model, **Figure 5** shows a typical observed attenuation of velocity at (x,y,z = 0.606, 0.585, 2.150) and the corresponding evaluated results after the stop of 50m^3/h ventilation. The attenuating velocity was measured by hot-wire anemometers. The velocity distribution evaluated by RNG model was also consistent well with the experimental observations. The validity of RNG model for the attenuating velocity was thus verified through a series of comparative study.

The study made clear that the flow adjacent to a wall surface plays an important role for the tritium transport in a ventilated room. The Renormalization Group Theory (RNG) model was selected especially for practicable calculation time as well as reasonable precision in velocity especially adjacent to the wall surface. The velocity distribution in a ventilated room as well as the attenuation of velocity was well evaluated by the TBEHAVIOR code.

3.2 Application of the code to the tritium behavior in a fusion plant

A matter for consideration is whether the code is applicable to the tritium behavior even in an actual room of a few thousand m^3 or more. A comparative study on tritium behavior was conducted between experimental observation in the 3000 m^3 room and the corresponding evaluated results.

The graphs (a) and (b) in **Figure 6** show the experimental observation in the Case1 and its corresponding evaluated result, respectively 13). The 3.7×10^{10} Bq of pure tritium was intentionally released from the Point A in Figure 2 with purging by nitrogen gas with the velocity of 0.2 m/s in 10 seconds. The point A is near a corner of the room and some apparatuses were surrounding here. Furthermore, the velocity around the point was stagnant even during ventilation. Since the ventilation was intentionally stopped just before the tritium was released into the room, tritium plume was spread by the ‘attenuating flow’ as well as the purge flow. Tritium behavior leaked from the Point A was thus difficult to evaluate with the code. **Figure 7** shows the particle plots for the visual understanding of evaluated tritium behavior of Case 1. From the comparison between calculated result and experimental observation in Figure 6, the time until all monitors became their uniform values (～2400sec) and stable concentrations (～1.0×10^{7} Bq/m^{3}) were in satisfactory agreement between them. What is significant judging from the numerical results is that even a weak attenuating flow less than 10mm/s after the stop of ventilation made tritium concentration uniform promptly. As for the behavior of RM-9 that was placed at the most distant point from the point A, the behavior was still consistent well. As for the behavior of RM-1 and RM-2 that were close to the point A, each maximum concentration was consistent. Nevertheless, their elapsed time at maximum concentration and subsequent behavior were slightly different. This difference was naturally due to our proposed simulation procedure that the presence of apparatuses in the room was not considered in the mesh partition model. The most important point shown in Figure 6 is that the effect of apparatuses on the tritium behavior was dominant only to a limited area as long as they were not apparent barriers to the movement of tritium plume. The presence of apparatuses did not generally affect tritium behavior since the volumetric ratio of apparatus to the total volume of the room was small. Numerical study on tritium behavior in an actual-scale tritium handling room always gets into difficulty since the calculation time becomes unbearably long due to the subdivided mesh that reflects the presence of apparatuses. The proposed method is not somewhat strict, the result however indicates that the outline of tritium behavior in a room can be practically evaluated. As for the behavior of RM-5, its vibration was in good agreement. The location of RM-5 was near the center of the room and the flow around here was stagnant. This agreement thus shows that the tritium behavior in a room can be practically evaluated by this code.

Tritium release in the stagnant flow is one of the most feasible scenarios as an unexpected tritium leakage. Case 2 was also performed to discuss how the tritium was spread in a stagnant flow. The 3.7×10^{10} Bq of pure tritium was intentionally released from the Point B in Figure 2 with purging by nitrogen gas with the velocity of 0.2 m/s in 10 seconds. The graphs (a) and (b) in **Figure 8** show the experimental observation in the Case 2 and its corresponding evaluated result, respectively[11)]. The time until all monitors became their uniform values (～2400sec) and stable concentrations (～1.0×10^{7} Bq/m^3) were in good agreement between them. Although the stagnant flow further attenuated after the stop of ventilation, tritium was still mixed promptly by the attenuating flow. As for the behavior of RM-9 that was most distant from the point B, the behavior was still consistent well. On the other hand, the tritium behavior at the point close to the leakage is generally difficult to evaluate since an intricate movement of plume just formed should be simulated. We see from Figure 8 that the observed maximum concentrationof RM-5 (1.74×10^{8} Bq / m^3) was well evaluated even though the monitor was the closest from the point B. The behavior of RM-1 and RM-2 was also practically evaluated even with our proposed procedure that the presence of apparatus was not considered in the mesh partition model.

In case of a large amount of tritium leakage, buoyancy due to the large density difference between tritium and atmosphere affects tritium behavior. Case 3 was performed to discuss the effect of buoyancy on tritium behavior. In this experiment, the 3.7×10^{10} Bq of pure tritium was previously diluted by 4 normal liters of deuterium in the tritium container (volume: 2 liters) to simulate a large amount of tritium leakage. The gas was released from the Point B in Figure 2 with purging by nitrogen gas with the velocity of 4.07m/s in 300 seconds. The graphs (a) and (b) in **Figure 9** show the experimental observation in the room and its corresponding evaluated result, respectively [14)]. The time until all monitors became their uniform values (～600sec) and stable concentrations (～1.0×10^{7} Bq/m^3) were in good agreement between them. The outline of tritium behavior was practically evaluated by the proposed method judging from the behavior of each monitor. Although the effect of buoyancy was limited to the initial period after the release, the spread of tritium was promoted by buoyancy. It led to the shortening of elapsed time until the concentration became uniform.

The evaluation of tritium behavior in a ventilated 3000 m^3 room were consistent with the experimental observations in all our planned cases. The preceding results prove that the ‘TBEHAVIOR’ becomes a practical code to evaluate leaked tritium behavior in a room of a few thousand m^3 or more.

4. Conclusions

The application of three-dimensional TBEHAVIOR code to the tritium behavior in a room of 3000 m^3 was verified. The conclusions are as follows.

