

Study of Pressurized Water Reactor Design Models

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Abstract
This study of pressurized water reactor design models involves the application of linear regression analysis on two typical Water-Cooled Nuclear Reactor design models, viz Pressurized Water Reactor Design I (PWRD I) and Pressurized Water Reactor Design II (PWRD II). Empirical expressions are obtained for PWRD I model and PWRD II model. The results of the statistical analyses on these two types of nuclear reactor models reveal that the PWRD II promises to be more stable and therefore safer. The implication of this research effort to Nigeria's nuclear power project is discussed.
Keywords: Linear Regression Analysis, Pressurized Water Reactor Design Models, Safety Factor, Ỳ, Optimization, Stability Margin in Nuclear Power Reactor Designs

INTRODUCTION

Pressurized water reactors (PWRs) constitute the majority of all nuclear power plants and are one of three types of light water reactor (LWR). The other types being boiling water reactors (BWRs) and supercritical water reactors (SCWRs). A failure of a component in the operating system may create a situation and a deviation from the normal operating conditions for example the most serious accident is a loss-of-coolant accident (LOCA) in the primary system a Pressurized Water Reactors and Boiling Water Reactors [1]. Experience have shown that Pressurized Water Reactors (PWRs) could be susceptible to hydrogen buildup when core cooling fails and eventually accidents[2], for example, the *pressurized water reactor(PWR)* at Three Mile Island Unit 2 (TM1-2) nuclear power reactor accident at Pennsylvania in United States of America(USA)[3] the PWR nuclear incidents *at* Davis-Besse Nuclear Power Station in Oak Harbor, Ohio, USA[4] and the PWR shutdown at Palisades, Michigan, USA[5]. others include three PWR at Oconee Nuclear Station located on Lake Keowee near Seneca, South Carolina, USA [5] and the PWR San Onofre Nuclear Generating Station (SONGS) located on the Pacific coast of California is an inoperative nuclear power plant, now planned to be decommissioned. The plant's unit 1and 2 reactors had to be shut-down in January 2012 due to premature wear found on over 3,000 tubes in the recently replaced steam generators. However, the United States Nuclear Regulatory Commission (NRC) is currently investigating the events that led to the closure [6]. These are few of the pressurized water reactor nuclear incidents on record.

There have been several report and analysis on the safety of these PWR's taking into account the specific design features of these reactors, these include 'Status of thermohyraulic research in nuclear safety and new challenges'[7], 'Loss-of-Coolant Accidents (LOCA) in PWRs'[8], 'Accident analysis for nuclear power plants with pressurized water reactors' [9] and Investigation of PWR accident situations' [10].

These accidents may perhaps be as a result of design concept process of PWR (which could involve novel technologies) that have inherent risk of failure in operation and were not well studied/understood, for example 'Nuclear Plant Risk Studies'[11], there has been several report analysis on the cost of failure on these PWR's, this include; 'Nuclear Power futures, costs and benefits'[12], 'A preliminary assessment of major energy accidents'[13] and 'International Atomic Energy Agency (IAEA) technical reports on nuclear energy series'[14].

Failure may be recognized by measures of risks which include performance, design fault, obsolete components, human errors and accident. These risks can be defined and quantified as the product of the probability of an occurrence of failure and a measure of the consequence of that failure. Since the objective of engineering is to design and build things to meet requirements, apart from cost implication, it is important to consider risk along with performance, and technology selections made during concept design. Engineering council guidance on risk for the engineering profession defined "Engineering Risk" as "the chance of incurring a loss or gain by investing in an engineering project" and defined 'risk' as the possibility of an adverse outcome [15]. Similar definitions are given by Modarres [16], Molak [17] and Blanchard [18], that risk is a measure of the potential loss occurred due to natural or human activities.

In this work, Ordinary Least Square (OLS) methodology, which is largely used in nuclear industry for modeling safety, is employed. Some related previous works on the application of regression analysis technique include: 'Regression Approach to a Simple Physics Problem' [19], 'Linear regression gives faster, more accurate leak figure for PWR coolant'[20],'Counter-current flow limitations during hot leg injection in pressurized water reactors with a multiple *linear regression* model'[21], 'Experimental study of a trickle-bed reactor operating at

