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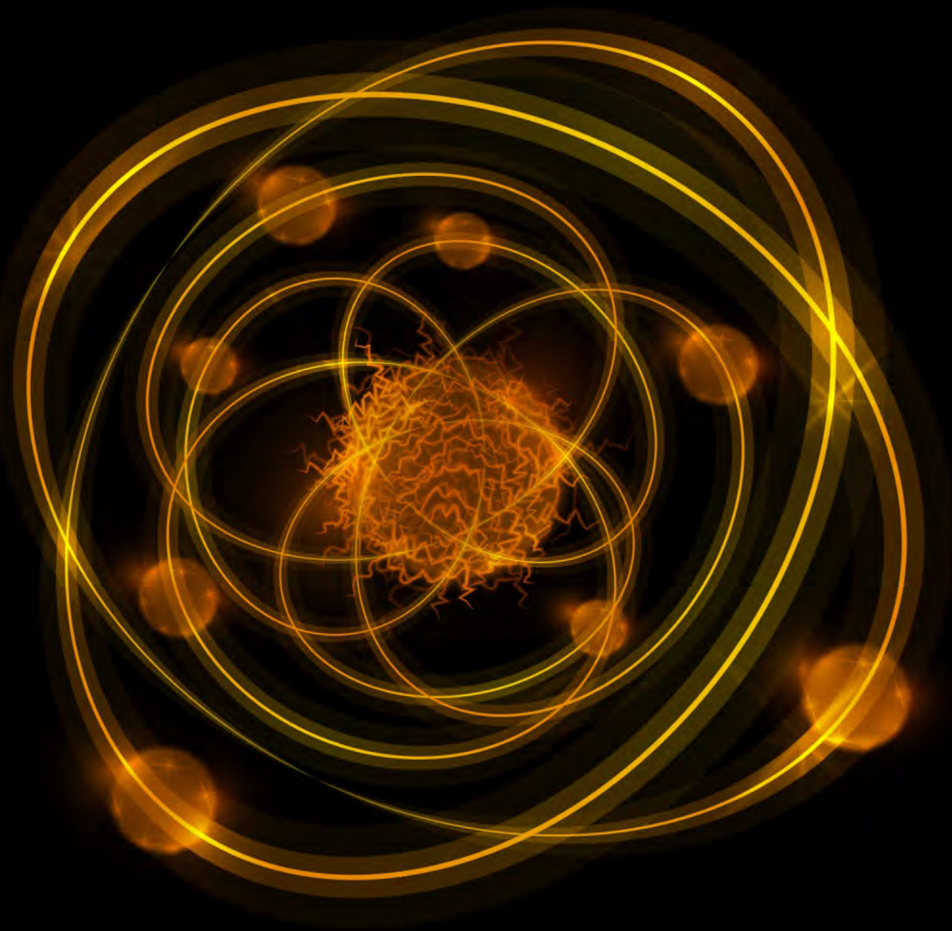

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Development of ToSPACE for Pipe Wall Thinning Management in Nuclear Power Plants

Kyeong Mo Hwang[1], Hun Yun[1], Hyeok Ki Seo[1], Geun Young Lee[2], Kyung Woo Kim[2]

[1]Material Engineering Department, Gimcheon, Korea
[2]ByN Company, Daejeon, Korea
Email: hkm@kepco-enc.com

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Abstract

A number of piping components in the secondary system of nuclear power plants are exposed to aging mechanisms such as FAC (Flow-Accelerated Corrosion), cavitation, flashing, SPE (Solid Particle Erosion), LDIE (Liquid Droplet Impingement Erosion), etc. Those mechanisms may lead to thinning, leak, or rupture of the components. Due to the pipe ruptures caused by wall thinning in Surry unit 2 of USA in 1986 and in Mihama unit 3 of Japan in 1994, the pipe wall thinning management has emerged as one of the most important issues in nuclear power plants. To manage the pipe wall thinning in the secondary system, Korea has used a foreign program since 1996. As using the foreign country's program for long term, it was necessary to improve from the perspective of the users. Accordingly, KEPCO-E & C has started to develop the 3D-based pipe wall thinning management program (ToSPACE, Total Solution for Piping And Component Engineering management) from eight years ago, and the development was successful. This paper describes the major functions included in ToSPACE program, such as 3D-based DB (Database) buildup, development of FAC and erosion evaluation theories, UT (Ultra-sonic Test) data reliability analysis, field connection with 3D, automatic establishment of long-term inspection plan, etc. ToSPACE program was developed to allow site engineers performing the selection of inspection quantity at each refueling outage, UT data reliability analysis, UT evaluation, determination of next inspection timing, identification of the inspecting and replacing components in 3D drawings, etc., to access easily.

Keywords

ToSPACE, Pipe Wall Thinning, Flow-Accelerated Corrosion (FAC), Liquid Droplet Impingement Erosion (LDIE), Reliability Analysis, 3D Management, Long-Term Inspection Plan

1. Introduction

As operating time progresses, carbon steel piping components in the secondary system of nuclear power plants gradually get thinner resulting from aging mechanisms, such as FAC (Flow-Accelerated Corrosion), cavitation, flashing, LDIE (Liquid Droplet Impingement Erosion), and SPE (Solid Particle Erosion). These mechanisms induce the wall thinning of components and finally lead to components rupture [1] [2]. The damages are closely related to fluid such as water or wet steam inside the components. The notable events were the pipe ruptures in Surry unit 2 in 1986 and in Mihama unit 3 in 1994. Those events evoked several casualties and economic damage.

As of 2018, a total of 24 nuclear power plants are operating in Korea. The secondary side piping in the Korean nuclear power plants has also experienced the pipe wall thinning events and, as operating time increases, the events are expected to increase gradually. To manage the pipe wall thinning, there have been several programs for pipe wall thinning management so far such as CHECWORKS program of USA, BRT-CICERO program of France, and COMSY program of Germany. Korea has used the CHECWORKS program since 1996. However, a number of site engineers have advised to develop our own program considering the site applicability to get rid of the inconvenience of users. Accordingly, KEPCO-E&C started to develop a 3D-based pipe wall thinning management program called ToSPACE (Total Solution for Piping And Component Engineering management) from 2013 after collecting opinions from site engineers and launched the program at the end of 2016. This paper describes major functions included in ToSPAEC, which are different from the existing foreign programs.

2. Major Functions of ToSPACE

2.1. Introduction of ToSPACE

ToSPACE is an engineering software for managing the wall thinning phenomenon that occurs in the piping of nuclear, fossil, and combined thermal power generation plants. It includes detailed functions for overall pipe wall thinning management such as susceptibility analysis for selecting target systems and lines, 3D modeling and DB buildup, wall thinning prediction, inspection data analysis, and establishment of long-term inspection plan. By using this program, it is possible to generate DB simultaneously with 3D modeling, and predict various thinning mechanisms, such as FAC, LDIE, SPE, cavitation, and flashing. Also, reliability analysis of a large number of inspection data is possible, and the next inspection timing reflecting the evaluation result of inspection data is automatically determined. The results of the prediction and inspection data evaluation are automatically fed back to long-term inspection plan. The major functions of ToSPACE are as follows:

- Management of plant operating information and design data
- Susceptibility analysis of systems and lines

- DB buildup at the same time of 3D construction
- Water chemistry analysis for heat balance cycle
- Network analysis of pipelines
- Thermal hydraulic analysis
- Wall thinning analyses for FAC, LDIE, SPE, cavitation, and flashing
- Feedback of wall thinning prediction and inspected data evaluation results to susceptibility analysis
- Identification of the wall thinning prediction results on 3D
- Inspected data reliability analysis
- Wear and wear rate analysis using inspected data
- Calibration of wall thinning prediction results
- Identification of inspected and replaced locations on 3D
- Establishment of long term inspection plan

Subsequently, some of the key functions listed above are described in detail.

2.2. Susceptibility Analysis

Susceptibility analysis is the process of selecting systems and lines operated under conditions where wall thinning can occur in the entire plant systems and lines. The susceptibility analyses in ToSPACE are performed first for systems and then line susceptibility analysis is performed for the selected systems. Variables that are considered in the system susceptibility analysis include the safety related, personnel hazard, power generation, event experience, etc., and users can change the variables. Variables that are considered in the line susceptibility analysis include the fluid phase, event experience by aging mechanism, installation of orifices or control valves, noise of pipeline, operating temperature, flow velocity, dissolved oxygen, etc., and users can also add or delete the variables.

The susceptibility analysis in ToSPACE utilizes system and line list that are prepared at the stage of design. Once the form is extracted from the susceptibility analysis window of ToSPACE, the susceptible systems and lines are selected when selecting a list corresponding to the selection criteria and importing the form into ToSPACE. The wall thinning mechanism affecting the pipeline is unknown during susceptibility analysis, but once the wall thinning analysis, the subsequent module, has been performed, the results are fed back to determine the wall thinning mechanisms and the wear rate of the pipeline. **Figure 1** shows an example of susceptibility analysis screen. In the figure, the left side is the system susceptibility analysis screen, and the right side is the line susceptibility analysis screen.

2.3. 3D DB Construction

To manage the pipe wall thinning, a component database of target systems and pipelines susceptible to thinning should be constructed. The number of target components that need to be managed per unit reaches 20,000, including the large and small bore piping, and the number of data to be entered in a program is about one million. Making this data to be a database takes a lot of time and effort, and there is a high possibility of human error caused by worker's mistake.

As a way to prevent these problems and facilitate user deployment of database, a 3D-based database-building method was developed and reflected in ToSPACE program. Figure 2 shows an example of a screen that builds a 3D-based database. Namely, once data such as pipe size, thickness, material, pressure, temperature, insulation information, etc. are entered at the starting point where the database is being built, the database is automatically created by connecting pipes on 3D. This approach can reduce human error to a minimum level because users create a database while visually checking the shape of the piping layout. In addition, the installation location of the equipment such as steam generator, turbine, heater, pump, etc. may be placed in the same space coordinates as the site, and once the 3D model has been created, the entire pipeline group may be moved to another location.