1) A series of evaluated results indicated that a flow adjacent to a wall surface plays an important role for tritium transport in a ventilated room. The Renormalization Group Theory (RNG) model was selected as Low-Reynolds model for practical calculation time as well as to reasonable precision in evaluation of velocity from engineering viewpoint.
2) Evaluation of attenuating behavior is important since the ventilation is normally stopped for the confinement in the case of an accidental tritium leakage. An attenuating behavior can also be evaluated well by RNG model.
3) The effect of apparatuses on tritium behavior was dominant only to a limited area as long as they were not apparent barriers to the movement of tritium plume. The presence of apparatuses did not generally affect tritium behavior since the volumetric ratio of apparatus to the total volume of the room was small.
4) Even an attenuating or stagnant flow of less than 10mm/s in a room mixed tritium concentration uniform promptly.
5) Although the effect of buoyancy was limited to the initial period after the release, the spread of tritium was promoted by buoyancy. It led to the shortening of elapsed time until the concentration became uniform.

Acknowledgements

Cooperation of all TPL staffs and TSTA staffs are gratefully acknowledged.

References

1) Final Safety Analysis Report of Tritium Systems Test Assembly at the Los Alamos National Laboratory, Los Alamos National Laboratory, TSTA-SAR, 1996.
2) Y. Naruse, Y. Matsuda, K. Tanaka, Tritium Process Laboratory at the JAERI, *Fusion Eng. Des.,* **12**, 293 (1990).
3) P. Schira, E. Hutter, G. Jourdan, R. Penzhone, The Tritium Laboratory Karlsruhe: Laboratory design and equipment, *Fusion Eng. Des.*, **18**, 19 (1991).
4) J. R. Bartlit, J. L. Anderson, R. A. Jalbert, , R. V. Carlson, K. Okuno, T. Ide, H. Fukui, M. Enoeda , Y. Naruse, Dispersion and Removal of Tritium Released into the Main Cell of TSTA, *Proc. of 13th SOFE, Knoxville, TN., U. S. A.,* 798 (1989).
5) T. Hayashi, K. Kobayashi, Y. Iwai et al., "Tritium behavior in the Caisson, a simulated fusion reactor room", *Fusion Eng. Des.*, **51-52**, 543 (2000).
6) K. Kobayashi, T. Hayashi, Y. Iwai, M. Nishi: *Proceeding of the Specialist Research Meeting on Environmental Behavior of Hydrogen Isotopes,* Research Reactor Institute Kyoto Univ., KURRI-KR-53, 10 (1999), [In Japanese].
7) K. Kobayashi, T. Hayashi, Y. Iwai, M. Nishi, "Results of experimental study on detritiation of atmosphere in large space", *Fusion Eng. Des.*, **58-59**, 1059 (2001).
8) K. Kobayashi, T. Hayashi, Y. Iwai, N. Asanuma, M. Nishi, "Tritium Behavior Study for Detritiation of Atmosphere in a Room", *Fusion Sci. Technol.*, **41**, 673 (2002).
9) T. Hayashi, K. Kobayashi, Y. Iwai, M. Nishi: *Proceeding of the International Workshop on Environmental Behavior and Biological Effects of Tritium,* Research Reactor Institute Kyoto Univ., KURRI-KR-61, 125 (2000).
10) T. Hayashi, K. Kobayashi, Y. Iwai, N. Asanuma, S. O’hira, M. Nishi, "Tritium Confinement Demonstration Using Caisson Assembly fro tritium Safety Study at TPL/JAERI", *Fusion Sci. Technol.*, **41**, 647 (2002).
11) Y. Iwai, T. Hayashi, T. Yamanishi, K. Kobayashi and M. Nishi, "Simulation of Tritium Behavior after Intended Tritium Release in Ventilated Room," *J. Nucl. Sci. Technol.*,**38** , 63 (2001).
12) Y. Iwai, T. Hayashi, K. Kobayashi and M. Nishi, "Simulation study of intentional tritium release experiments in the caisson assembly for tritium safety at the TPL/JAERI," *Fusion Eng. Des.*, **54**, 523 (2001).

13) T. Hayashi, K. Kobayashi, Y. Iwai, T. Yamanishi, M. Nishi, K. Okuno, R. V. Carlson, R.S. Willms, D. Hyatt, B. Roybal : Tritium Behavior Intentionally Released in the Radiological Controlled Room under the US-JAPAN Collaboration at TSTA/LANL, *Fusion Thecnol.,***34** , 521 (1998).

14) K. Kobayashi, T. Hayashi, S. O'hira, M. Nishi, R. V. Carlson, R.S. Willms, D. Hyatt: *Proceeding of the Scientific Meeting on Behavior and Distributions of Radionuclides Related to Health Physics and Chemical Speciations and Kinetic Model for Hydrogen Isotope in the Environment,* Research Reactor Institute Kyoto Univ., KURRI-KR-30, 132 (1998), [In Japanese].

15) B. E. Launder and D. B. Spalding, The numerical calculation of turbulence flows, *Comp. Meth. Appl. Mech. Eng.,* **3**, 269 (1974).

16) B. E. Launder and B. I. Sharma, Application of the energy-dispassion model of turbulence to the calculation of flow near a spinning disc, *Letter in Heat and Mass Transfer* **1,** 131 (1974).

17) K. Y. Chien, Prediction of channel and Boundary-layer flows with a low Reynolds number turbulence model, *AIAA J.* **20,** 33 (1982).

18) V. Yakhot, S. A. Orgazag: *J. Sci. Comput.* , **1**, (1986), 3.