high pressure**:** two-phase pressure drop and liquid saturation using regression analyses techniques' [22]. Others are, 'Posts about *pressurized water reactors* and data re-analyzed using *linear regression* analysis' [23], 'Stochastic Modeling of Deterioration in Nuclear Power Plants Components'[24] and "Optimization of The Stability Margin for Nuclear Power Reactor Design Models Using Regression Analyses Techniques"[25], where the effective of Regression
Analyses Techniques 'RAT' in the Optimization of the Safety Factor in Nuclear Reactor Design Model was established.
This work provides a mathematical expression for predicting "Safety Factor", Ỳ, (dependent variables) given the values of independent variables or input parameters for a typical Pressurized water reactor design model. Furthermore, the mathematical expression can be used to determine the contribution of coolant flow rates (which is the independent variables) to the nuclear reactor stability, given the value of dependent variable. A comparative analysis of two Pressurized Water Reactor Design Model via the use of RAT would be carried out. Due to the major role of nuclear safety problems in thermo-hydraulic research, the explanations of this paper are restricted to nuclear reactor safety factor, stability margin, optimization, questions and issues.

THE RESEARCH OBJECTIVES:
To apply the linear regression technique on Pressurized Water Reactors for the determination of their Safety Factor in terms of their coolant which in turn is a measure of the reactor's stability and to carry out a comparative analysis of two different PWR design models.

RESEARCH DESIGN/APPROACH
Theory and experience has shown that, for nuclear power plants, coolants (which is water in this case study) plays significant role in the safety of the reactor during operation in preventing reactor damage during accident. Hence, in this work, in assessment of some typical pressurized water reactor designs, the input parameter considered is the coolant (which is the water flow rate in the reactor during operation).
The typical nuclear reactor designs are coded as PWRD I and PWRD II which stands for Pressurized Water Reactor Design I and Pressurized Water Reactor Design II.
The data used are those for typical Pressurized water reactor similar to:
(a) The Three Mile Island Unit 2 (TM1-2) in Pennsylvania (which had an accident on March 28, 1979) – PWRD I
(b) The PWR *at* Davis-Besse Nuclear Power Station in Oak Harbor, Ohio, USA involved in dangerous accident on June 9, 1985 and PWR shutdown at Palisades, Michigan, USA (which had an accidents on October 5, 1966) – PWRD II.
With the input data of each of these different design models, a linear regression analysis technique is applied using, Number Cruncher Statistical Software (NCSS). The results give a model equation for each of the different design models which can be used to make prediction on the reactor stability. In Tables 1 and 2, the values of design input parameters Similar to the PWR at Three Mile Island Unit 2 (TM1-2) and the PWR at Davis-Besse Nuclear Power Station in Oak Harbor, Ohio, with the PWR at Palisades, Michigan respectively are presented.
The results obtained in form of model equations for each different design were analysed and used to determine the reactor stability.
Table 1: Design Input Parameters of a Typical Pressurized Water Reactor (PWR) Similar to Three Mile Island Unit 2 (TM1-2) damaged reactor near Pennsylvania in USA

Nos. of trial (j)	Safety factor	Coolant (water) flow rate in kg/s PWRD I
1	1.30	100
2	1.40	200
3	1.40	300
4	1.50	400
5	1.45	500
6	1.60	600
7	1.55	700
8	1.70	800
9	1.72	900
10	1.55	1000
11	1.70	1100
12	1.72	1200
13	1.80	1300

Source : [26]

Table 2: Design Input Parameters of a Typical Pressurized Water Reactor (PWR) Similar to the accident PWR *at* Davis-Besse Nuclear Power Station in Oak Harbor, Ohio, USA and the PWR shutdown at Palisades, Michigan, USA

Nos. of trial (j)	Safety factor	Coolant (water) flow rate in kg/s PWRD II
1	1.20	100
2	1.25	200
3	1.30	400
4	1.35	600
5	1.40	800
6	1.45	1000
7	1.50	1200
8	1.55	1400
9	1.60	1600
10	1.70	1800

Source: [27]

In order to evaluate the models, the following tests were carried out as applicable to regression analysis technique:

- F-test which is the overall test of the designs
- t-test which is the test of the individual design
- Autocorrelation (whether a present error(s) is/are dependent on the last error(s))
- Testing the significance of regression coefficients, b_i (i.e. the contribution or effect of each design input parameter on the reactor stability, assuming all other parameters are held constant).
- Check for systematic bias in the forecast (where the average error is zero)
- Normality test.

RESULTS AND ANALYSES

1. Pressurized Water Reactor Design I (PWRD - I)

The results of the application of the linear regression analysis of the data in Table 1 and 2 are presented as follows: These regression analyses were carried out on two different water-cooled nuclear reactor designs with the use of statistical software known as Number Cruncher Statistics Software (NCSS).

