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CINTICHEM MODIFIED PROCESS- ^{99}MO PRECIPITATION STEP: APPLICATION OF STATISTICAL ANALYSIS TOOLS OVER THE REACTIONAL PARAMETERS

Rodrigo Teodoro[1], Carla R. B. R. Dias[1], Eutimio Gustavo Fernández Núñez[2], João A. Osso Jr.[1]

[1] Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242 05508-000 São Paulo, SP

[2]Universidade de São Paulo, Escola Politécnica, Departamento de Engenharia Química.
Av. Prof. Luciano Gualberto, trav. 3, 380, Butanta, 05508-900 - Sao Paulo, SP

teodoro_rodrigo@yahoo.com.br
jaosso@ipen.br

ABSTRACT

Precipitation of ^{99}Mo by α-benzoin oxime (α-Bz) is a standard precipitation method for molybdenum due the high selectivity of this agent. Nowadays, statistical analysis tools have been employed in analytical systems to prove its efficiency and feasibility. IPEN has a project aiming the production of ^{99}Mo by the fission of ^{235}U route. The processing uses as the first step the precipitation of ^{99}Mo with α-Bz. This precipitation step involves many key reaction parameters. The aim of this work is based on the development of the already known acidic route to produce ^{99}Mo as well as the optimization of the reactional parameters applying statistical tools. In order to simulate ^{99}Mo precipitation, the study was conducted in acidic media using HNO_3, αBz as precipitant agent and NaOH /1%H_2O_2 as dissolver solution. Then, a Mo carrier, $KMnO_4$ solutions and ^{99}Mo tracer were added to the reaction flask. The reactional parameters (α-Bz/Mo ratio, Mo carrier, reaction time and temperature, and cooling reaction time before filtration) were evaluated under a fractional factorial design of resolution V. The best values of each reactional parameter were determined by a response surface statistical planning. The precipitation and recovery yields of ^{99}Mo were measured using HPGe detector. Statistical analysis from experimental data suggested that the reactional parameters α-Bz/Mo ratio, reaction time and temperature have a significative impact on ^{99}Mo precipitation. Optimization statistical planning showed that higher αBz/Mo ratios, room temperature, and lower reaction time lead to higher ^{99}Mo yields.

1. INTRODUCTION

Following the world trends, Nuclear Medicine applications in Brazil have been widely growing in the past few decades. The isotope molybdenum-99 (^{99}Mo) has been supplied to the medical community, and its decay product, technetium-99m (^{99m}Tc), is one of the most used diagnostic imaging agents[1]. ^{99m}Tc (half life: 6 h) is readily-available to clinical radiopharmacies through ^{99}Mo-^{99m}Tc generators. Its excellent nuclear and chemical characteristics enable high quality images with low radiation doses to patients, making it very versatile for attaching to different chemical substances[2].

The Brazilian demand, attended solely by IPEN-CNEN/SP, reaches out more than 320 generators per week with a total activity of about 16.7 TBq (450 Ci), which corresponds to 4% of the overall ^{99}Mo global demand at an importation cost of US$20 million/year, most of it from Nordion, Canada.

The world's supply of ^{99}Mo is centered on five large research reactor operations, which are aging over 40 years old and, recently, have been unreliable due to closures for repairs of leaks, leading to an unstable supply of this important radionuclide. In particular, the shutdown of the NRU reactor has triggered a global shortage in nuclear medical isotopes, which has made the situation particularly problematic from a medical standpoint[1]. This recent ^{99}Mo 'crisis' deeply affected the distribution of generators in Brazil. In order to circumvent this situation, CNEN, supported by a government action decided to develop their skills concerning the production of ^{99}Mo, through the construction of the Brazilian Multipurpose Reactor (BMR).

The main route to produce ^{99}Mo is by fissioning highly enriched uranium (HEU) in ^{235}U. Consistent with increasingly critical non-proliferation concerns brought about by the use of HEU in training, research, test and isotope production reactor fuels, conversion of research reactors from HEU to low enriched uranium (LEU) acquiring strong momentum worldwide. This implies that an important number of commercial operations involving LEU training, research, test and isotope production reactor fuels are foreseeable in the near future[3].