2.4. Thermal-Hydraulic Analysis

Thermal-hydraulic analysis means the calculation of heat transfer and fluid flow behavior inside pipelines according to its layout shape, friction loss, and heat transfer characteristics. Although a number of programs are provided to calculate the thermal-hydraulics of fluid flow inside a pipeline, the calculation logic should be included within the program to perform the analysis with ToSPACE,

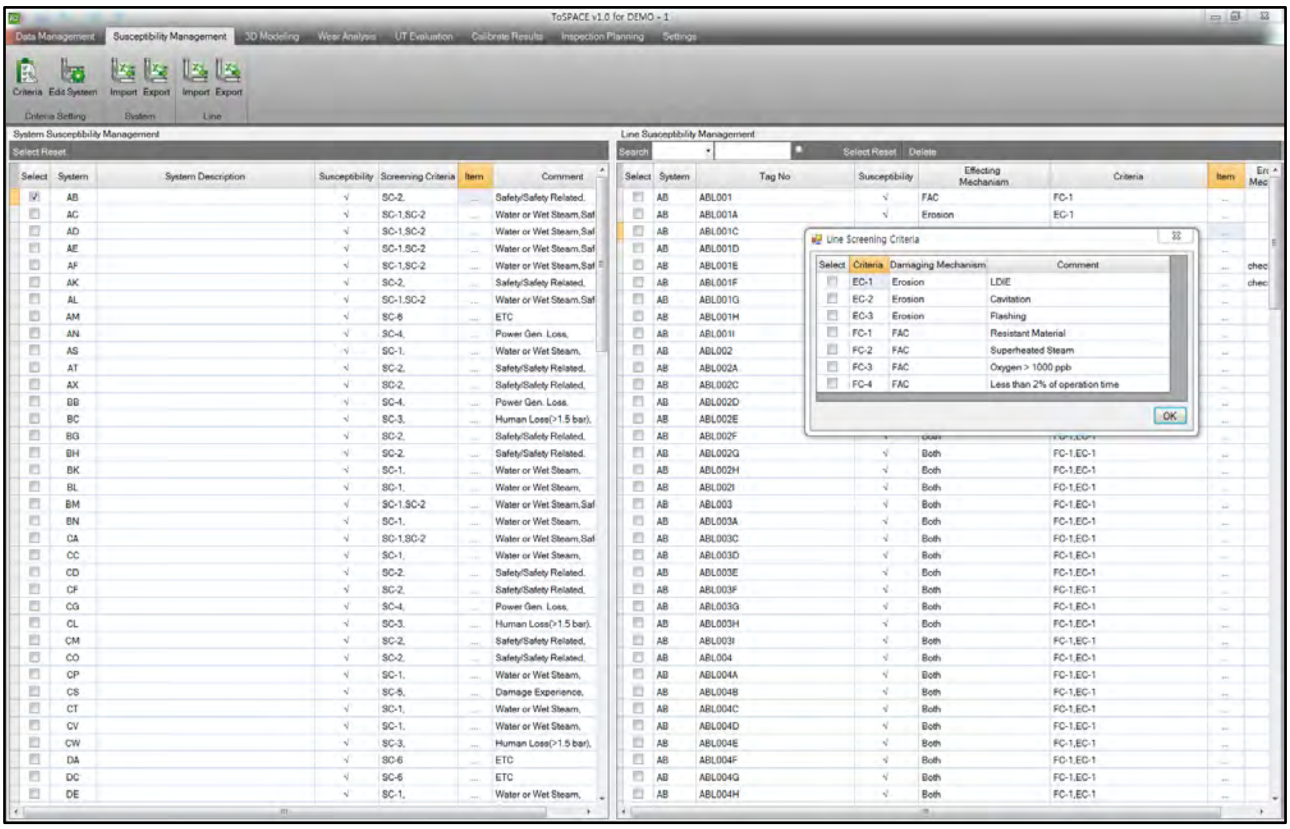

Figure 1. Example of a susceptibility analysis screen.

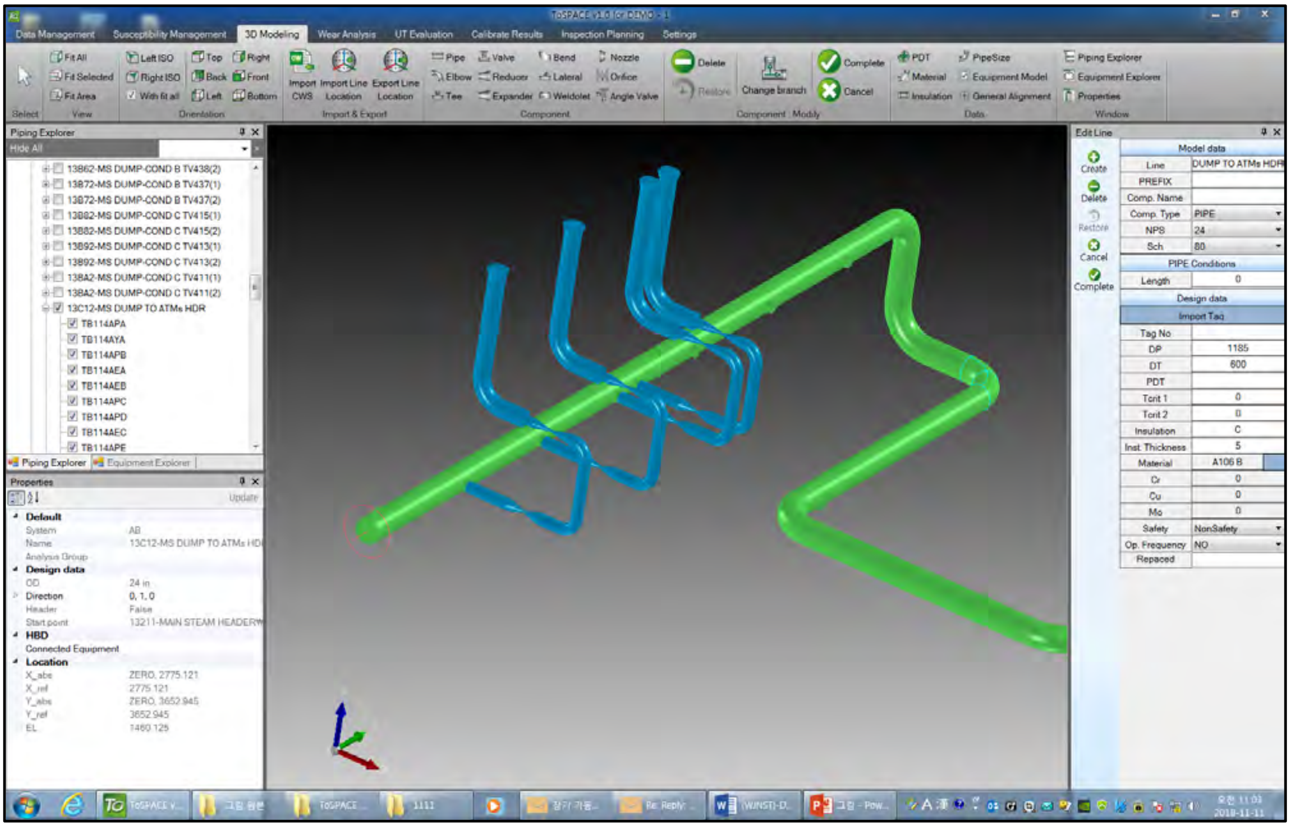

Figure 2. Example of 3D-based database building screen.

and the analysis results should be available as input data for wall thinning analysis such as FAC, LDIE, cavitation, etc.

Accordingly, logic to interpret the thermal-hydraulic characteristics of the single- and two-phase fluid piping and logic to automatically analyze the pipe network (piping layout) were developed. The pipe network analysis logic can maximize the utilization of the program by allowing users to automatically handle the pipe network. Until recently, the users have manually determined the pipe network for thermal-hydraulic analysis in a program. Equations (1) through (4) is the basic formulas for thermal-hydraulic analysis under the condition of single phase fluid [3].

$$\frac{P_{in}}{\rho g}+\frac{v_{in}^2}{2g}+z_{in}=\frac{P_{out}}{\rho g}+\frac{v_{out}^2}{2g}+z_{out}+h_L \tag{1}$$

$$\dot{m}=\rho A v \tag{2}$$

$$h_L=\left(f\frac{L}{d}+K_L\right)\frac{v^2}{2g}, \tag{3}$$

$$\overline{Nu}=\frac{h_i d_i}{k}=0.023Re_D^{4/5}Pr^{0.3}, \tag{4}$$

where $\dot{m}$ is mass flow rate and h_L is head loss. P, v, g, ρ, f, and K_L denote pressure, flow velocity, gravity acceleration, density, friction factor, and total loss coefficient.

Equations (5) through (8) are the basic theoretical formulas applied for the thermal-hydraulic calculation under two-phase fluid conditions [4]. Overall pressure drop can be expressed as a sum of pressure drop due to friction, pressure drop due to density difference at inlet and outlet, and pressure drop due to change in locational energy.

$$\Delta P_{total} = \Delta P_{frict} + \Delta P_{acc} + \Delta P_{static}, \tag{5}$$

$$\Delta P_{frict} = \frac{G^2}{2\rho_{tp}}\left(f_{tp}\frac{L}{d} + K_{total}\right), \tag{6}$$

$$\Delta P_{acc} = G^2\left\{\left(\frac{1}{\rho_{tp}}\right)_{out} - \left(\frac{1}{\rho_{tp}}\right)_{in}\right\}, \tag{7}$$

$$\Delta P_{static} = \rho_{tp} gz \cdot \sin\theta, \tag{8}$$

where G is mass flux and the remaining parameters are identical to them appleid to single-phase fluids.

2.5. FAC Prediction Theory

FAC is a corrosion phenomenon in which the pipe corrosion of carbon steel material is accelerated by fluid flow and is widespread in the secondary side piping of nuclear power plants.