(i) Empirical Expression for Safety Factor, $\grave{Y}$

The data obtain in Tables 1 which represents typical parameters for Pressurized Water Reactor Design I (PWRD I) was modified in other to obtain the best fit for the model. The new conceptual design reactor model optimizes the performance of the Three Mile Island Unit 2 (TM1-2) reactor which was severely damaged.

The linear regression model equation to be solved is given by:

$$\grave{Y} = B_0 + B_1 X_j + e_j \quad (1)$$

where, B_0 is an intercept, B_1 is the slope and

X_j is the rate of flow of coolant and e_j = error or residual.

The model empirical expression for the Safety Factor $\grave{Y}$ is obtained, as**:**

$$\grave{Y} = (1.3150) + (0.0004)*(X_j) + e_j \quad (2)$$

Where, 1.3150 is an intercept, 0.0004 is a slope, X is the rate of flow of water coolant, e = error or residual and j = 1,2,3,…,14.

Equation (1.2) is the model empirical expression that could be applied to make predictions of the Safety Factor $\grave{Y}$ on this type of (PWRD I).

Note:

❖ The linear regression equation is a Mathematical Model describing the relationship between Safety Factor, $\grave{Y}$, and the coolant (input parameter, X).

❖That the linear regression equation predicts Safety Factor based on their value. The value of Safety Factor depends on the values of design water coolant flow rate.

❖The influence of all other variables on the value of Safety Factor is lumped into the residual (error - e_j).

The Linear Regression Plot Section on PWD I is shown in Figure 1:

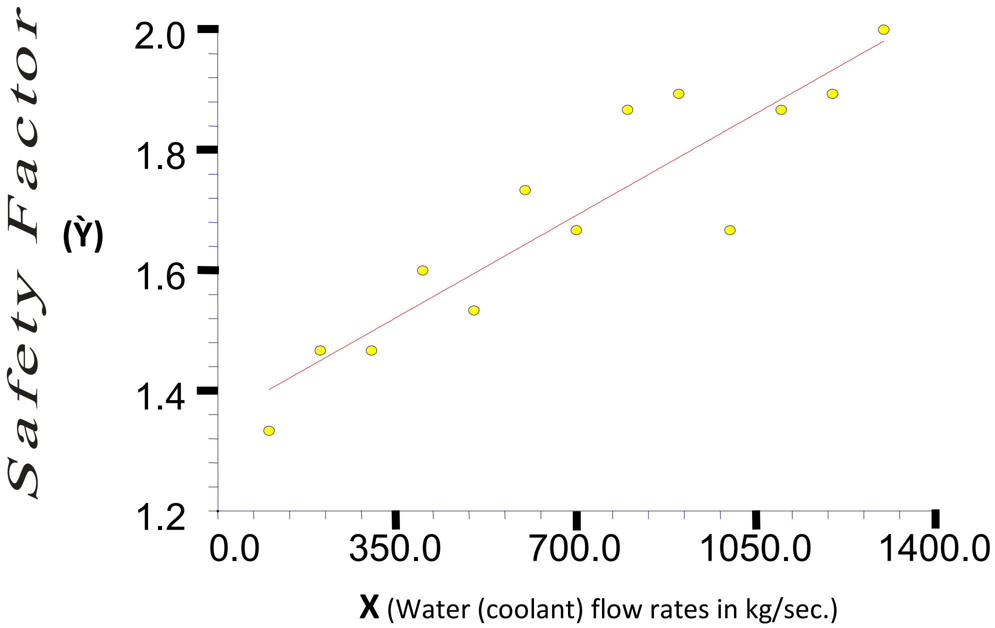

Figure 1. Safety Factor (Ỳ) as a function of water (coolant) flow rate (X)

- The plot Figure 1 shows the relationship between Safety Factor, Ỳ, and the water (coolant) flow rates, X. The straight line implies a linear relationship between Ỳ and X while the closeness of the points to the line indicates that the relationship is strong.

(ii) F -test Result

Table 3 is the summary of the F-test result on PWRD I as shown.