Through a project coordinated by the International Atomic Energy Agency (IAEA-CRP), the acid dissolution process of U metal targets (Cintichem modified) has been widely discussed, aiming an optimization of the process and reducing the amount of waste generated. After the dissolution of the targets a precipitating agent is employed for the isolation of ^{99}Mo from other by-products of ^{235}U fission. Several hydroyoximes were used as selective reagents for solvent extraction of molybdenum (VI) in acid medium, such as α-benzoin oxime (α-Bz), the hydroxyacetoplenone-oxime and oxime-hydroxybenzophenone. Among them, α-Bz was chosen because it is more selective for Mo (VI), thereby reducing the co-precipitation of other fission products.

Protocols containing the optimal parameters such as the choice of acid to dissolve the target, precipitating agent, reaction conditions of precipitation, purification and quality control are already available in laboratory scale. However, to meet Brazilian domestic demand and also the BMR perspectives, each parameter should be adjusted to the characteristics of the reactor (i.e, power and position of irradiation) and targets to be irradiated in order to optimize the process and reducing the amount of waste produced. In this sense, the aim of this work is based on the improvement of the already known acidic route to produce ^{99}Mo as well as the optimization of the reactional parameters applying statistical tools.

2. METHODS

2.1. Simulation of ^{99}Mo precipitation

A mimetic of the acid dissolution process of LEU foils was performed in acidic media using 2 mL of 1mol.L^{-1} HNO_3, 2% α-benzoine oxime (α-Bz) as precipitant agent and (0.1 mol.L^{-1})NaOH /1%H_2O_2 as dissolver solution. Moreover, 0.5 mL of a Mo carrier solution (MoO_3 10-30 mg/mL) and 2.5% $KMnO_4$ solution were added to the reaction in order to simulate both the macroscopic precipitation of ^{99}Mo and LEU foils dissolution, respectively[4]. The following parameters were evaluated: the αBz/Mo ratio and the Mo carrier content. The filtration was carried out using a glass frit filtration unit. Samples were taken before the precipitation of ^{99}Mo, from the filtrate, precipitate washing and dissolution. The precipitation and recovery yields of ^{99}Mo were measured by γ-ray spectroscopy using an HPGe detector.

2.2. Screening Statistical planning

A Fractional Factorial Design of resolution V was held as an early step within a statistical strategy for optimizing the overall process of precipitation and recovery of ^{99}Mo. In this sense, both significance and magnitude of the independent variables effects [αBz/Mo molar ratio, Mo carrier content, reaction time and temperature, and cooling time of the reaction mixture] as well as their interactions were evaluated for the recovery yields of ^{99}Mo. Upper and lower limits were established for the five independent variables under analysis based on studies already reported in the literature[4].The definition of the experimental matrix and the subsequent statistical analysis were performed using the computer program Statgraphics Plus (Statistical Graphics Co., Rockville, MD, EUA). Also three experimental runs were added to the basic experimental design (16 experiments) in order to estimate the experimental error, thus allowing the analysis of the statistical significance in the mathematical model as well as the variables under study. The statistical significance and magnitude of each independent variable and their interactions were obtained through the analysis of variance and multiple linear regressions, respectively.