There are several programs that can predict FAC, such as CHECWORKS of USA, BRT-CICERO of France, and COMSY of Germany. FAC prediction theory in CHECWORKS is based on the Chexal-Horowitz equation [5], prediction theory in BRT-CICERO is based on the Sanchez-Caldera equation [6], and FAC prediction theory in COMSY is based on the Kastner-Riedle equation [7].

KEPCO-E & C has developed a Korea's unique FAC prediction theory based on the existing foreign theories, experimental test data, millions of inspection data accumulated over 20 years, and CFD (Computational Fluid Dynamics) analysis results for numerous cases. Equation (9) is the FAC prediction theory that can be applied to single- and two-phase fluid flow.

$$\dot{m}_{FAC} = FG\left(v^{b_1} D_i^{b_2} e^{b_3 + pH} \frac{1}{Cr^{b_4} Cu^{b_5} Mo^{b_6}}\right) \tag{9}$$

F, G (G_A of upstream component, G_B of downstream component) are shown in Equations (10) and (11). $f(T)$, $f(O_2)$, and $f(Q)$ are the function of temperature, dissolved oxygen, and steam quality. v is flow velocity and D_i is inside diameter. b_1 through b_6, A_1, α, t_1, and y_0 in Equation (12) are constants.

$$F = f(T)\cdot f(O_2)\cdot f(Q) \tag{10}$$

$$G_B = G_A + \frac{G_A' \cdot g(x)}{10 \cdot y_0}, \tag{11}$$

$$g(x) = A_1 \times e^{-\left(\frac{\left(\frac{L}{D}\right)+\alpha}{t_1}\right)} + y_0 \tag{12}$$

2.6. LDIE Prediction Theory

Liquid droplet impingement erosion (LDIE) is an erosion phenomenon that causes the thickness thinning of pipe wall, due to the impact forces caused by the liquid droplets contained in the steam hitting the wall of pipes or the surface of equipment. The prediction models, that can predict the liquid droplet impingement erosion rate theoretically, are Sanchez-Caldera model [8] presented by MIT (Massachusetts Institute of Technology), Heymann model [9] presented by Westinghouse Co., etc. However, none of the models presented above accurately relates to the magnetite (Fe_3O_4) formed on the pipe wall and the liquid film flowing on the magnetite.

Accordingly, KEPCO-E & C has developed a new theoretical formula based on the existing documents, experimental test data, and CFD analysis results for numerous cases, which can be applied to the secondary side piping environment in nuclear power plants [10] [11]. Equation (13) indicates the initiation stage before erosion occurs and Equation (14) indicates the stabilization stage during which erosion occurs at the same time as magnetite dissolving.

$$\dot{m}_i = C_0 \cdot \left(m_d \cdot v_d^2\right)^{\alpha} \cdot N_d \cdot S_m \cdot f\left(AC\right), \tag{13}$$

$$\dot{m}_{LDIE} = C_1 \cdot m_d \cdot v_d^2 \cdot N_d \cdot f\left(Hv\right) \cdot f\left(\theta\right) + \dot{m}_i, \tag{14}$$

Each parameter is described as follows:

$\dot{m}_i$: Mass loss rate at initiation stage, g/cm^2·h

$\dot{m}_{LDIE}$: Mass loss rate at stabilization stage, g/cm^2·h

$C_0 = 1.15 \times 10^{-11}$

$C_1 = 1.0 \times 10^{-12}$

α: Constant (0.2)

m_d : Mass of a droplet, g

v_d : Velocity of droplets, m/s

N_d : Number of droplets

S_m : Solubility of magnetite, g/m^3

$f\left(T\right)$: Temperature correction factor

$f\left(AC\right)$: Alloy content correction factor

$f\left(Hv\right)$: Vickers hardness correction factor

$f\left(\theta\right)$: Collision angle correction factor

2.7. SPE Prediction Theory

Solid particle erosion differs from liquid droplet impingement erosion in that the pipe wall thickness is thinned due to the collision of solid particles, not liquid droplets. Generally, it is easy to think that solid particles do not exist because the systems in nuclear power plants are operated in clean conditions. Due to the feature of operation of the systems such as the steam generator blow down system and raw water recirculation system, it is highly probable that the systems will contain fine solid particles. Solid particles can also be generated by fine particle removal by valve or pump operation and erosion of piping and equipment.

Although the theoretical models for predicting the solid particle erosion are Ian Finnie model [12], Kosel model [1], etc., they are not enough to be applied to sites such as nuclear power plants. Accordingly, KEPCO-E&C has developed a new SPE prediction formula based on the experimental test data and CFD analysis results for numerous cases, which can be applied to the secondary side piping environment in nuclear power plants [13].

Equation (15) is applicable to a range between 25˚C and 95˚C of fluid temperature and Equation (16) is applicable to a range between 95˚C and 280˚C of fluid temperature.

$$\dot{m}_{SPE} = \frac{\varphi KRA}{\rho t}\left[B + C_0\left(T - 25\right)\right]\cdot 10^{-4}, \tag{15}$$

$$\dot{m}_{SPE} = \frac{\varphi KRA}{\rho t}\left[B + C_1\left(T - 95\right)\right]\cdot 10^{-4}. \tag{16}$$

where K and R are shown in Equations (17) and (18). $\dot{m}_{SPE}$, φ, T, ρ, t, λ, and d_s are SPE rate (g/cm^2·h), collision angle, temperature, density, operating time, inverse time constant, and particle size. And, A, B, C_0, C_1 are experimental constants.

$$K = 245.71\cdot\ln\left(t - \lambda\right) - 165.54, \tag{17}$$

$$R = 0.9277\cdot\ln\left(d_s\right) + 3.4038. \tag{18}$$

2.8. UT Data Reliability Analysis Method

When a nuclear power plant is operated for a long period of time, the thickness of its secondary side piping may gradually become thinner under high temperature and high velocity fluids, and may eventually rupture. To prevent this damage, the utilities periodically measure the thickness of a certain amount of piping and evaluate the thinning conditions, and repair or replace them if necessary. As the UT evaluation methods for assessing the pipe wall thinning state, there are band method, blanket method, point to point method, etc. However, if there is even one error data among the many thickness data about 100 or 250 obtained for each pipe opening, the reliability of the UT evaluation result to determine the next inspection timing and the remaining life may be problematic.

Accordingly, KEPCO-E & C has developed two UT data reliability analysis methods: SAM (Square Average Method) for one inspection and Multi-SAM methods for over two inspections, which can be applied before performing the UT evaluation [14]. SAM method is to compare one point with the surrounding eight points as shown in **Figure 3** and Equation (19).

$$\alpha x_{(i,j)} \ge \frac{1}{8}\left\{x_{(i-1,j-1)} + x_{(i,j-1)} + \cdots + x_{(i,j+1)} + x_{(i+1,j+1)}\right\}, \tag{19}$$

where α denotes weight factor, i and j are grid coordinates, and x denotes pipe wall thickness at a point.

Multi-SAM method is applied to a component inspected over twice. First, the thickness change rate (x^*) by inspection timing is calculated and the occurrence

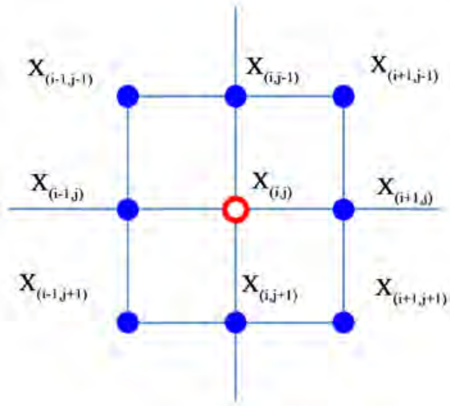

Figure 3. SAM method.

probability of x^* is a method of analyzing reliability through three sigma method as shown in Equation (20).

$$x^* = \frac{\left\{\left(T_{cur} - T_{pre}\right)/T_{pre}\right\} \times 100}{\text{Operating Time}}, \tag{20}$$

where x^* denotes the thickness change rate (%/year). T_{cur} is current inspection thickness and T_{pre} is previous inspection thickness. Operating time means the time difference between the previous inspection timing and current inspection timing.

2.9. UT Evaluation Method

UT evaluation methods are a way to assess the condition of pipe wall thickness. EPRI (Electric Power Research Institute) of the United States suggested several UT evaluation methods such as band method, blanket method, point to point method, etc.

Band method compares the maximum and minimum thicknesses in the circular direction of the inspected pipe with the data measured once. Blanket method compares the maximum and minimum thicknesses among the data set of blanket type with the data measured once. The blanket is then moved to another location on the piping component and the process is repeated. However, the disadvantage of these methods is that they do not reflect its thickness deviation that could exist in the piping from the time of its manufacture. Point to point method is to determine the wear rate at a same point by dividing the differential thickness into the operating time when inspecting the same pipe more than once. This method uses only two inspection data, even though it has been measured several times, and uses a point with a large thickness difference among the total data, so the data for which no thinning occurs can be determined by the typical wear rate of the inspected piping component.

Accordingly, KEPCO-E & C has developed two UT evaluation methods: E-Cross method applicable to a data set inspected only once and M-PTP method applicable to data sets inspected more than once, which can reflect the manufacturing characteristics of pipe and determine the representative wear rate of an inspected piping component at which the actual thinning occurs. As shown in Table 1 and Equation (21), the wear determined by E-Cross method is the difference between the maximum thickness of the average thickness in rows and columns at minimum thickness and the minimum thickness, except for the total of nine data from (D, 8) to (F, 10) including the smallest of the data and the surrounding eight data in the entire data set.

$$\text{Wear} = \max\left(\text{raw avg., column avg.}\right) - t_{\min}. \tag{21}$$

To apply the M-PTP Method, all the average values of nine data set from the final inspected data set of a piping component should be calculated and then identified whether the thinnest point is included in the minimum value's grid range of the nine data set. If the thinnest point is included in the minimum value's grid range of the nine data set, the represented wear is determined to be the maximum thickness difference among the nine points. If not, the representative wear is determined by the difference between the thickest value at the minimum value's grid range and the thinnest value among all thickness values of the inspected piping component. This method is to perform the UT evaluation in the area where the actual thinning occurs.