Table 3: Summary of F-test Statistical Data on PWRD I

Parameter	Value
Dependent Variable	Ỳ
Independent Variable	X
Frequency Variable	None
Weight Variable	None
Intercept(B_0)	1.3150
Slope(B_1)	0.0004
R^2	**0.8421**
Correlation	**0.9176**
Mean Square Error	**4.068482×10^{-3}**
Coefficient of Variation	0.0407
Square Root of MSE	6.378465×10^{-2}

- ❖ The value of correlation at 0.9176 (92%) shows that the model is very good and could be of significant practical application.
- ❖ The value 4.068482×10^{-3} for the mean square error (MSE) indicates that the error e_j is minimized at optimal.
- ❖ The coefficient of determination (R^2) value of 0.9176 indicates that 81.36% of the variation in the Safety Factor, Ỳ, could be accounted for by, X, coolant flow rate for PWRD I. this value further proves that the model is good;

2. Pressurized Water Reactor Design II (PWRD II)

We also considered sample from Pressurized water reactor (PWR) in PWRD II, by performing experiment on PWRD II taken input parameters from reactor similar to the shutdown *pressurized water reactor (PWR)* at Palisades, Michigan, USA.

The data was modified in other to obtain the best fit for the model.

(i) Empirical Expression for Safety Factor, Ỳ

The data obtained in Table 2 which represents typical parameter for Pressurized Water Reactor Design II (PWRD II) was modified in order to obtain the best fit for the model. The new conceptual design reactor model optimizes the performance of the shutdown *pressurized water reactor (PWR)* at Palisades, Michigan, USA and the accident PWR *at* Davis-Besse Nuclear Power Station in Oak Harbor, Ohio, USA.

The model empirical expression for the Safety Factor Ỳ is obtained, as:

$$\grave{Y} = (-91.9048) + (1.8810)*(X_j) + e_j \quad (1.3)$$

where,
-91.9048 is an intercept,
1.8810 is a slope,
X is the rate of flow of water coolant and
e = error or residual and j = 1,2,3,…,13.

- The equation (1.3) is the model empirical expression that could be applied to make predictions of the Safety Factor, Ỳ, on this type of (PWRD II) model

The Linear Regression Plot Section on PWRD II is shown in Figure 2

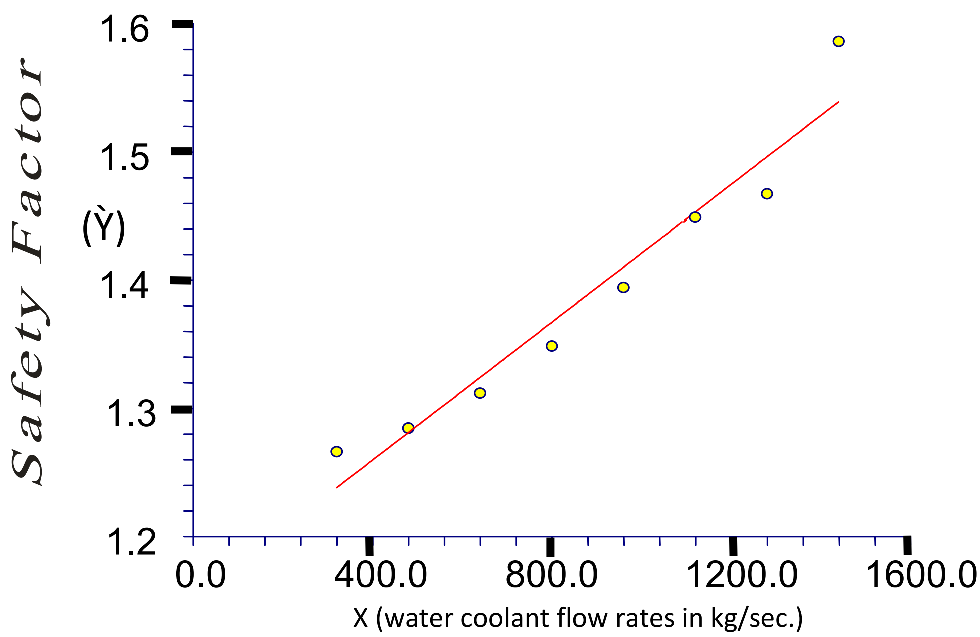

Figure 2: Safety factor (Ỳ) a function of water (coolant) flow rate (X)

The plot in Figures 2 shows the relationship between Safety Factor, Ỳ and the Water (coolant) flow rates, X. The straight line shows that there is a linear relationship and the closeness of the points to the line indicates that the relationship is strong.

Next is the summary of the **F** -test result on PWRD II as shown in Table 3.