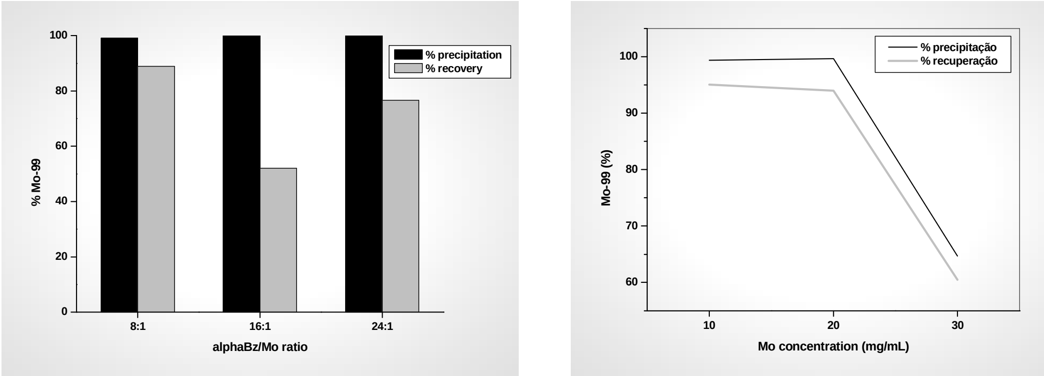
2.3. Optimization Statistical Planning

From the results obtained in the Screening Statistical Planning (Fractional Factorial Design of resolution V) and the independent variables found to have statistical significance in the overall ^{99}Mo process, statistical design of an optimal response surface type (Central Composite Design) was used as a tool of analysis. This stage of the experimental procedure's primary goal is to determine the values of each independent variable that provide the greatest overall efficiency of ^{99}Mo production.

3. RESULTS

3.1. Simulation of Mo precipitation

Preliminary studies were conducted in order to define the relevant parameters for statistical planning. In a set of experiments already stated by our group, the highest ^{99}Mo precipitation and process recovery yields (98.72% and 95.27%, respectively), were reached out under the initial conditions. As noted in figure 1A, ^{99}Mo precipitation is above 95% even at the highest αBz-Mo ratio evaluated (24:1). Differences among recovery rates were largely dependent on the characteristics of the precipitates. A drastic decrease of both ^{99}Mo precipitation and recovery rates can be observed for the highest amount of Mo carrier studied (Fig. 1B), which corroborates with the reaction stoichiometry.



(A) (B)

Figure 1. Evaluation of ^{99}Mo precipitation with α-Bz as function of (A) α-Bz/Mo ratio and (B) Mo carrier concentration.* ***Under optimized conditions: 2% α-Bz; boiling (0.8 mol.L^{-1})NaOH /1%H_2O_2; 5 mg of Mo carrier (from 10 mg/mL solution) in case A. Volume of dissolution (10-12 mL) for all cases.***

3.2. Screening Statistical planning

The screening statistical planning was applied to select variables with statistical significance. The magnitude (or size) of the bar of each variable with a direct relationship (+) or reverse (-) in the Pareto charts indicates a greater or lesser influence on the response variables, which consist of percentages of ^{99}Mo precipitation and recovery. The selection of upper and lower limits of each variable was done based on protocols from the literature. It is noteworthy that the temperature is a crucial factor, since a natural warming of the targets occurs during the uranium processing.

As illustrated in Figures 2 and 3, temperature, reaction time and their interactions are inversely proportional to the percentages of both precipitation and recovery of ^{99}Mo. The α-Bz/Mo ratio has an inverse effect, which means that the greater the α-Bz ratio used in the model, the higher the percentage of ^{99}Mo precipitation and recovery (Fig. 2 and 3).

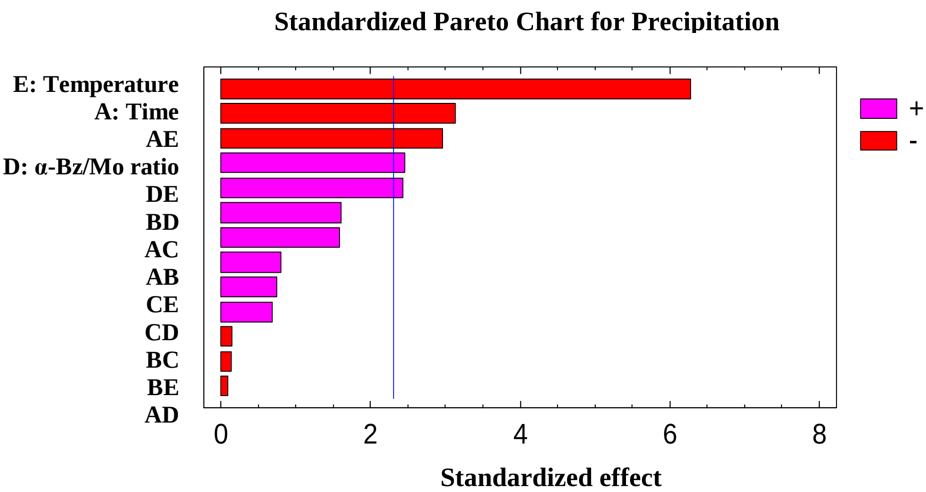


Figure 2. Statistical significance of the variables in the percentage of ^{99}Mo precipitation. (A) Time; (B) Mo carrier; (C) Cooling reaction time before filtration; (D) α-Bz/Mo ratio and (E) Temperature.