Table 1 Ventilation conditions of TRE at the TSTA in LANL

	Before TRE	After TRE started
	Flow rate [m^3/s] (velocity [m/s])	Flow rate [m^3/s] (velocity [m/s])
Supply Duct	0.743 / each duct (3.000)	0 (0)
Exhaust Duct	1.082 / each duct (5.176)	0 (0)
Through the joints between roof and walls	1.356	0
Through the holes on the walls	0.678	0

Table 2 Locations of ducts in the Main Cell of TSTA

	x [m]	y [m]	z [m]
Supply Duct 1	7.60	4.53	4.00
Supply Duct 2	7.60	8.46	4.00
Supply Duct 3	7.60	12.49	4.00
Supply Duct 4	7.60	16.51	4.00
Supply Duct 5	7.60	20.40	4.00
Supply Duct 6	7.60	24.47	4.00
Exhaust Duct 1	1.60	4.53	8.50
Exhaust Duct 2	1.60	8.46	8.50
Exhaust Duct 3	1.60	12.49	8.50
Exhaust Duct 4	1.60	16.51	8.50
Exhaust Duct 5	1.60	20.40	8.50
Exhaust Duct 6	1.60	24.47	8.50

Table 3 Locations of release points and tritium monitors in the Main Cell of TSTA

	x [m]	y [m]	z [m]
Tritium Release Point A	1.95	15.21	0.75
Tritium Release Point B	-3.15	0.50	-1.22
RM 1	-0.50	6.60	3.68
RM 2	-2.30	9.30	-0.62
RM 3	-3.90	12.30	3.48
RM 4	3.70	5.90	0.78
RM 5	1.40	14.40	0.78
RM 6	5.02	5.18	0.66
RM 7	3.90	21.40	3.08
RM-8	-2.40	0.50	-1.22
RM-9	7.10	25.00	0.28