2.10. 3D Management

In operating nuclear power plants, the thicknesses of a given amount of the piping components are inspected for managing piping wall thinning on an overhaul basis. To inspect the pipe wall thickness, the works such as selection of inspecting components, identification of installed location at a site, installation and removal of scaffolding should be performed in advance of UT inspection. To perform these works, it is necessary to identify the exact location of the piping components in a plant and to determine whether the inspections have been performed and the piping components have been repaired or replaced.

Table 1. Application example of E-Cross Method.

	A	B	C	D	E	F	G	H	I	J	K	L	Avg.
1	0.565	0.524	0.48	0.466	0.46	0.451	0.5	0.542	0.591	0.602	0.57	0.566	0.526
2	0.574	0.539	0.51	0.454	0.417	0.453	0.477	0.530	0.585	0.61	0.588	0.579	0.526
3	0.577	0.545	0.497	0.441	0.438	0.463	0.489	0.541	0.574	0.607	0.583	0.578	0.528
4	0.592	0.549	0.497	0.424	0.436	0.475	0.497	0.543	0.583	0.605	0.579	0.577	0.530
5	0.583	0.551	0.507	0.433	0.447	0.472	0.506	0.540	0.593	0.601	0.547	0.573	0.529
6	0.589	0.537	0.506	0.443	0.433	0.467	0.489	0.536	0.619	0.594	0.530	0.582	0.527
7	0.571	0.531	0.504	0.443	0.423	0.454	0.498	0.556	0.607	0.577	0.533	0.582	0.523
8	0.565	0.530	0.495	0.432	0.412	0.454	0.500	0.560	0.607	0.582	0.556	0.586	0.553
9	0.566	0.537	0.492	0.429	**0.409**	0.455	0.485	0.549	0.601	0.586	0.567	0.586	0.552
10	0.574	0.531	0.47	0.431	0.421	0.450	0.491	0.550	0.589	0.579	0.568	0.598	0.550
11	0.575	0.533	0.447	0.437	0.443	0.453	0.495	0.532	0.575	0.575	0.563	0.598	0.519
12	0.551	0.503	0.457	0.464	0.450	0.464	0.481	0.498	0.565	0.563	0.539	0.585	0.510
Avg.	0.574	0.534	0.489	0.445	0.439	0.461	0.492	0.540	0.591	0.590	0.560	0.583	

Since ToSPACE program was developed on a 3D basis, the installed location and the status of inspection or replacement in the past can be confirmed in three dimensions. Figure 4 shows an example of 3D display included in ToSPACE. The piping components have been developed to work in conjunction with the 3D function, so design and operating information, inspection and replacement information, and thinned status can be easily identified with the naked eyes and work plans in a site can be easily established.

2.11. Analysis Automation

In the past, it took a lot of manpower and time to manually designate the type of analytical pipelines and to set various analysis conditions step by step for performing the water chemistry analysis, network flow analysis, and wear rate analysis.

On the contrary, ToSPACE simultaneously performs the several types of analyses, such as chemistry analysis, network flow analysis, and FAC, LDIE, cavitation, and flashing analyses after entering the boundary conditions at the inlet and outlet with the pipeline group to be analyzed on 3D. Accordingly, users can access the program with much convenience and significantly reduce the analysis time. Figure 5 shows an example screen that sets the boundary condition for the wear rate analysis using ToSPACE. Figure 6 shows an example of the wear rate analysis result. On screen, the red color indicates the piping components with high wear rate while the yellow color means the low wear rate components.

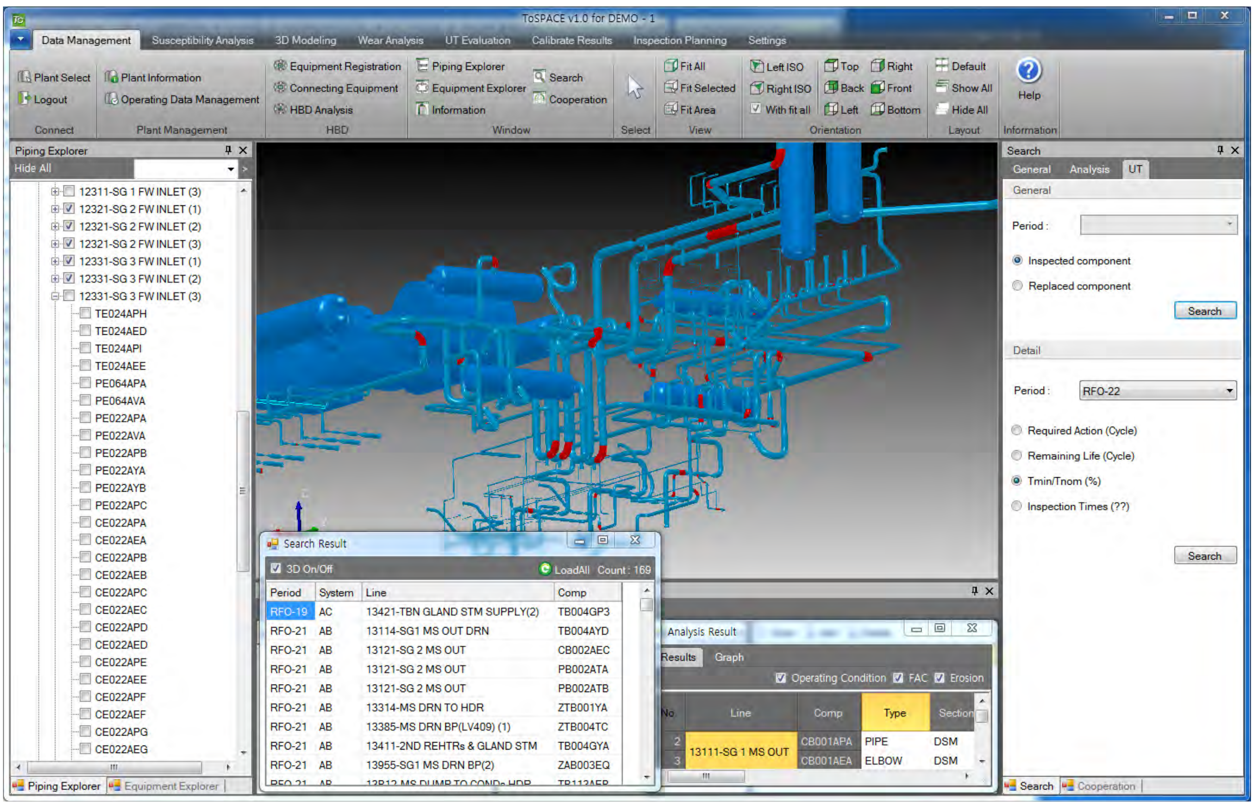

Figure 4. 3D display included in ToSPACE.

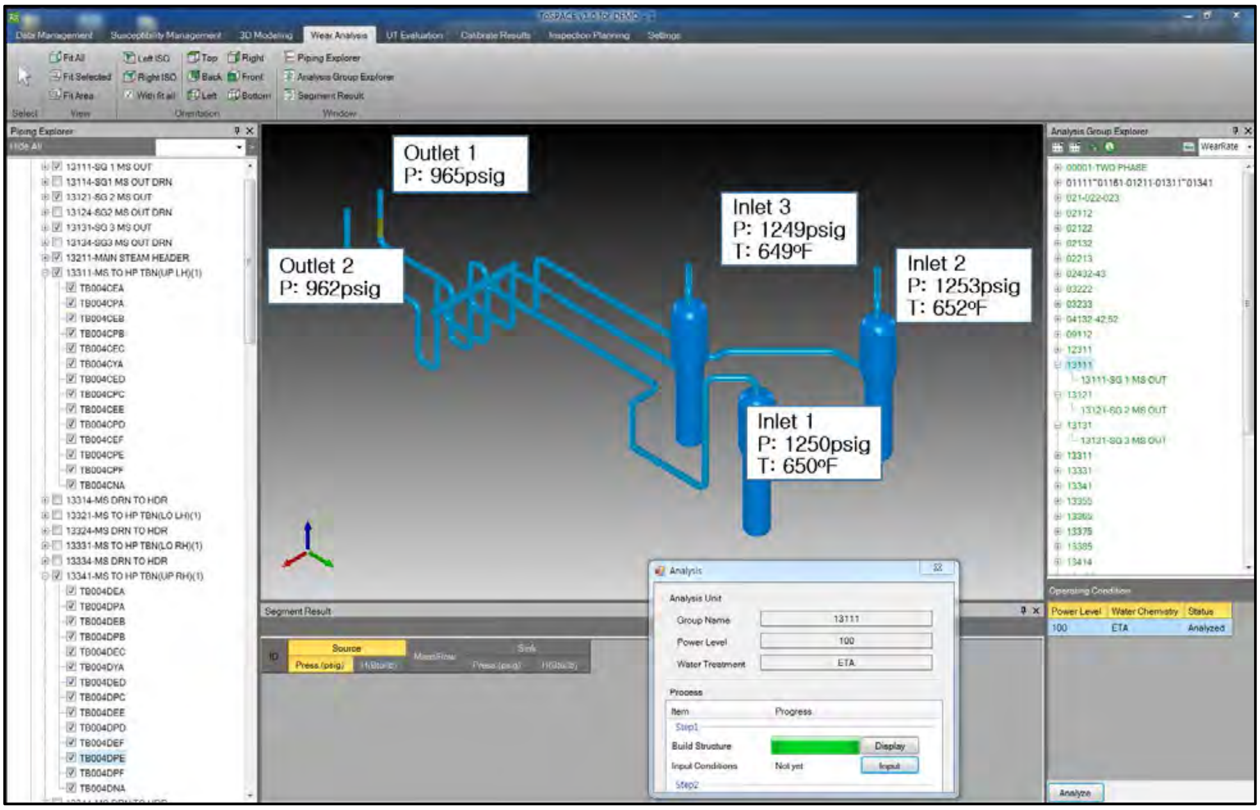

Figure 5. Display for boundary condition setting.