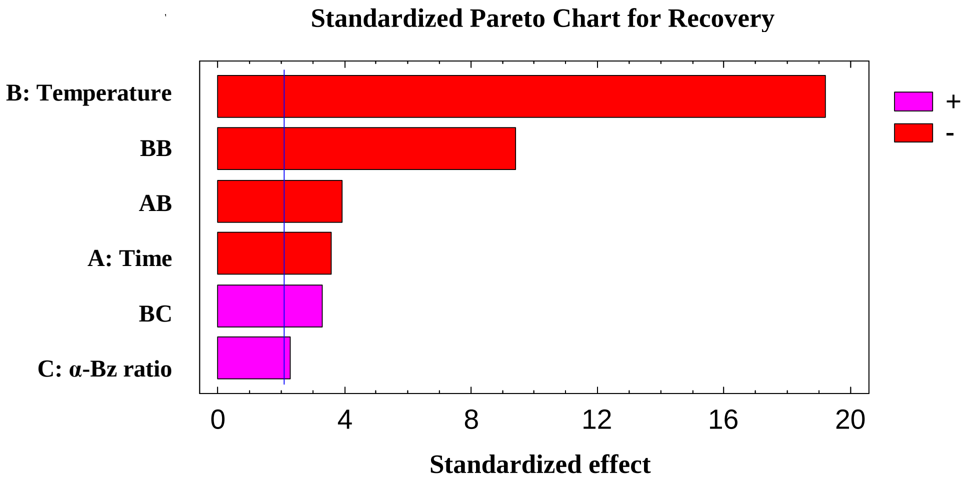


Figure 3. Statistical significance of the variables in the percentage of ^{99}Mo recovery.

This behavior can be explained by the characteristics of the precipitate. When the reaction mixture is subjected to high temperatures in higher reaction time, the precipitate is rigid and has dark colored (possibly indicating a degradation of the complex), it becomes difficult to dissolve even using higher molarity of the dissolution solution [(0.8 mol L^{-1})NaOH / 1% H_2O_2].

Regarding the α-Bz/Mo ratio is noteworthy that previous studies were performed to achieve optimal values in percentages of precipitation and recovery of ^{99}Mo. To achieve higher α-Bz/Mo ratios, a larger volume of α-Bz solution (dissolved in 0.4 mol L^{-1}NaOH) was applied in preliminary experiments. Thus, we used an equimolar amount of nitric acid (HNO_3) in the reaction mixture to neutralize the excess base and acidify as well, favouring the precipitation of the complex.

According to the findings of the first analysis, the magnitude of the three variables with significance in the model can be seen by tilting the sign and value of modular slope and size of the projections of these lines on the shaft of the variable responses in Figures 4 and 5, respectively, to the percentages of precipitation and recovery of ^{99}Mo. As noted, the smaller the reaction time and temperature, the higher the precipitation and recovery yields of ^{99}Mo. However, higher α-Bz/Mo ratios resulted in higher precipitation and recovery yields of ^{99}Mo. Moreover, figures 4 and 5 also indicate that the study of narrow bands of independent variables, causes significant changes in the values of the dependent variables or response variables.

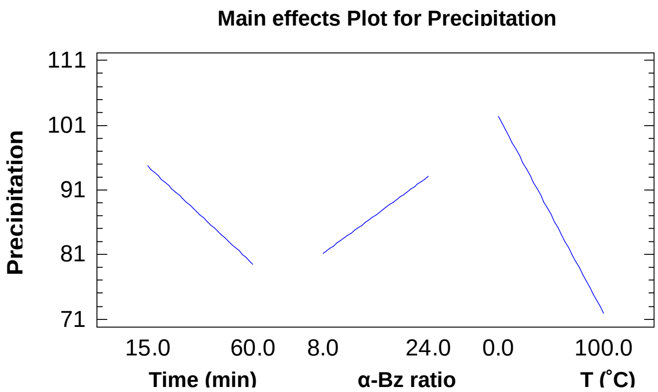


Figure 4. Effects of variables in the percentage of ^{99}Mo precipitation.