(ii) F-test Result

The F-test result on PWRD II is shown in Table 4

Table 4: Summary of F-test Statistical Data on PWRD II

Parameter	**Value**
Dependent Variable	Ỳ
Independent Variable	X
Frequency Variable	None
Weight Variable	None
Intercept (B_0)	-91.9048
Slope (B_1)	1.8810
R^2	**0.9039**
Correlation	**0.9516**
Mean Square Error	**3.883174×10^{-3}**
Coefficient of Variation	0.2109
Square Root of MSE	1.425526×10^{-2}

- ❖ The value of correlation at 0.9516 shows that the model is very good and could be of significant practical application.
- ❖ The value 3.883174×10^{-3} for the mean square error (MSE) indicates that the error e_j is minimized at optimal.
- ❖ The R^2 value of 0.9039 indicates that 90.10% of the variation in Ỳ (Safety Factor) would be accounted for by the water coolant flow rate, X, for PWRD II
  The value of $R^2 = 0.9039$, therefore, proves that the model is good and valid.

3. SUMMARY/CONCLUSION

This work focus on the Pressurized water reactors design models with the use of linear regression analysis technique. Two typical Pressurized water reactors designs viz PWRD I and PWRD II are considered. A typical example of PWRD I is the *pressurized water reactor (PWR)* at Three Mile Island Unit 2 (TM1-2) while a typical of PWRD II are the accident PWR *at* Davis-Besse Nuclear Power Station in Oak Harbor, Ohio and the PWR at Palisades in Michigan.

The empirical expressions for the optimization of nuclear reactor Safety Factor (Ỳ) as functions of coolant flow rate for Pressurized Water Nuclear Reactor Design Models (PWNRDM) are obtained as**:**

(i) $\grave{Y} = (1.3150) + (0.0004)*(X_j) + e_j$, for PWRD I

(ii) $\grave{Y} = (-91.9048) + (1.8810)*(X_j) + e_j$, for PWRD II

These are the model equations that could be applied to make predictions of the safety factor, Ỳ, on these types of Pressurized water reactor design models.

The empirical expressions may also be used for the calculation of the Safety Factor of the reactors which in turn is a measure of the reactor's stability.

The t-test carried out on these model equations gives a promising level of acceptability or validity. Also, the empirical formulae derived can be used to determine the contribution of coolant to the stability of the reactor.

The Table 5 highlights the summary results on coolant effects on water reactors.

Table 5. Summary Results on Coolant Effects on Water Reactors

Types of Nuclear Power Reactor Design Model	**Correlation** values between Safety factor and Coolant	**R^2** Indicating goodness-of -fit	**Mean Square Error** values at which error is minimized at optimal
Pressurized Water Reactors Designs			
PWRD I	0.9176	0.8421	4.068482×10^{-3}
PWRD II	0.9516	0.9176	3.883174×10^{-3}

❖ Figure 3 is a graphical representation comparing the correlation values of PWRD I and PWRD II. It is obvious that the Pressurized water reactor design II (PWRD II), is more stable in terms of Safety Factor. It is also understandable that PWRD II with correlation value of 0.9516 is better optimized than PWRD I with correlation value of 0.9176.