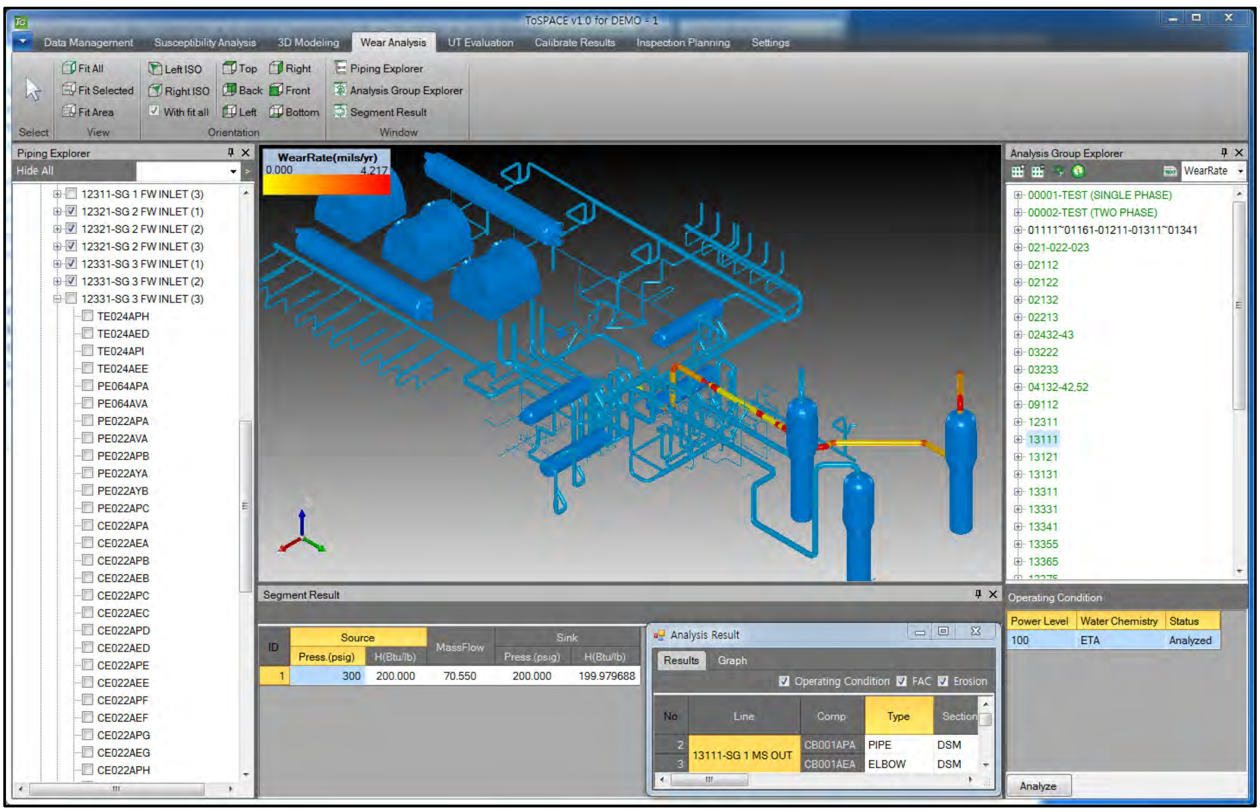

Figure 6. Display of wear rate analysis result.

2.12. Automatic LTIP Establishment

Until now, the site engineers in charge of the pipe wall thinning management have manually established a long-term inspection plan referring to the wear rate analysis result. This was one of the hardest works for site engineers because it took a lot of time requiring a considerable engineering judgment.

Accordingly, the functions establishing the long-term inspection plan (LTIP) and selecting the inspecting components by operating cycle were developed and loaded into ToSPACE program with logic that was clicked or automatically established in the program. The procedure for selecting the inspecting components by operating cycle is as follows:

1) Click manually on 3D for RC (Regulatory Comment of a regulatory body) locations

2) Click manually on 3D for OE (Other-plant Experience) locations

3) Click manually on 3D for BI (Baseline Inspection) locations

4) Click manually on 3D for EJ (Engineering Judgement) locations

5) Determine automatically within program for UE (UT Evaluation result) locations

6) Determine automatically within program for SIA (Safety Impact Analysis) locations.

Figure 7 shows an example display for the LTIP establishment. The inspecting component determination method based on 6) SIA above is applied to determine newly inspecting components, which determines the target components of inspection based on the results of the risk ranking evaluation by scoring several variables such as nuclear safety, operating frequency, design pressure, design temperature, replacement history, wear evaluation result, UT evaluation result, etc.

The calculation method for selecting inspection components according to SIA method is shown in Equations (22) and (23).

$$T_i = \frac{N_p \times A_i}{\sum_{i=1}^{k} A_i}, \tag{22}$$

$$A_i = N_p \times \vartheta \times f_i \times \frac{N_i - n_i}{\sum_{i=1}^{k} B_i}, \tag{23}$$

where the variables are as follows:

T_i = Number of inspecting components

N_p = Number of determined components for inspection

A_i = Basic value of a pipeline

i = Pipeline number

k = Number of total pipelines

ϑ = Weighting factor

f_i = Factor to reflect inspecting components

N_i = Number of components requiring inspection

n_i = Number of previously inspected components

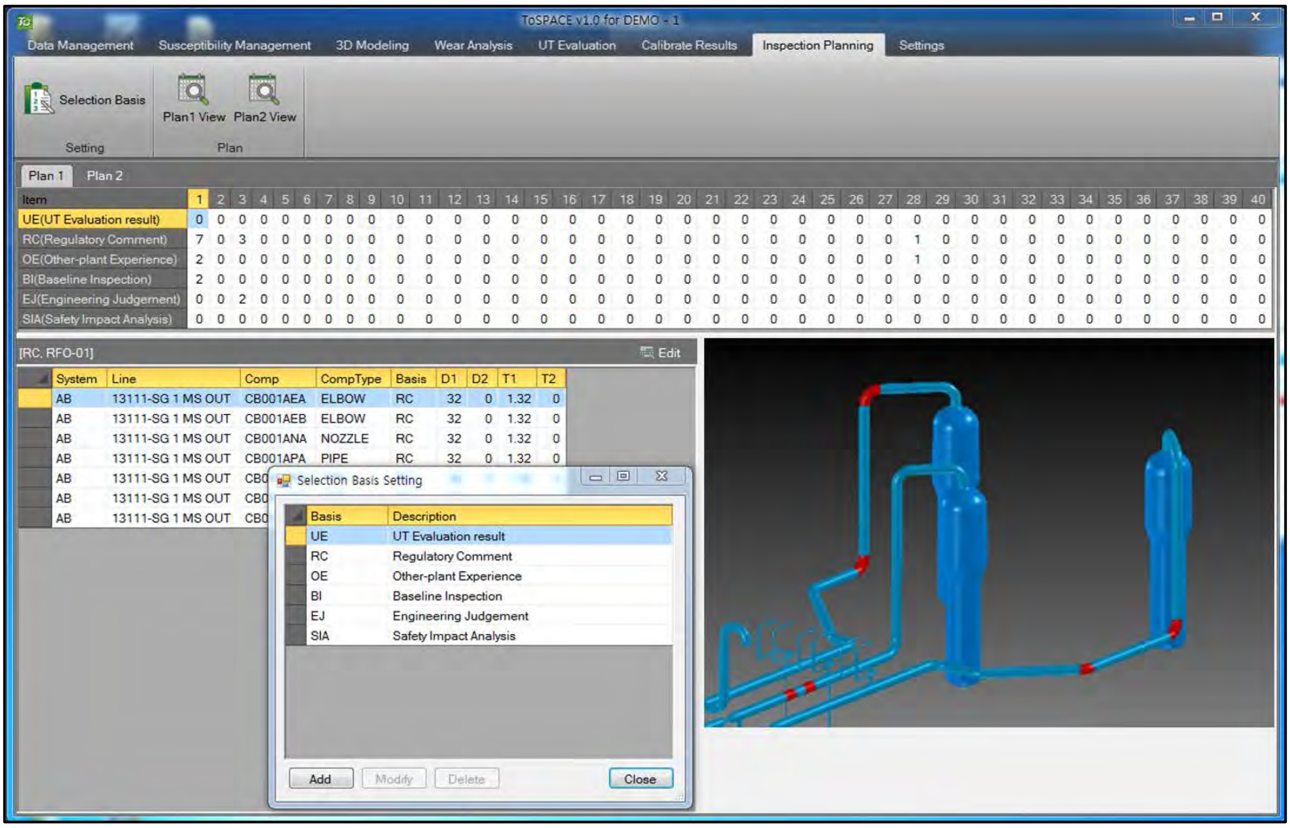

Figure 7. Display for LTIP establishment.

3. Conclusions

For the past 30 years, Korea has used overseas program to manage the pipe wall thinning in nuclear power plants. While the maintenance period in nuclear power plants is getting shorter, the use of the existing program was so complex and took a lot of manpower and time. As the needs to develop a new program that is easily accessible and easy to use by engineers on site were raised, KEPCO-E & C has developed ToSPACE program since 2013.

ToSPACE program allows the site engineers to perform various works, such as susceptibility analysis and selection of inspecting components by operating cycle within the program, and creates a database at the same time as creating a three dimensional drawing. Also, ToSPACE simultaneously performs several types of analysis, such as chemistry analysis, network flow analysis, and FAC, LDIE, cavitation, and flashing analyses after entering the boundary conditions at the inlet and outlet with the pipeline group to be analyzed on 3D. Accordingly, users can access the program with great convenience and significantly reduce the analysis time. The results of wear rate analysis are fed back to the susceptibility analysis and can be automatically reflected in the selection of components to be inspected by operating cycle.

As mentioned above, ToSPACE is a program developed using new concepts that are not implemented by the existing other programs, which can contribute to dramatically reducing the time and effort of the site engineers.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] EPRI (2004) Recommendations for Controlling Cavitation, Flashing, Liquid Droplet Impingement, and Solid Particle Erosion in Nuclear Power Plant Piping Systems. TR-1011231.