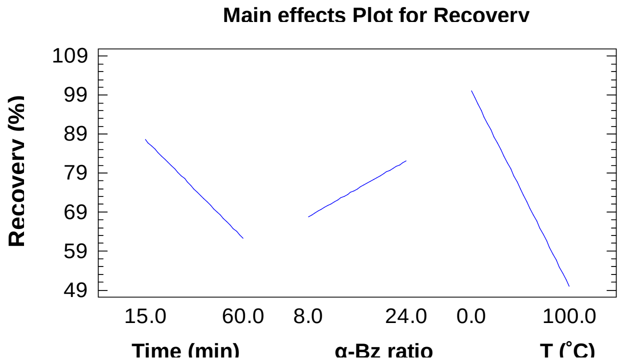


Figure 5. Effects of variables in the percentage of ^{99}Mo recovery.

3.3. Optimization Statistical planning

The optimization design (3^3) was performed to find the optimal values for ^{99}Mo precipitation and recovery within the ranges evaluated in the statistical screening planning for each variable.

Figures 6 and 7 show that the variables temperature and reaction time have an inverse influence on the percentages of ^{99}Mo precipitation and recovery, that is, the higher the temperature values applied to the model, the lower the responses (dependent variables). To a greater degree, it was observed that the temperature is crucial to obtain high values of response variables, especially when it concerns the ^{99}Mo recovery. Also, a slight significant influence was observed in the interaction between time and temperature. With regard to the α-Bz/Mo ratios evaluated, no significant influence on precipitation was observed in contrast to the significant influence on the ^{99}Mo recovery obtained.

These findings corroborate with those previously described in the statistical screening planning, since the complex formed at high temperatures is susceptible to a possible deterioration, characterized by a solid, hard and dark aspect of the precipitate, making it difficult to dissolve. Concerning α-Bz/Mo ratio, optimal conditions for ^{99}Mo precipitation were found even in the higher range evaluated. This represents an indication that on a production scale, even though the amount of Mo carrier from the fission process is variable, the amount of α-Bz can be fixed. Also, the significant influence of temperature and α-Bz/Mo ratio can be mitigated through the application of milder temperatures during heating.

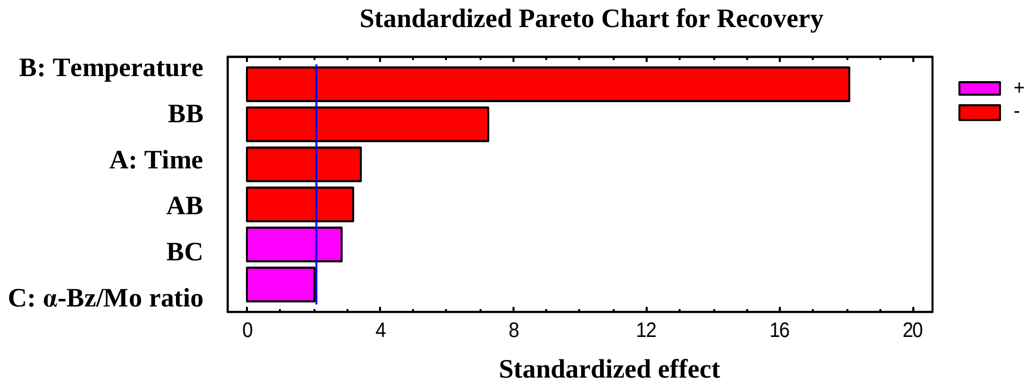


Figure 6. Statistical significance of the variables in the percentage of ^{99}Mo precipitation.