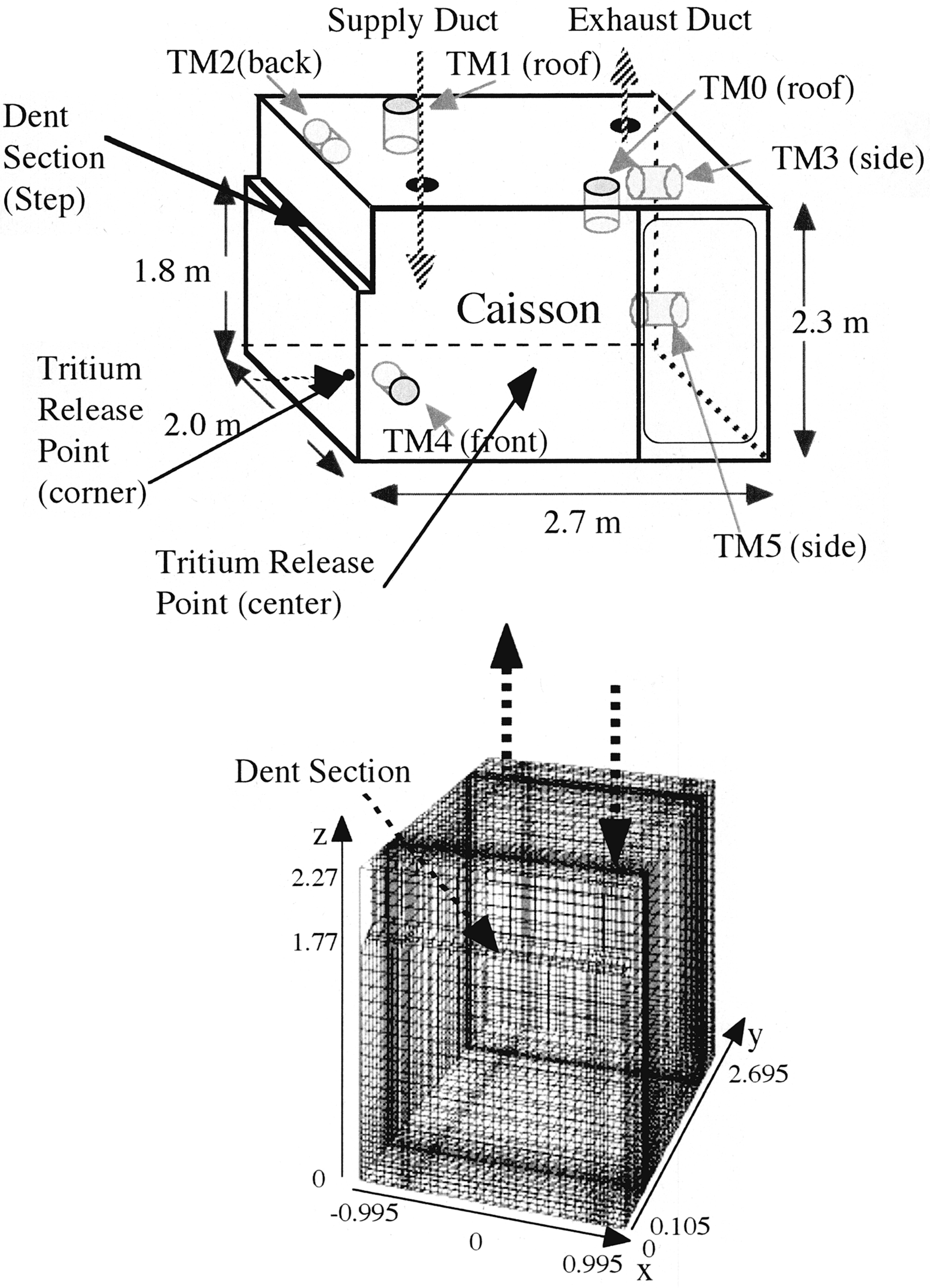


Figure 1 Mesh partition of the Caisson

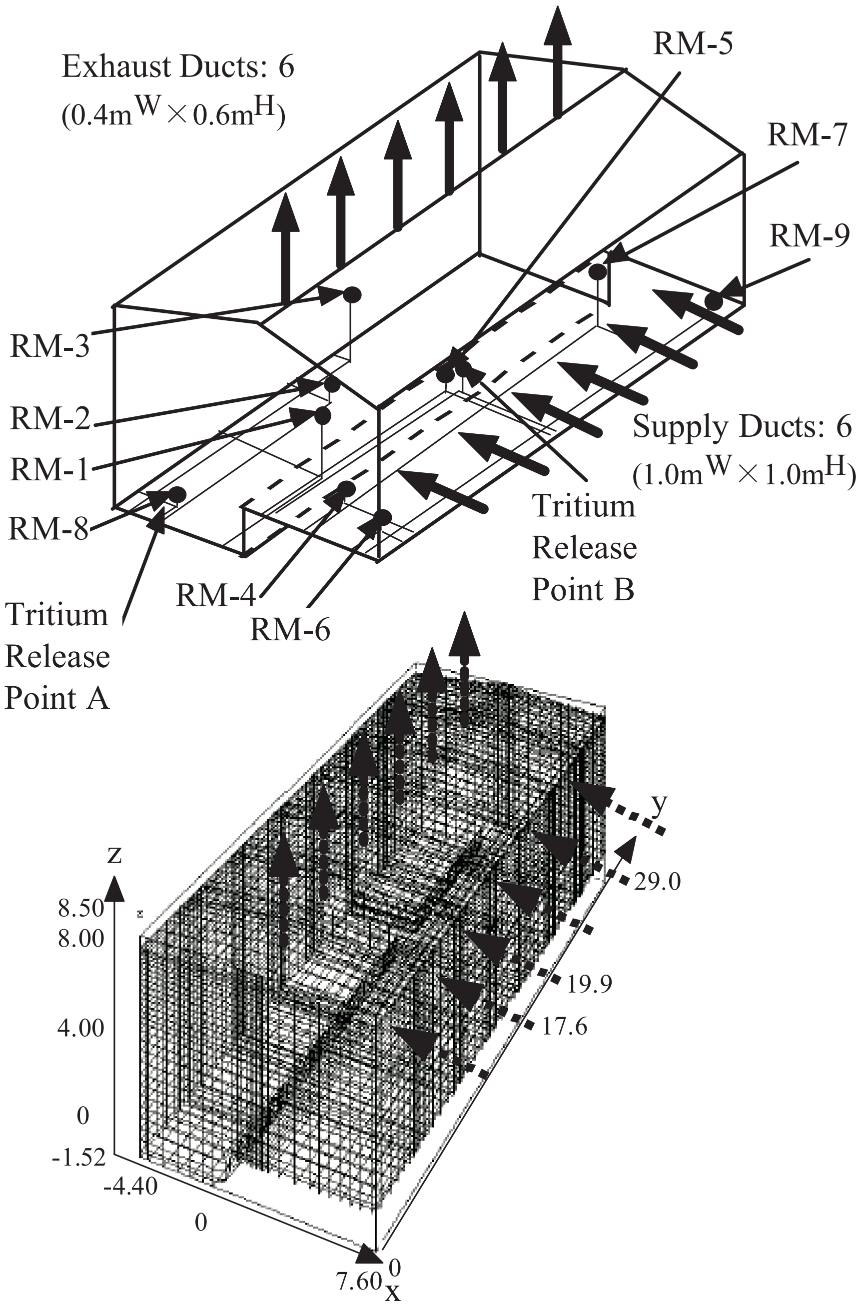


Figure 2　Mesh partition of the TSTA “Main Cell”