[2] Hwang, K.M. (2013) Cause Analysis for the Wall Thinning and Leakage of a Small Bore Piping Downstream of an Orifice. *Corrosion Science and Technology*, **12**, 227-232. https://doi.org/10.14773/cst.2013.12.5.227

[3] Cengel. Y.A. and Cimbala, J.M. (2005) Fluid Mechanics Fundamentals & Applications. McGraw-Hill, New York.

[4] Idelchik, I.E. (2005) Handbook of Hydraulic Resistance. Jaico Publishing House, Mumbai.

[5] EPRI (2012) CHECWORKS™ Steam/Feedwater Application (SFA) Version 4.0. TR-1025251.

[6] Qiu, G., Mansour, C. and Trevin, S. (2013) BRT-CICERO™ Development at EdF: A brief History of Operating Feedback. R&D Programs and Software Improvement, FAC 2013, Avegnon France.

[7] Kastner, W., Erve, M., Henzel, N. and Stellwag, B. (1990) Calculation Code for Erosion Corrosion Induced Wall Thinning in Piping Systems. *Nuclear Engineering and Design*, **119**, 431-438. https://doi.org/10.1016/0029-5493(90)90182-W

[8] Keck, R.G. and Griffith, P. (1987) Prediction and Mitigation of Erosive-Corrosive Wear in Secondary Piping Systems of Nuclear Power Plants. Massachusetts Institute of Technology, NUREG/CR-5007, 1-15.

[9] Heymann, F.J. (1969) High-Speed Impact between a Liquid Drop and a Solid Surface. *Journal of Applied Physics,* **40**, 5113-5122. https://doi.org/10.1063/1.1657361

[10] Hwang, K.M., Lee, C.G., Bhang, K.J. and Yim, Y.S. (2011) A Study on the Design of a Pipe Affected by Liquid Droplet Impingement Erosion. *Journal of Mechanical Science and Technology*, *B*, **35**, 1097-1103.

[11] Hwang, K.M., Seo, H.K., Lee, C.K. and Nam, W.C. (2017) Development of a LDIE Prediction Theory in the Condition of Magnetite Formation on Secondary Side Piping in Nuclear Power Plants. *World Journal of Nuclear Science and Technology*, *B*, **7**, 1-14. https://doi.org/10.4236/wjnst.2017.71001

[12] Levy, A.V. (1995) Solid Particle Erosion and Erosion-Corrosion of Materials. ASM International, Materials Park, Ohio.

[13] Lee, C.K. (2012) Solid Particle Erosion Analytical Approach for Nuclear Power Plants. *Corrosion and Protection*, *B*, **10-11**, 26-31.

[14] Yun, H., Hwang, K.M. and Lee, C.K. (2013) Development of Safety Factors for the UT Data Analysis Method in Plant Piping. *World Journal of Nuclear Science and Technology*, **3**, 143-149. https://doi.org/10.4236/wjnst.2013.34024

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Application of a Mathematical Model to the Sierra Indiana Ore Leaching Process Containing Thorium, by Means of H_2SO_4 Solution and HCl

Pedro Orrego, Peter Fleming, Jorge Skeet, Ramón Ávila

Departamento de Materiales Avanzados, Comisión Chilena de Energía Nuclear, Santiago, Chile
Email: Pedro.orrego@cchen.cl, Peter.fleming@cchen.cl

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Abstract

The existence of the thorium element in the ores from the Atacama region, Chile, and its importance in the activities of the nuclear industry, have generated the interest of the Chilean Nuclear Energy Commission (CChEN) to study the technical feasibility of its recovery, like ThO_2 through the implementation of hydrometallurgical techniques, such as leaching, solvent extraction, among others. The present work has become a report about the research carried out in the Extractive Metallurgy Area of the Department of Advanced Materials of CChEN, whose objective is to know the behavior of the thorium element when the mineral carrier is leached. The leaching tests were carried out in a glass reactor in batch mode, by mechanical agitation, varying different operational parameters, such as: type of leaching solution, concentration of acid in the solution, system temperature and granulometry of the mineral. The results indicate that there is technical feasibility for the recovery of thorium by leaching the mineral carrier with hydrochloric and/or sulfuric solution. The highest recovery of thorium for a sulfuric solution was 70.0% and for a hydrochloric solution of 83.8%, so the process presents a good efficiency in both cases. For a hydrochloric solution, the mathematical model of the thorium recovery efficiency obtained is:

$$Y = 31.14 + 26.25 * X_1 + 8.69 * X_2 - 0.82 * X_3 + 9.5 * X_{12} - 0.83 * X_{13} - 3.71 * X_{23} - 1.83 * X_{123} + 6.46$$

The concentration of HCl and temperature, as well as their interaction, significantly affect the recovery of thorium for Sierra Indiana mineral, as well as temperature and granulometry. The previous model gives a good representativeness of 99.98%. For a sulfuric solution, the mathematical model of the thorium recovery efficiency obtained is:

$$Y = 29.78 + 25.92 * X_1 + 0.99 * X_2 - 1.05 * X_3 - 2.05 * X_{12} - 9.84 * X_{13} - 5.26 * X_{23} - 3.87 * X_{123} + 15.18$$

The model indicates that the recovery of thorium for the mineral is significantly affected by the concentration of sulfuric acid, and to a lesser degree by the temperature and granulometry. The model provides a representativeness of 98.3%.

Keywords

Thorium, Leaching, Sierra Indiana, Atacama, Chile, Metallurgy

1. Introduction

The thorium corresponds to a radioactive chemical element belonging to the actinides, which is highly electropositive and its main oxidation state is +4. It is possible to find it dispersed in a large part of soils and rocks, presenting mainly as ^{232}Th and in a more concentrated form in minerals of monazite, thorite and/or torianite, reaching in the latter an average concentration of 70% [1].

In Chile, several areas with the presence of thorium have been identified through the use of geochemical, radiometric and aerospectrometric techniques and analysis. One of these zones corresponds to Sierra Indiana, located in the Atacama region, 60 km north of the city of Copiapó. It is formed by a sequence of volcanic rocks, from the Lavas and Brechas unit, of lower Cretaceous age, intruded by plutons of the Upper Cretaceous age, presenting lithologies from diorites to aplites [2].

The sample of treated mineral presents a rock composed of feldspars of the plagioclase type, mixed with ferromagnesians of blackish green color, associated with fibrous amphibole. It presents opaque minerals like magnetite transformed to hematite, associated with minerals included in the group of "Radioactive Complex Oxides of Fe, Ti, U, *Th* and REE", as can be seen in **Figure 1**. It also presents opaque minerals associated with systems of guides and streaks, composed by ferromagnesians. The fractionation of the ferromagnesians can give a series of minerals like ilmenite and spheno [3].

2. Experimental Procedure and Results

To obtain a concentrate of thorium oxide (ThO_2), from the carrier mineral from Sierra Indiana, it was proposed to study the general process reported in the diagram of **Figure 2**, which includes the stage of crushing and grinding the ore, in order to decrease the particle size and release the element of interest, to be subsequently leached. After the leaching stage is the application of solvent extraction process, to purify and concentrate the solution containing thorium, to subsequently implement the precipitation step obtaining a compound of this element, which will be calcined to obtain a concentrate of thorium oxide.

Then, the experimental procedure carried out to specify the tests destined to the leaching stage is reported, in order to recover the thorium element from its mineral matrix. These tests were carried out in the laboratories of the Extractive Metallurgy Area of the Department of Advanced Materials of the Chilean Nuclear Energy Commission (CChEN).

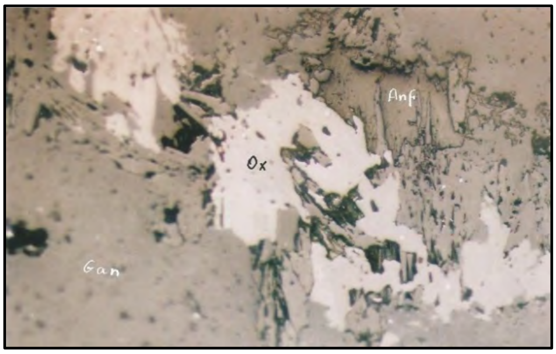

Figure 1. Polished cut. The micrograph shows mineralization of "radioactive complex oxides" [Ox] related to developing crystals of spheno type (dark color), in contact with fibrous amphibole (chrysolite or tremolite) [Anf]. The rest of the sample is bargain [Gan]. Increase 10 × 20. Parallel Nicoles. Scale 1 cm. = 50 microns (Boris Alarcón Farías, 2014).

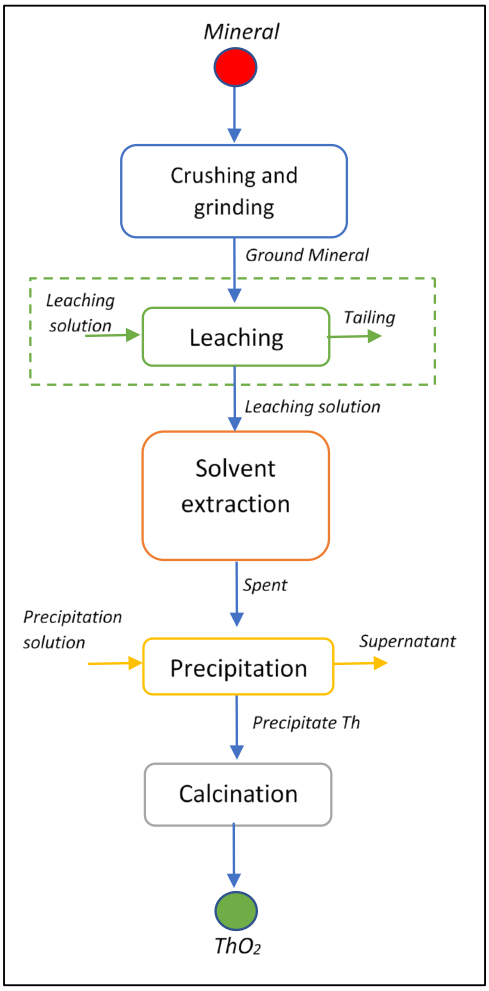

Figure 2. Thorium oxide concentrate (ThO_2) process, from Sierra Indiana ore.