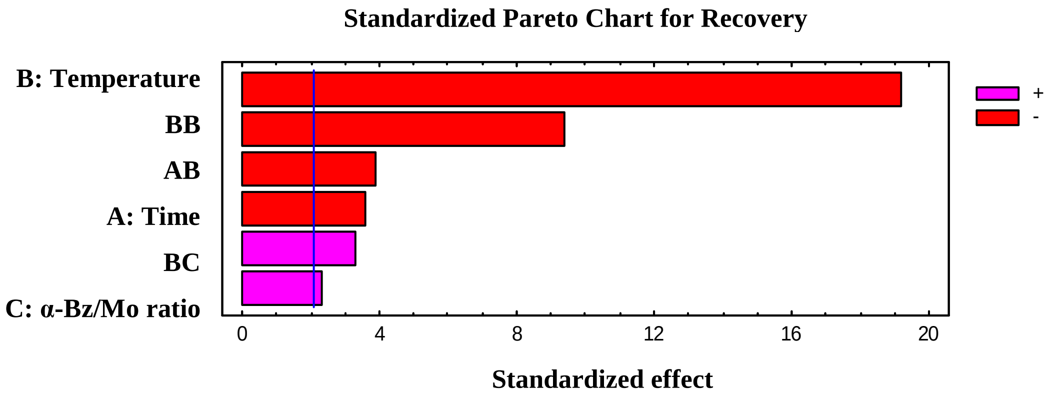


Figure 7. Statistical significance of the variables in the percentage of ^{99}Mo recovery.

Corroborating with the first analysis of the optimized system, the largest percentages oscillations in ^{99}Mo precipitation and recovery can be observed for temperature, however small oscillations were observed in the intervals of α-Bz/Mo ratio and reaction time studied (FIG. 8 and 9).

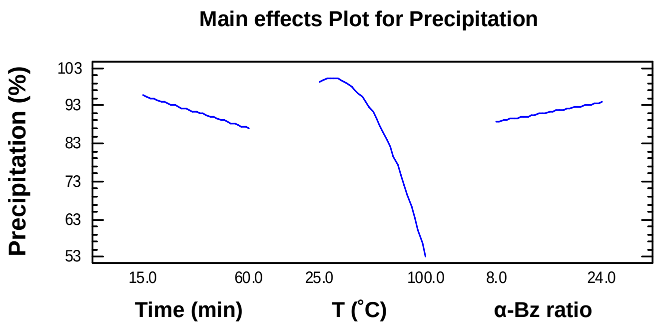


Figure 8. Effects of variables in the percentage of ^{99}Mo precipitation.

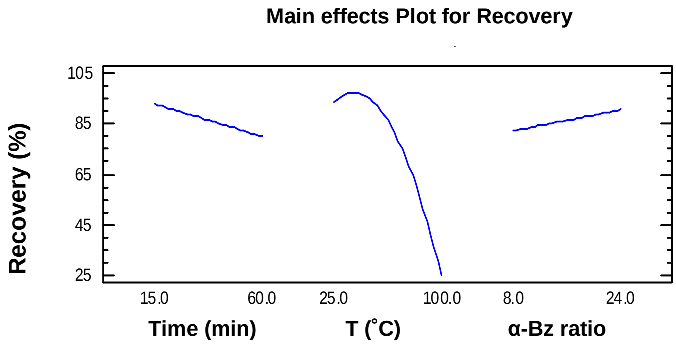


Figure 9. Effects of variables in the percentage of ^{99}Mo recovery.

The graphical representation of a statistical model for ^{99}Mo precipitation is shown in Figure 10. Particularly, α-Bz/Mo ratio was set to represent 3D response surface that describes the universe of variable rainfall in the area studied for the variables temperature and reaction time.

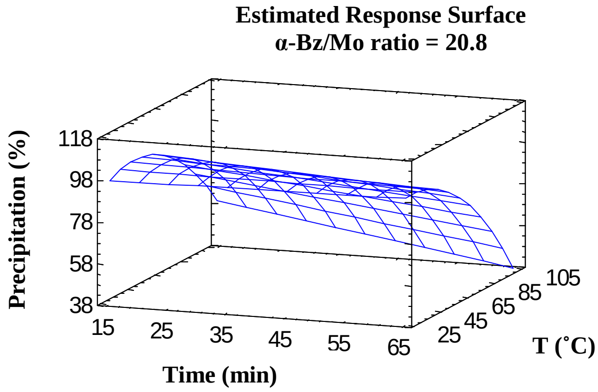


Figure 10. Representation of the ^{99}Mo precipitation surface response at constant α-Bz/Mo ratio (20.8).

4. CONCLUSIONS

The results presented here agree with the prior ones published in the literature and showed the importance of the statistical tools to minimize the number of experiments and to proper analyze the results obtained.

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