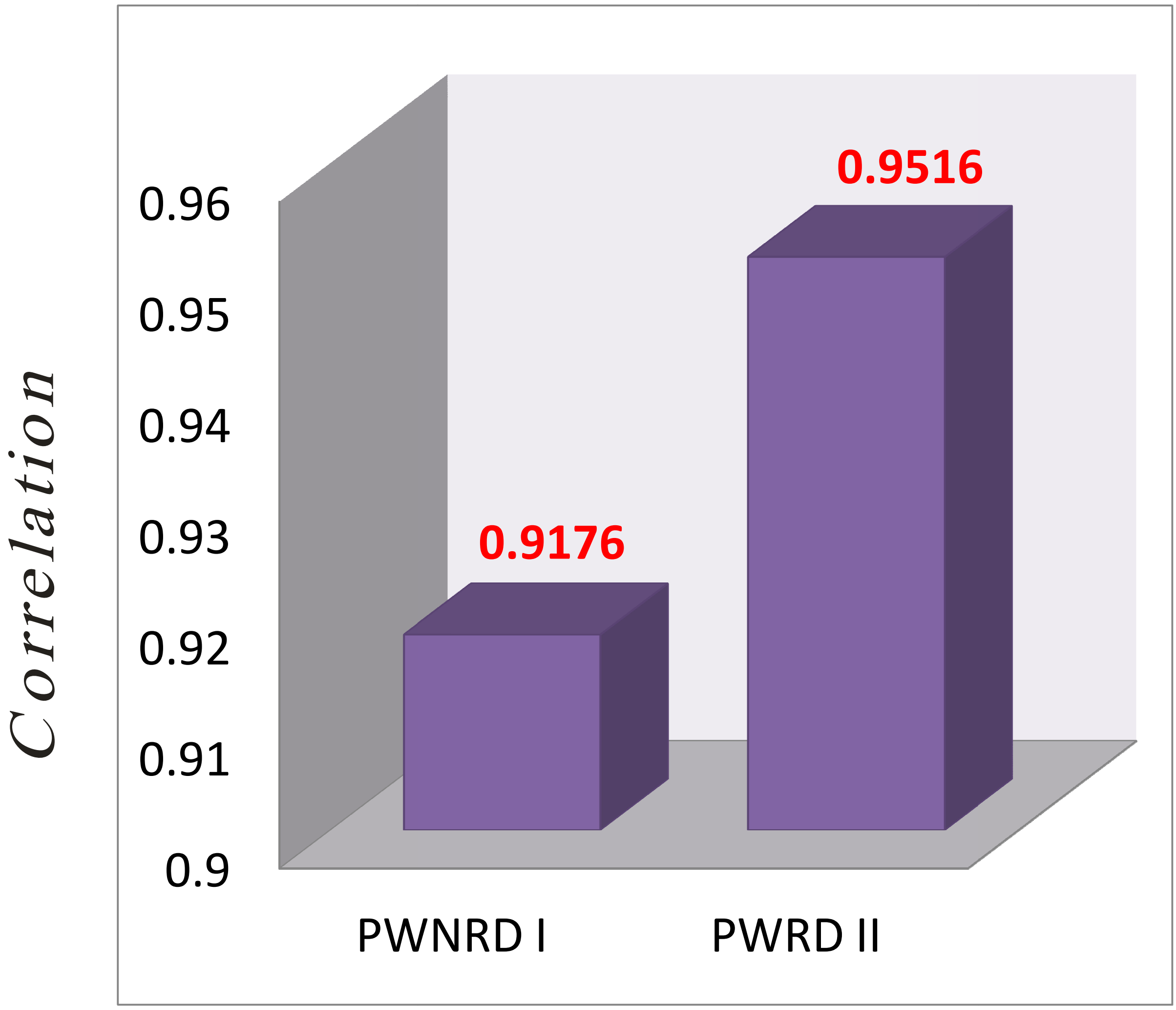

Figure 3. Pressurized Water Reactor Design Models

❖ In Figure 4 the graphical representation shows the $\mathbf{R^2}$ values of Pressurized Water Reactor designs (PWRD I) and (PWRD II). These bar charts reveal that, PWRD I have lower value of coefficient of determination (R^2), than the PWRD II. It is also clear from the figure that the values of PWRD II are better optimized than PWRD I.

PWRD II promises greater stability with coefficient of determination value of 0.9176 and could be seen that it has the best stability and possibly the safer when compared with PWRD I with coefficient of determination value of 0.8421.