2.1. Physical Characterization of the Mineral

The physical characteristics of the mineral are reported in **Table 1**. It was mentioned that the density was determined by the pycnometric method and natural humidity through the method described in the ASTM-D2216 standard [4].

The values obtained indicate that the mineral has a typical behavior of the ores located in the northern zone of Chile, Atacama region, which was considered to define operational parameters in the crushing and grinding stage.

2.2. Chemical Characterization of the Mineral

The concentration of the elements of interest present in the mineral are reported in **Table 2**.

This characterization has allowed to know the average grade of thorium in this mineral, which is one of the highest detected in the Atacama region. Additionally, this information is essential to theoretically know the stoichiometric consumption of acid in the leaching process and to define some values of the operational parameters. The mineral has a high percentage of elements such as iron, calcium and aluminum, considered important impurities that must be eliminated in stages after leaching process.

2.3. Granulometric Test

The ore samples were subjected to a process of size reduction, using a jaw crusher and a planetary mill, obtaining sizes of 100% - 200% # and 100% - 60% #, whose distribution is shown in **Figure 3**.

When performing a chemical characterization by size, there is evidence of an increase in the concentration of Th between meshes 20 (525 ppm) and 45 (1025 ppm), and a decrease of 73% between meshes 100 (1078 ppm) and 140 (288.8 ppm). Its maximum point was reached with the 60 mesh, with a value of 2621 ppm of Th, then decay to a concentration of 366.6 ppm under 200 mesh, what is possible to observe in **Figure 4**. This distribution of thorium through the different mesh sizes does not obey a normal behavior, so it will be the subject of future research studies.

Table 1. Physical characterization of the mineral.

Parameter	Value/unit
Mineral density	2.84 [tons/m^3]
Natural humidity	0.52%

Table 2. Concentration of minerals present in Sierra Indiana.

Element	Th (ppm)	U (ppm)	REE (ppm)	Fe (%)	Cu (ppm)
Conc.	778.7	15.17	487.0	1.9	24.4
Element	**Mo (ppm)**	**Ca (%)**	**Al (%)**	**Ti (ppm)**	**Si (%)**
Conc.	<50.0	3.0	1.9	1342.0	25.4

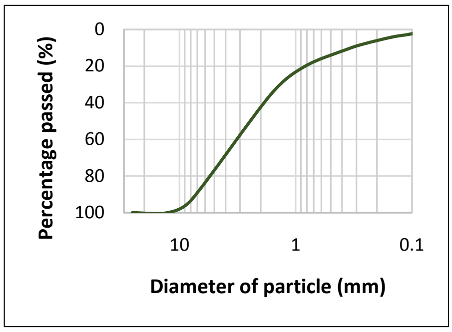

Figure 3. Granulometric curve, Sierra Indiana ore.

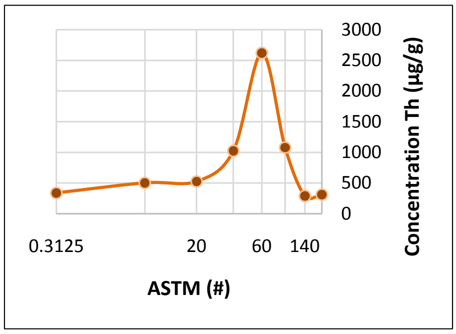

Figure 4. Th concentration by size for Sierra Indiana ore.

2.4. ISO pH Test

The purpose of these tests, also known as "*rolled bottle leaching test*", is to know the general consumption of acid, by the mineral. The implemented system corresponds to a roller agitator, where a pulp of ore was treated in bottles of 10 liters each one, measuring the pH of the solution in different time intervals, until reaching a constant value. Two solutions, corresponding to a sulfuric and hydrochloric matrix, were used separately. The results obtained indicate that, the consumptions of acid for sulfuric acid are 125.5 [kg H_2SO_4/tonne Mineral] and 937.2 [kg H_2SO_4/kg Th], for hydrochloric acid are 70.3 [kg HCl/tonne Mineral] and 534.2 [kg HCl/kg Th].

2.5. Leaching Tests

The leaching process consists, basically, in the partial dissolution of the elements present in the mineralogical species that constitute the carrier rock, by means of an aqueous solvent solution, that is, it allows the individual or group separation of soluble elements by means of a leaching agent, obtaining a rich solution or loaded with the element of interest and others, known as Pregnant Leach Solution (PLS).

The leaching of thorium, using a solution of hydrochloric acid, can generate the following main chemical reactions [5] [6]:

$$Th^{4+} + 2\mathrm{Cl}^{-} \leftrightarrow Th\mathrm{Cl}_2^{2+} \quad (1)$$

$$Th^{4+} + 3\mathrm{Cl}^{-} \leftrightarrow Th\mathrm{Cl}_3^{+} \quad (2)$$

$$Th^{4+} + 4\mathrm{Cl}^- \leftrightarrow Th\mathrm{Cl}_{4(aq)} \quad (3)$$

$$Th^{4+} + 5\mathrm{Cl}^- \leftrightarrow Th\mathrm{Cl}_5^- \quad (4)$$

In the case of a sulfuric solution, are the following chemical reactions:

$$Th^{4+} + \mathrm{H_2SO_4} \leftrightarrow Th\mathrm{SO_4^{2+}} + 2\mathrm{H}^+ \quad (5)$$

$$Th^{4+} + 2\mathrm{H_2SO_4} \leftrightarrow Th\left(\mathrm{SO_4}\right)_2 + 4\mathrm{H}^+ \quad (6)$$

In order to determine the best efficiency in the recovery of thorium from its mineral matrix, the following operational parameters were studied, which, in addition, significantly influence the operating costs:

- Acid concentration in leaching solution.
- System temperature.
- Granulometry.

Two sets of 11 experiences each one were carried out, according to model 2^3 methodology. The tests were carried out inside a 2 liter glass reactor, by mechanical agitation, in a batch system, heated through the use of a heating plate. The leaching ratio was (S/L) = 1.

The procedure used was: empty the acid solution inside the reactor, turn on the agitation system (400 RPM) and heating, when reaching the required temperature the mineral is poured slowly, maintaining the system with constant agitation, for a period of 6 hours.

Once the process is finished, the pulp is filtered, in a system composed of a funnel carrying filter paper, attached to a flask connected to a vacuum pump, separating the Pregnant Leach Solution (PLS) from the tailing, which was washed with deionized water at pH 1.8 and a ratio (S/L) = 1, in order to eliminate any drag of acid solution in this solid.

2.5.1. Experimental Matrix

The system of experiences performed obeys the procedure for obtaining a model 2^3, according to Table 3.

The following values of the variables of interest for each leaching solution were tested, Table 4 and Table 5.

2.5.2. Recovery Efficiencies

Table 6 shows the thorium recoveries obtained in the leaching tests with sulfuric and hydrochloric solutions.

2.5.3. ANAVA Table and Mathematical Models

By means of the analysis of variance it is possible to perform the analysis of the applied mathematical model, which shows the behavior of the thorium when it is leached under these conditions.

From Table 7 and Table 8, together with the *Abbreviated Doolitle Method*, an analysis was developed to the mathematical model, to determine the influence of the variables studied in the percentage of thorium recovered from the ore, by means of the leaching technique, in this case X_1, X_2 and X_3 are the independent variables, corresponding to hydrochloric acid concentration, temperature and granulometry, respectively.

$$\begin{aligned} Y = 31.14 + 26.25 * X_1 + 8.69 * X_2 - 0.82 * X_3 + 9.5 * X_{12} \\ - 0.83 * X_{13} - 3.71 * X_{23} - 1.83 * X_{123} + 6.46 \end{aligned} \tag{7}$$

When evaluating the results of the ANAVA with the *Minitab program*, **Figure 5**, it is feasible to visualize the individual effect of the factors under study, the graph shows that by increasing both the concentration of acid and temperature, it leads to an improvement in the recovery of thorium, thus with the granulometry, which does not have significant influence.

Regarding the effect of the interaction of the studied factors, it is possible to mention that the hydrochloric concentration together with the temperature shows a positive behavior, that is, it presents an improvement in the recovery of thorium. When analyzing the influence of acid concentration and particle size, it shows a decrease in the recovery of thorium at higher concentrations of acid, the same behavior occurs with the interaction between temperature and granulometry.

In the case of sulfuric acid, **Table 9** and **Table 10**, together with the *Abbreviated Doolitle Method*, the following model was developed:

$$\begin{aligned} Y = 29.78 + 25.92 * X_1 + 0.99 * X_2 - 1.05 * X_3 - 2.05 * X_{12} \\ - 9.84 * X_{13} - 5.26 * X_{23} - 3.87 * X_{123} + 15.18 \end{aligned} \tag{8}$$

When evaluating the results of the ANAVA with the *Minitab program*, **Figure 6**, it is feasible to visualize the individual effect of the factors under study, the graph shows that when increasing the acid concentration, it leads to an improvement in the recovery of thorium, not so with the temperature and granulometry, which has no significant influence.

Regarding the interaction of the factors studied, this does not significantly influence the recovery of thorium.

Table 3. Experimental matrix, model 2^3.

#exp	Design	Acid conc.	Temp. ˚C	Granul.
1	I	-	-	-
2	A	+	-	-
3	B	-	+	-
4	AB	+	+	-
5	C	-	-	+
6	AC	+	-	+
7	BC	-	+	+
8	ABC	+	+	+
9	B	-	+	-
10	AB	+	+	-
11	C	-	-	+

Table 4. Values of the variables tested for a sulfuric solution.

Solution H_2SO_4	-	+
Acid concentration	0.1 M	3.7 M
Temperature	25˚C	60˚C
Granulometry	<60 #	<200 #

Table 5. Values of the variables tested for a hydrochloric solution.