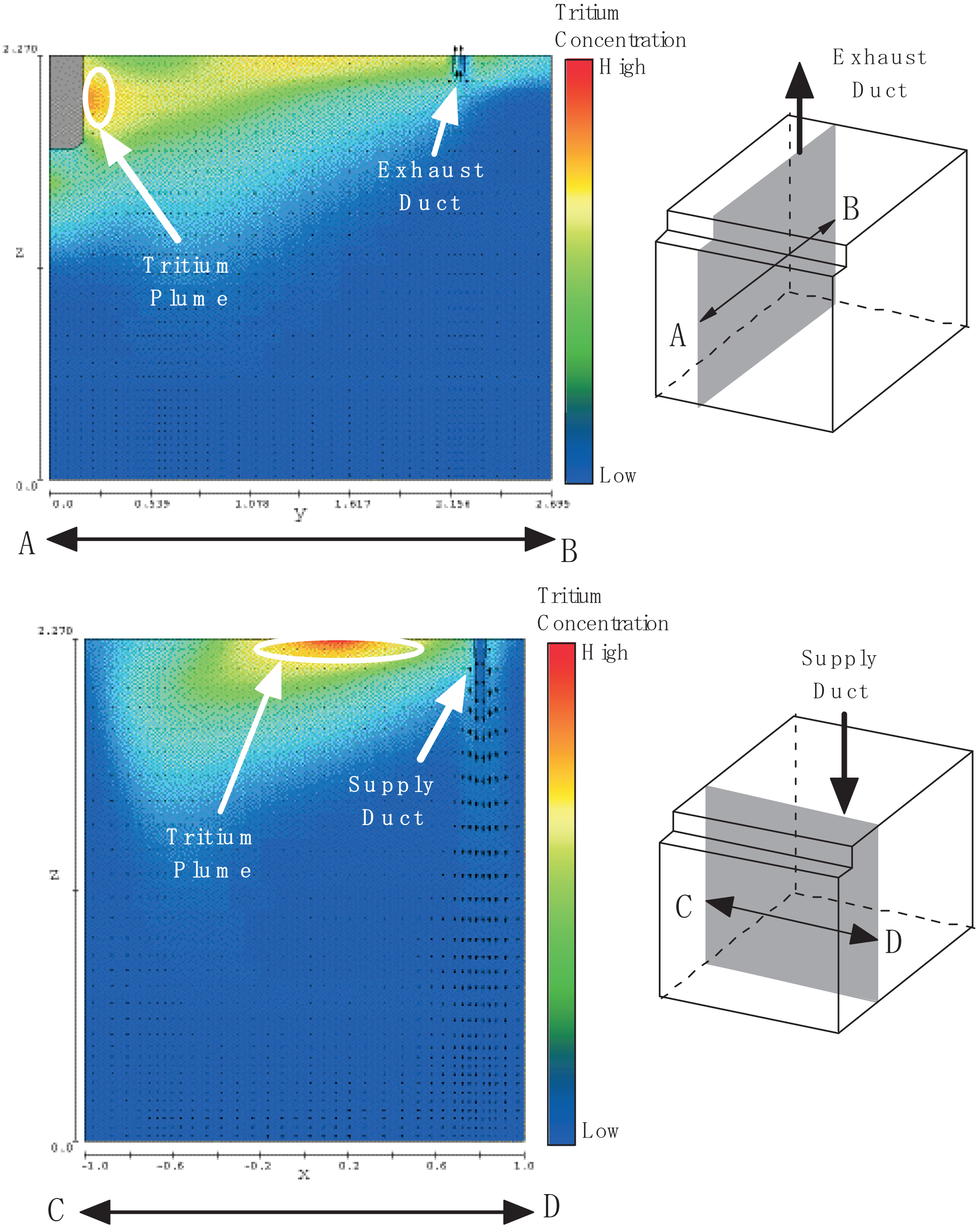


Figure 3 Typical shot of tritium distribution in a ventilated Caisson

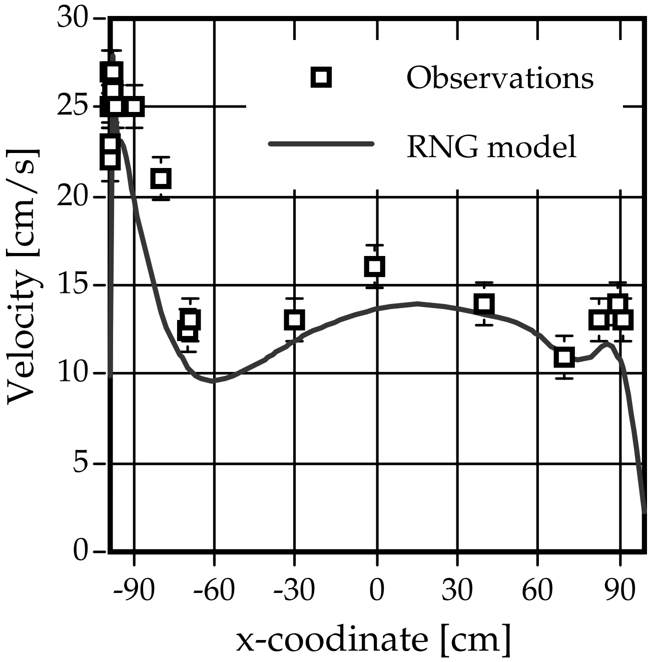


Figure 4　Observed velocity distribution along x direction in the Caisson and the corresponding evaluated results

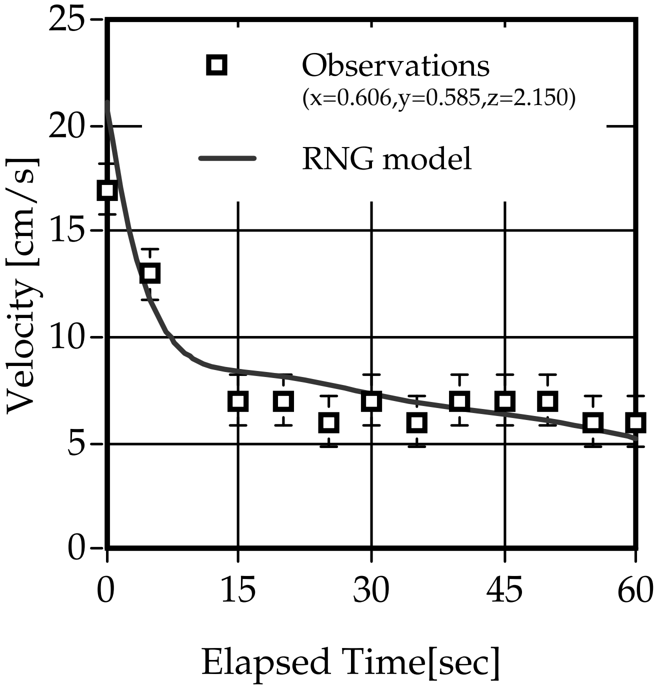


Figure 5　Observed attenuation of velocity and the corresponding evaluated results after the stop of ventilation