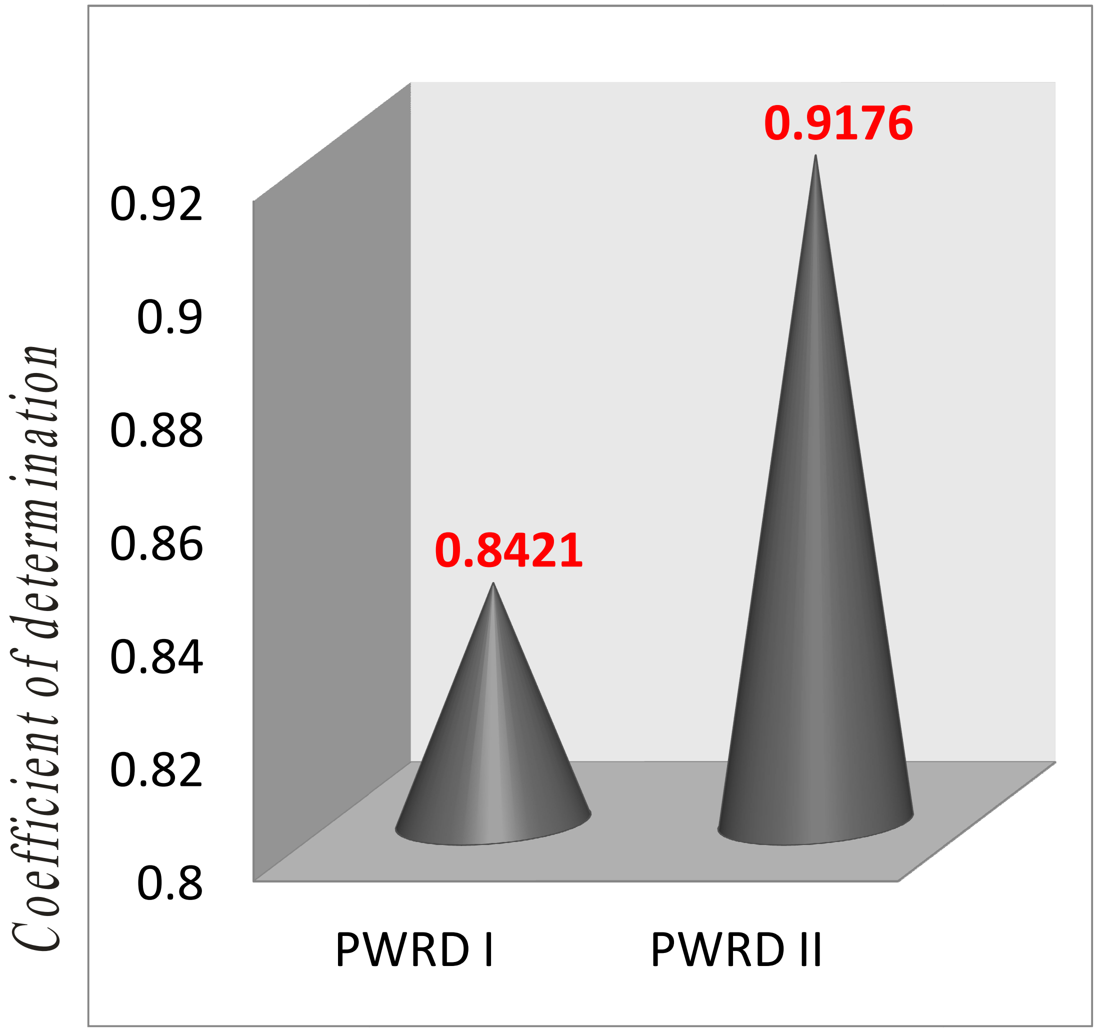

Figure 4. Pressurized Water Reactor Design Models

❖ Furthermore, in Figure 5, the bar charts reveal that PWRD I have higher values of the mean square of error, than the PWRD II. Therefore, since PWRD II have minimal mean square of error it indicates that PWRD II models may promises more safety features than PWRD I models.