Solution HCl	-	+
Acid concentration	2.0 M	7.0 M
Temperature	25˚C	60˚C
Granulometry	<60 #	<200 #

Table 6. Percent recovery of Th, in sulfuric and hydrochloric leaching tests.

# Exp.	% recov. Th H_2SO_4	% recov. Th HCl
1	2.1	3.8
2	48.7	35.3
3	5.1	5.8
4	70.0	81.7
5	5.5	8.3
6	64.9	43.1
7	2.8	2.2
8	47.8	68.4
9	5.4	6.1
10	66.2	83.8
11	5.1	6.9

Table 7. ANAVA. Leaching solution HCl, Part 1.

Source of variation	Sum of squares	Degrees of freedom	Middle square
$\sum Y_i^2$	21,686.22	11	1971.47
Because X_0	10,845.56	1	10,845.56
Because X_1	8843.30	1	8843.30
Because X_2	719.32	1	719.32
Because X_3	0.52	1	0.52
Because X_{12}	1100.28	1	1100.28
Because X_{13}	14.83	1	14.83
Because X_{23}	126.38	1	126.38
Because X_{123}	32.79	1	32.79
Residual sum of squares	3.23	3	1.08
Mismatches	−3.23	1	−3.23
Experimental error	6.46	2	3.23

Table 8. ANAVA. Leaching solution HCl, Part 2.

Source of variation	F	$F\alpha_{0.05}$	$F\alpha_{0.01}$
Because X_1	2737.86	18.5	98.5
Because X_2	222.7	18.5	98.5
Because X_3	0.16	18.5	98.5
Because X_{12}	340.64	18.5	98.5
Because X_{13}	4.59	18.5	98.5
Because X_{23}	39.13	18.5	98.5
Because X_{123}	10.15	18.5	98.5
Residual sum of squares	0.33	18.5	98.5
Mismatches	−1	18.5	98.5
R^2 (%)			99.98

Table 9. ANAVA. Leaching solution H_2SO_4 Part 1.

Source of variation	Sum of squares	Degrees of freedom	Middle square
$\sum Y_i^2$	18,256.86	11	1659.71
Because X_0	9628.53	1	9506.54
Because X_1	7799.50	1	8300.35
Because X_2	11.55	1	12.52
Because X_3	9.59	1	8.21
Because X_{12}	−25.36	1	14.47
Because X_{13}	122.58	1	15.57
Because X_{23}	259.01	1	244.38
Because X_{123}	147.22	1	147.22
Residual sum of squares	304.25	3	101.42
Mismatches	289.07	1	289.07
Experimental error	15.18	2	7.59

Table 10. ANAVA. Leaching solution H_2SO_4 Part 2.

Source of variation	F	$F\alpha_{0.05}$	$F\alpha_{0.01}$
Because X_1	28.71	18.5	98.5
Because X_2	0.04	18.5	98.5
Because X_3	0.03	18.5	98.5
Because X_{12}	0.05	18.5	98.5
Because X_{13}	0.05	18.5	98.5
Because X_{23}	0.85	18.5	98.5
Because X_{123}	0.51	18.5	98.5
Residual sum of squares	0.35	18.5	98.5
Mismatches	1	18.5	98.5
R^2 (%)			98.3

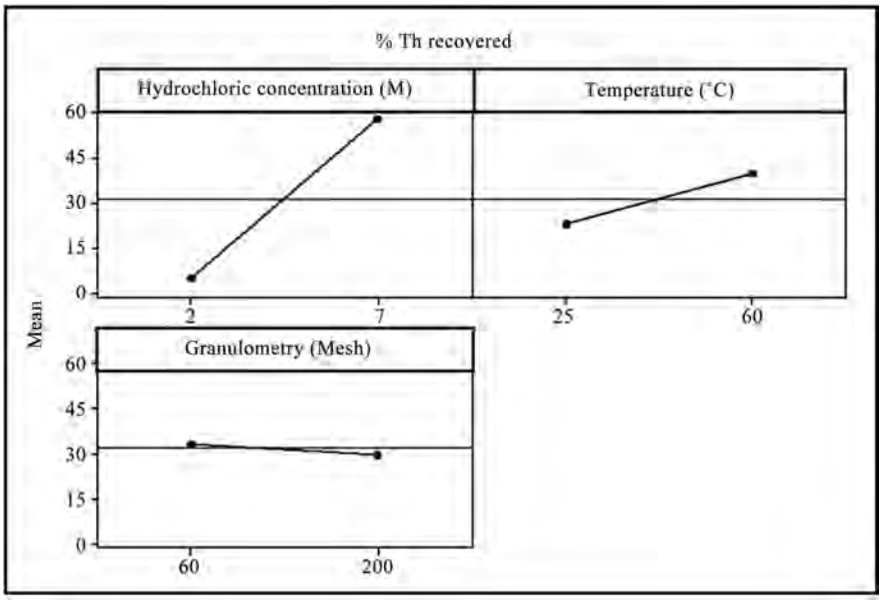

Figure 5. Individual effects of the factors under study in the recovery of Th, by leaching with HCl from Sierra Indiana ore.

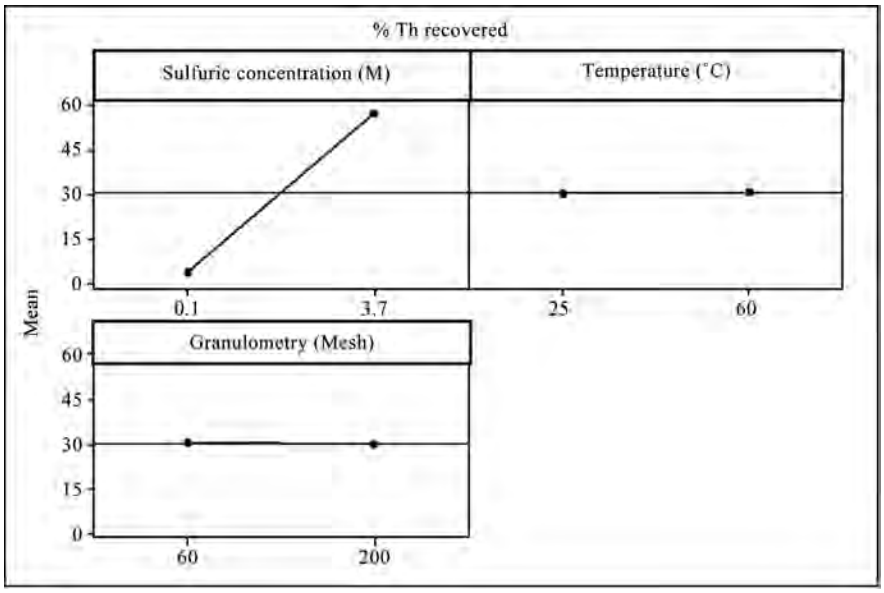

Figure 6. Individual effects of the factors under study in the recovery of Th, by leaching with H_2SO_4 from Sierra Indiana ore.

3. Conclusions

3.1. Leaching

- It is technically feasible to recover thorium by leaching the mineral carrier, with hydrochloric and/or sulfuric solution.
- The highest recovery of thorium for a sulfuric solution was 70.0% and for a hydrochloric solution of 83.8%, so the process presents a good efficiency in both cases.

3.2. Model

- For a hydrochloric solution, the thorium recovery efficiency model obtained gives 99.98% representativeness and corresponds to:

$$Y = 31.14 + 26.25 * X_1 + 8.69 * X_2 - 0.82 * X_3 + 9.5 * X_{12} - 0.83 * X_{13} - 3.71 * X_{23} - 1.83 * X_{123} + 6.46$$

- The concentration of HCl and temperature, as well as their interaction, significantly affect the recovery of thorium for Sierra Indiana mineral, as well as temperature and granulometry.
- For a sulfuric solution, the thorium recovery efficiency model obtained represents 98.3% representativeness and corresponds to:

$$Y = 29.78 + 25.92 * X_1 + 0.99 * X_2 - 1.05 * X_3 - 2.05 * X_{12} - 9.84 * X_{13} - 5.26 * X_{23} - 3.87 * X_{123} + 15.18$$

- The model indicates that the recovery of thorium for the mineral is significantly affected by the concentration of sulfuric acid, and to a lesser degree by the temperature and granulometry.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Wickleder, M.S. (2006) The Chemistry of the Actinide and Transactinide Elements. 52-160.

[2] Fortín, H. (2002) Sector Mina Santo Domingo—Mina Atacama, investigación geológica preliminar por tierras raras y uranio.

[3] Alarcón, B. (2014) Estudio macroscópico petro-calcográfico de muestras pulidas "Sierra Indiana; Quebrada del Desierto y Carmen Norte" CCHEN.

[4] Norma ASTM-D2216 (2006) Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass.

[5] Sapsford, D.J., *et al.* (2012) Factors Influencing the Release Rate of Uranium, Thorium, Yttrium and Rare Earth from A Low Grade Ore. *Minerals Engineering*, **39**, 165-172. https://doi.org/10.1016/j.mineng.2012.08.002

[6] Rand, M., *et al.* (2007) Chemical Thermodynamics of Thorium—Volume 11. 226-244, 267-299.

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- Nuclear Track Detection
- Nuclear Tracks and Radiation Measurements
- Radiation Applications and Instrumentation
- Radioanalytical and Nuclear Chemistry
- Reactor and Nuclear Systems
- Reactor Science and Technology

We are also interested in short papers (letters) that clearly address a specific problem, and short survey or position papers that sketch the results or problems on a specific topic. Authors of selected short papers would be invited to write a regular paper on the same topic for future issues of the WJNST.

Notes for Intending Authors

Submitted papers should not have been previously published nor be currently under consideration for publication elsewhere. Paper submission will be handled electronically through the website. All papers are refereed through a peer review process. For more details about the submissions, please access the website.

Website and E-mail

http://www.scirp.org/journal/wjnst E-mail: wjnst@scirp.org