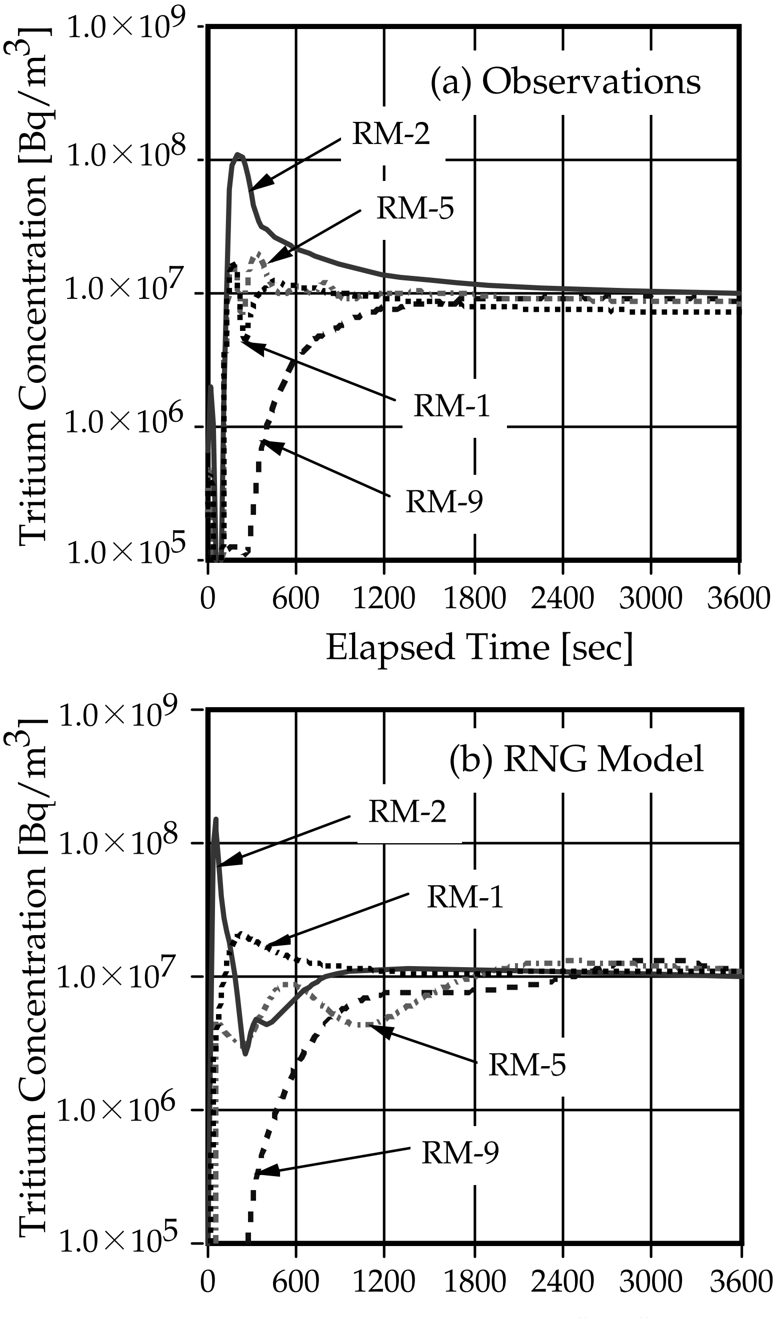
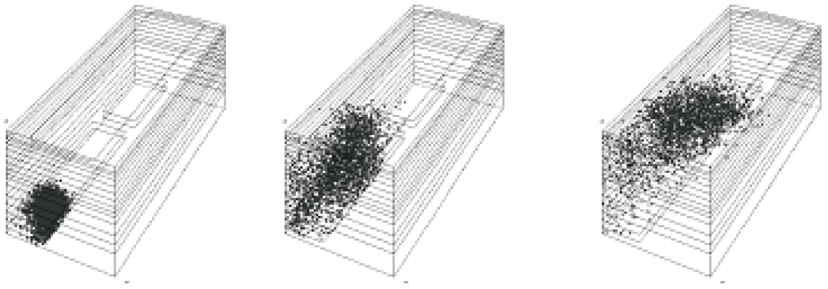


Figure 6　Experimental observation in the Case 1
and its corresponding evaluated result



10 sec 50 sec 100 sec

Figure 7 Particle plot of tritium for the visual understanding of tritium behavior in the first TRE

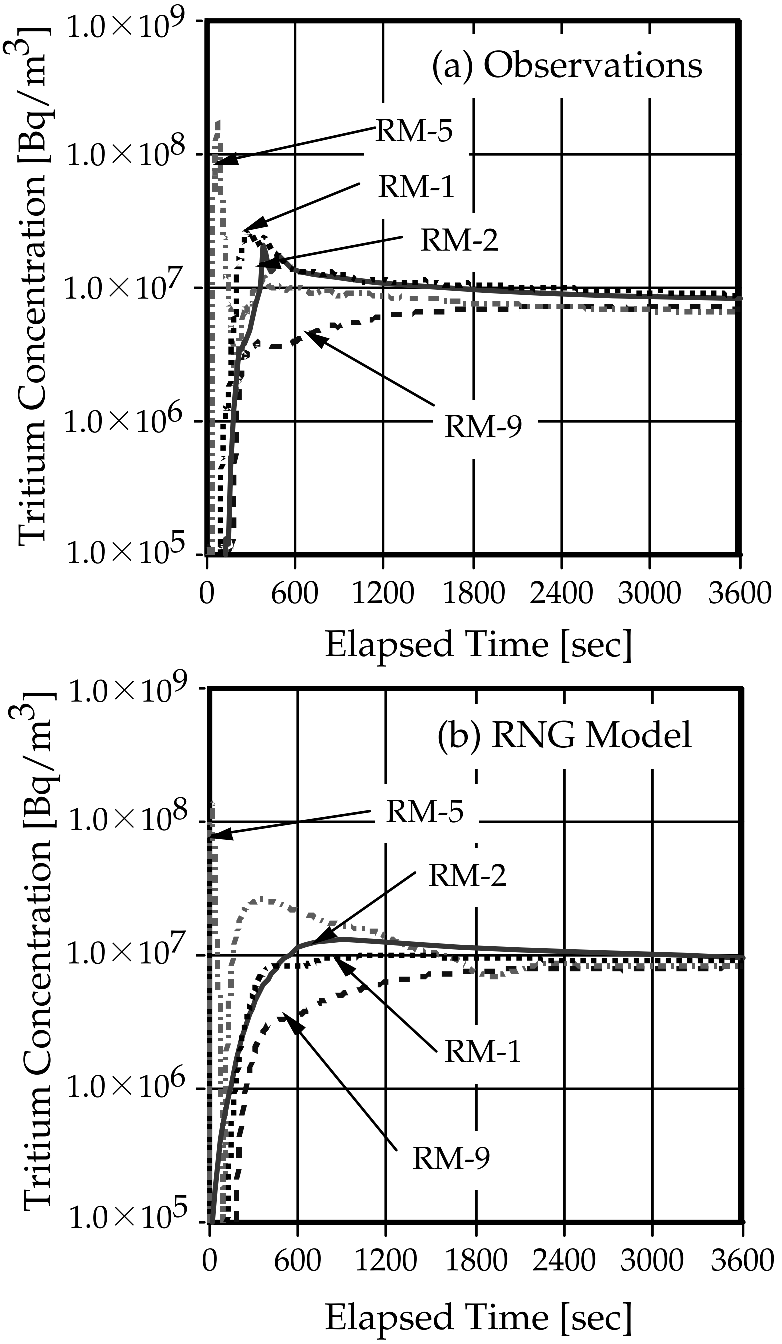


Figure 8　Experimental observation in the Case 2
and its corresponding evaluated result