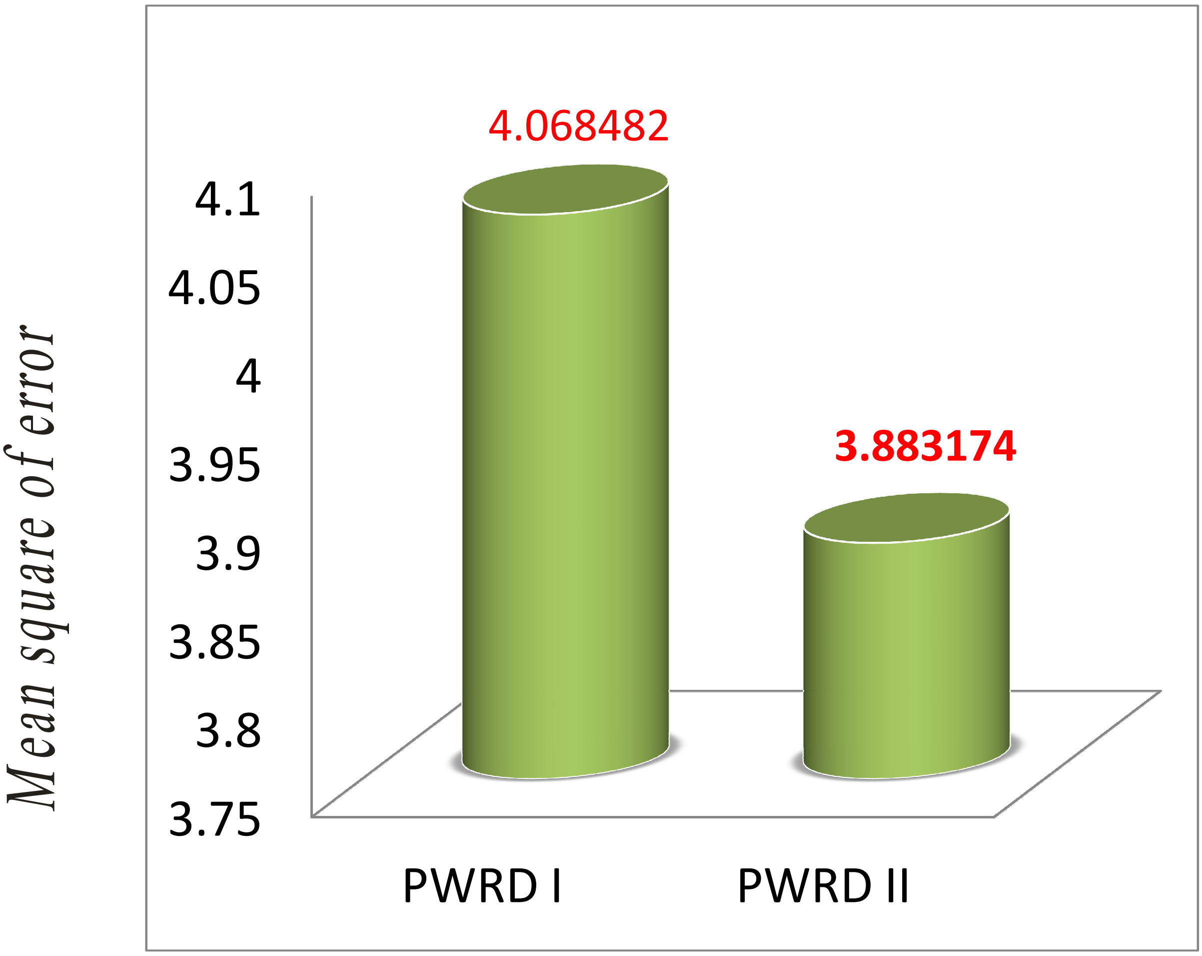

Figure 5. Pressurized Water Reactor Design Models

In conclusion, it has been further demonstrated that the stability margin of Pressurized Water Reactor Design Models can be considerably optimized by the application of Regression Analysis Technique (RAT) on the input design parameter. The implication of this research effort also proved that correlation, coefficient of determination (R^2) and mean square of errors are determinant factor of prediction in RAT.
A comparative analysis of the PWRD I and PWRD II carried out with the use of "RAT" shows that PWRD II with correlation value of 0.9516 may have more inherent Safety and Stability Margin than PWRD I. Likewise, a comparative analysis of the PWRD I and PWRD II shows that PWRD II with highest R^2 value of 0.9176 could be said to have more inherent Safety and Stability Margin than PWRD II. While further comparative analysis of the PWRD I and PWRD II reveals that PWRD II with minimal error value of 3.883174×10^{-3} proved to have more systematic safety features than PWRD I with minimal error value 4.068482×10^{-3}.
Moreover, a comparative analysis of the PWRD I and PWRD II carried out with the use of "RAT" shows that PWRD II with minimal error value of 3.883174×10^{-3} may have more inherent Safety and Stability Margin than PWRD I with minimal error value 4.068482×10^{-3}.
In this method of regression analysis the Safety Margin prediction of up to 4.84% has been validated for reactor design models on pressurized water reactor as an advantage over the current 5.1% challenging problem for plant engineers to predict the safety margin limit. According to Xianxun Yuan (2007, P49) in "Stochastic Modeling of Deterioration in Nuclear Power Plants Components" a challenging problem of plant engineers is to predict the end of life of a system Safety Margin up to 5.1% validation. However, the current design limits for various reactors Safety Factor in a nuclear power plant, defined by the relative increase and decrease in the parametric range at a chosen operating point from its original value, varies from station to station.
Finally, the proposed new method for reactor design concept with the use of coolant as input parameter and the discoveries on water coolant on safety factor shall provides a good, novel approach and method for multi-objective decision-making based on six dissimilar objectives attributes: evolving technology, effectiveness, efficiency, cost, safety and failure.

It is therefore suggested that for countries wishing to include nuclear energy for the generation of electricity, like Nigeria, the parameters of the selected nuclear reactor should undergo analysis via RAT for optimization and choice.

Acknowledgments
We thank Nigeria Atomic Energy Commission (NAEC) Abuja and Department of physics Nigerian Defence Academy (NDA) Kaduna for human and the material support during the research work.

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