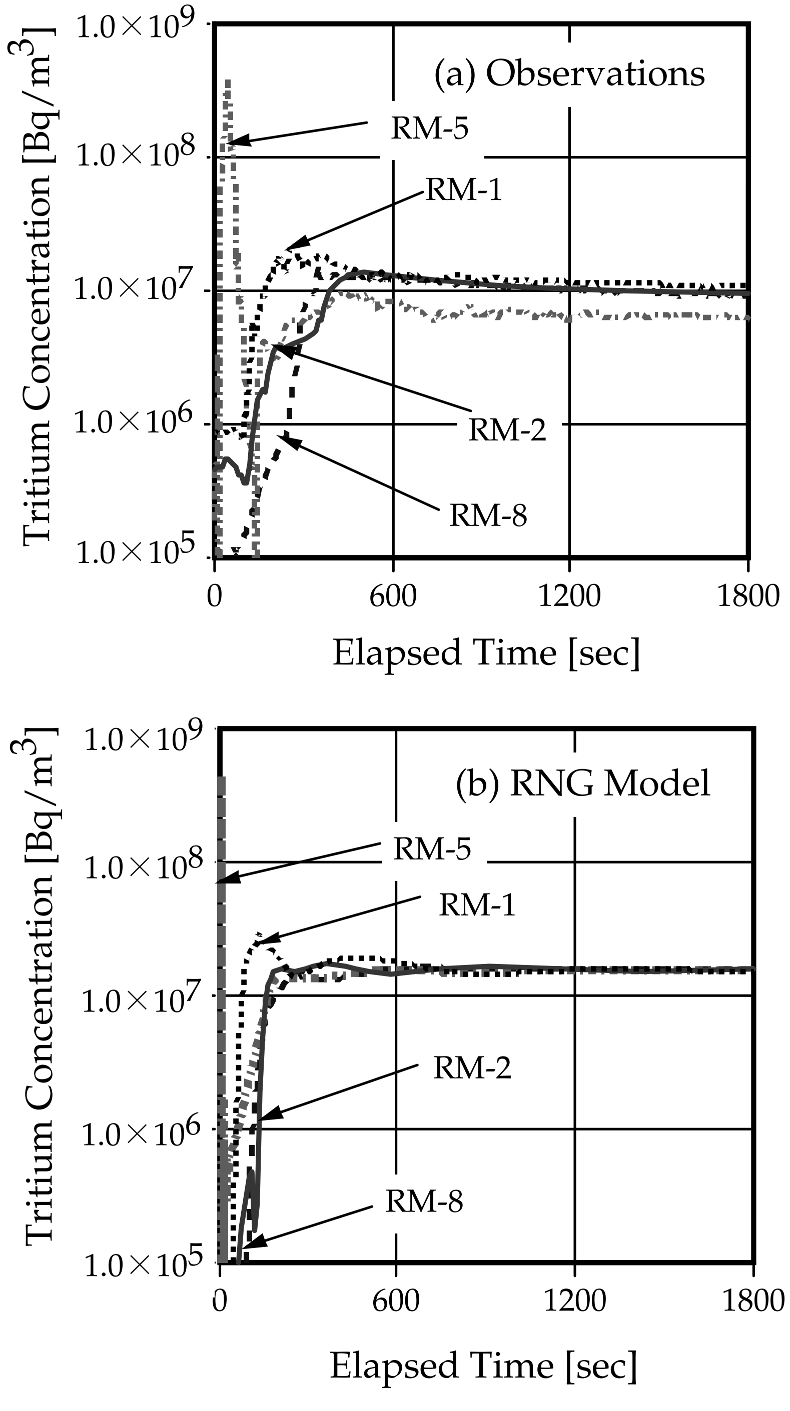


Figure 9 Experimental observation in the Case 3 and its corresponding evaluated result

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m^2
体積	立法メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m-1
密度（質量密度）	キログラム毎立法メートル	kg/m^3
質量体積（比体積）	立法メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
（物質量の）濃度	モル毎立方メートル	mol/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率	（数の）1	1

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表３．固有の名称とその独自の記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン(a)	rad		$m\cdot m^{-1}=1$(b)
立体角	ステラジアン(a)	sr(c)		$m^2\cdot m^{-2}=1$(b)
周波数	ヘルツ	Hz		s^{-1}
力	ニュートン	N		$m\cdot kg\cdot s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\cdot kg\cdot s^{-2}$
エネルギー，仕事，熱量	ジュール	J	$N\cdot m$	$m^2\cdot kg\cdot s^{-2}$
工率，放射束	ワット	W	J/s	$m^2\cdot kg\cdot s^{-3}$
電荷，電気量	クーロン	C		$s\cdot A$
電位差（電圧），起電力	ボルト	V	W/A	$m^2\cdot kg\cdot s^{-3}\cdot A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\cdot kg^{-1}\cdot s^4\cdot A^2$
電気抵抗	オーム	Ω	V/A	$m^2\cdot kg\cdot s^{-3}\cdot A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\cdot kg^{-1}\cdot s^3\cdot A^2$
磁束	ウエーバ	Wb	$V\cdot s$	$m^2\cdot kg\cdot s^{-2}\cdot A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\cdot s^{-2}\cdot A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\cdot kg\cdot s^{-2}\cdot A^{-2}$
セルシウス温度	セルシウス度(d)	℃		K
光束	ルーメン	lm	$cd\cdot sr$(c)	$m^2\cdot m^{-2}\cdot cd=cd$
照度	ルクス	lx	lm/m^2	$m^2\cdot m^{-4}\cdot cd=m^{-2}\cdot cd$
（放射性核種の）放射能	ベクレル	Bq		s^{-1}
吸収線量，質量エネルギー分与，カーマ	グレイ	Gy	J/kg	$m^2\cdot s^{-2}$
線量当量，周辺線量当量，方向性線量当量，個人線量当量，組織線量当	シーベルト	Sv	J/kg	$m^2\cdot s^{-2}$

(a) ラジアン及びステラジアンの使用は、同じ次元であっても異なった性質をもった量を区別するときの組立単位の表し方として利点がある。組立単位を形作るときのいくつかの用例は表４に示されている。

(b) 実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号“１”は明示されない。

(c) 測光学では、ステラジアンの名称と記号srを単位の表し方の中にそのまま維持している。

(d) この単位は、例としてミリセルシウス度m℃のようにSI接頭語を伴って用いても良い。

表４．単位の中に固有の名称とその独自の記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	$Pa\cdot s$	$m^{-1}\cdot kg\cdot s^{-1}$
力のモーメント	ニュートンメートル	$N\cdot m$	$m^2\cdot kg\cdot s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\cdot s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\cdot m^{-1}\cdot s^{-1}=s^{-1}$
角加速度	ラジアン毎平方秒	rad/s^2	$m\cdot m^{-1}\cdot s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\cdot s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\cdot kg\cdot s^{-2}\cdot K^{-1}$
質量熱容量（比熱容量），質量エントロピー	ジュール毎キログラム毎ケルビン	$J/(kg\cdot K)$	$m^2\cdot s^{-2}\cdot K^{-1}$
質量エネルギー（比エネルギー）	ジュール毎キログラム	J/kg	$m^2\cdot s^{-2}\cdot K^{-1}$
熱伝導率	ワット毎メートル毎ケルビン	$W/(m\cdot K)$	$m\cdot kg\cdot s^{-3}\cdot K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\cdot kg\cdot s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\cdot kg\cdot s^{-3}\cdot A^{-1}$
体積電荷	クーロン毎立方メートル	C/m^3	$m^{-3}\cdot s\cdot A$
電気変位	クーロン毎平方メートル	C/m^2	$m^{-2}\cdot s\cdot A$
誘電率	ファラド毎メートル	F/m	$m^{-3}\cdot kg^{-1}\cdot s^4\cdot A^2$
透磁率	ヘンリー毎メートル	H/m	$m\cdot kg\cdot s^{-2}\cdot A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\cdot kg\cdot s^{-2}\cdot mol^{-1}$
モルエントロピー，モル熱容量	ジュール毎モル毎ケルビン	$J/(mol\cdot K)$	$m^2\cdot kg\cdot s^{-2}\cdot K^{-1}\cdot mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1}\cdot s\cdot A$
吸収線量率	グレイ毎秒	Gy/s	$m^2\cdot s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\cdot m^{-2}\cdot kg\cdot s^{-3}=m^2\cdot kg\cdot s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\cdot sr)$	$m^2\cdot m^{-2}\cdot kg\cdot s^{-3}=kg\cdot s^{-3}$

表６．国際単位系と併用されるが国際単位系に属さない単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10800) rad
秒	”	1”=(1/60)’=(π/648000) rad
リットル	l、L	$1l=1\ dm^3=10^{-3}m^3$
トン	t	$1t=10^3\ kg$
ネーパ	Np	1Np=1
ベル	B	1B=(1/2)ln10(Np)

表７．国際単位系と併用されこれに属さない単位で
SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位であらわされる数値
電子ボルト	eV	$1eV=1.60217733(49)\times10^{-19}J$
統一原子質量単位	u	$1u=1.6605402(10)\times10^{-27}kg$
天文単位	ua	$1ua=1.49597870691(30)\times10^{11}m$

表８．国際単位系に属さないが国際単位系と
併用されるその他の単位

名称	記号	SI 単位であらわされる数値
海里		１海里=1852m
ノット		１ノット=１海里毎時=(1852/3600)m/s
アール	a	$1\ a=1\ dam^2=10^2m^2$
ヘクタール	ha	$1\ ha=1\ hm^2=10^4m^2$
バール	bar	$1\ bar=0.1MPa=100kPa=1000hPa=10^5Pa$
オングストローム	Å	1 Å$=0.1nm=10^{-10}m$
バーン	b	$1\ b=100fm^2=10^{-28}m^2$

表９．固有の名称を含むCGS組立単位

名称	記号	SI 単位であらわされる数値
エルグ	erg	$1\ erg=10^{-7}\ J$
ダイン	dyn	$1\ dyn=10^{-5}N$
ポアズ	P	$1\ P=1\ dyn\cdot s/cm^2=0.1Pa\cdot s$
ストークス	St	$1\ St=1cm^2/s=10^{-4}m^2/s$
ガウス	G	1 G ˆ10^{-4}T
エルステッド	Oe	1 Oe ˆ(1000/4π)A/m
マクスウェル	Mx	1 Mx ˆ10^{-8}Wb
スチルブ	sb	$1\ sb=1cd/cm^2=10^4cd/m^2$
ホト	ph	$1\ ph=10^4lx$
ガル	Gal	$1\ Gal=1cm/s^2=10^{-2}m/s^2$

表10．国際単位に属さないその他の単位の例

名称	記号	SI 単位であらわされる数値
キュリー	Ci	$1\ Ci=3.7\times10^{10}Bq$
レントゲン	R	$1\ R=2.58\times10^{-4}C/kg$
ラド	rad	$1\ rad=1cGy=10^{-2}Gy$
レム	rem	$1\ rem=1\ cSv=10^{-2}Sv$
X線単位		$1X\ unit=1.002\times10^{-4}nm$
ガンマ	γ	$1\gamma=1\ nT=10^{-9}T$
ジャンスキー	Jy	$1\ Jy=10^{-26}W\cdot m^{-2}\cdot Hz^{-1}$
フェルミ		$1\ fermi=1\ fm=10^{-15}m$
メートル系カラット		$1\ metric\ carat=200\ mg=2\times10^{-4}kg$
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	
ミクロン	µ	$1\ \mu=1\mu m=10^{-6}m$

（第７版，1998年改訂）