NUMERICAL INVESTIGATION OF THE DEFORMATION OF A CONTROL ROD SYSTEM DURING A DROP IMPACT SCENARIO IN A TYPICAL MATERIAL TESTING REACTOR

by

Adel ALYAN* * and Hesham ELKHATIB

Nuclear Research Center, Atomic Energy Authority, Cairo, Egypt

Scientific paper
https://doi.org/10.2298/NTRP190826001A

The control rod drop analysis is very important for safety analysis. A mathematical model of the control rod for the ETRR-2 reactor is presented. A computer program by the Engineering Equation Solver has been developed for investigation of the impact force and the final dropping velocity of the rod. Also, buckling deformation stresses have been simulated using commercial software, ABAQUS/CAE release 6.14-5. This paper describes the theoretical results required to obtain the von Mises stress at maximum impact force during the control rod drop. The control rod velocity after the rod reached the reactor core bottom has been predicted which reached up to 3.8 ms^{-1} after a drop time equal to 0.41 s at the end of the reactor core height. The results showed that the maximum and minimum von Mises stresses are 90 MPa and 6.345 MPa at maximum and minimum impact force of 6625 N and 755.73 N, respectively.

Key words: control rod, impact force, displacement, MTR research reactor

INTRODUCTION

The control rod drop-down time is very important for safety. One of the three factors necessary to ensure the reactor safety is reactivity control. The key reactivity control is the control rod drop-down time. The consequences of a control rod drop accident have been examined for the Canadian Super Critical Water Reactor. The study shows that almost all the transients reached a maximum fuel center line above (3100 K). Therefore fuel melting would occur in most cases and show the necessity for special safety system action for these events [1]. A non-linear dynamics response analysis software has been produced for the nuclear power plant which was used to calculate the control rod drop-down time. The displacement, velocity, acceleration and friction force of the rod has been calculated during its drop-down process and found that the collision has a large effect on the drop time of the control rod [2]. A numerical simulation and experimental analysis have been produced to analyze the drop of the rod in the Thorium Molten Salt Reactor (TMSR-SF1).

The driving mechanism transmission efficiency is deduced as a relationship with the dropping velocity of the rod. It was found that the fast drop time is about 2.02 s in the molten salt environment, which is matched with the reactor limiting drop time, 6 s [3]. A new method for the control rod analysis is suggested by the finite element method. This analysis model includes the structure and fluid parts, termed as a fluid and structure interaction (FSI). It was found that this method can simulate the fluid-structure coupled algorithm under the core conditions at an operating temperature [4]. This paper presents a mathematical model which permits the designers to study the effects of different parameters on the scram time. The model can be used in the preliminary design stage to optimize the design for the shortest control rod drop-down time.

DESCRIPTION OF THE REACTOR CONTROL ROD SYSTEM

The first shutdown system consists of six absorbing plates. The absorbing material is an alloy of Ag-In-Cd and clad with stainless steel. This alloy is used extensively in material testing reactors. The absorbing material has the following dimensions (width 144 mm, height 820 mm, thickness 3.6 mm). The control plates are placed inside guide boxes which have a parallel structure; there are two guide boxes at opposite sides of the core, with three control plates each. The guide boxes prevent interference between the control plates and fuel elements [5]. The control rod mechanism is located below the reactor core level.

* Corresponding author; e-mail: adelalyan@yahoo.com

Figure 1 depicts the schematic view of the control rod system which is placed inside the control room mechanism below the reactor. The main components of the system are:
– mechanism drive,
– pneumatic cylinder,
– compressed air tank, and
– flexible compressed air hose.

Taking into account that the reactivity control system is critical to reactor safety, a sufficient shut down reactivity shall be provided so that the reactor can be brought to a subcritical level and maintained subcritical with an adequate margin under all operational states and accident conditions, with the reactivity effect of experiments taken into account [6].

A drop impact analysis of a fuel assembly in a research reactor has been carried out by [7] to determine whether the fuel plate integrity is maintained in a drop accident. The direct impact of a fuel assembly on the pool bottom has been analyzed using implicit and explicit approaches.

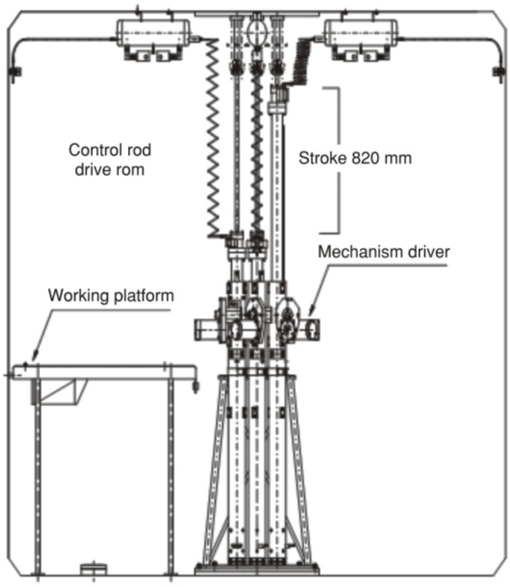

Figure 1. Schematic view of the control rod system

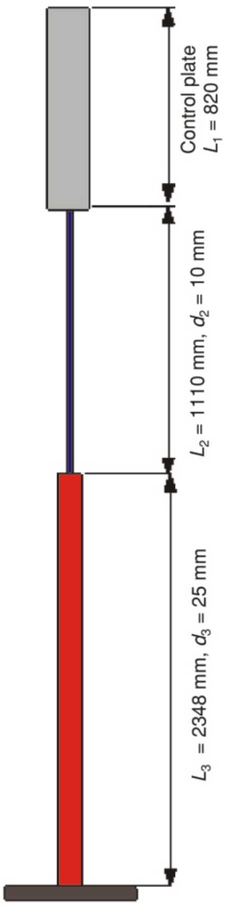

Figure 2. Schematic view of the control rod dimension

MATHEMATICAL MODEL

The mathematical model for the control rod drop in water has some assumptions and simplifications as follows:
– incompressible flow,
– purely axial flow,
– constant hydrostatic pressure head, and
– symmetric circumferential flow.

A simplified schematic diagram of the control rod is shown in figure fig. 3.

A model for the control rod simulation was created by using the ABAQUS/CAE release 6.14-5 code to simulate the deformation during the control rod

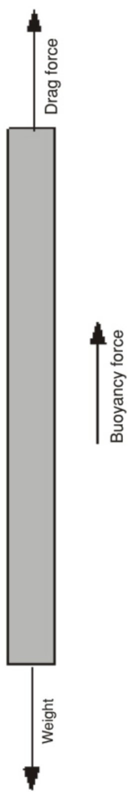

Figure 3. Simple model description of the control rod

Table 1. Control plate dimensions [5]

	Ag-In-Cd	Total with cladding
Width	144 mm	147 mm
Length	820 mm	1000 mm
Thickness	3.6 mm	5.3 mm

drop. Also, a Fourier series equation has been solved to simulate the buckling deformation. The solution of the Fourier series has been programmed by a commercial program which is called the engineering equation solver (EES). The materials and dimensions of the control rod are summarized in tab. 1.

The general equation for the rod's drop is written as, [7]

$$m\frac{\mathrm{d}v}{\mathrm{d}t} \quad (m \quad \rho V)\mathrm{g} \quad F \tag{1}$$

where m is the control rod mass, t – the time, V – the control rod volume, g – the acceleration of gravity, and F – the drag force. The submerged weight of the control rod is $(m - \rho V)$ g. In fluid dynamics, the drag equation is a practical formula used to calculate the drag force owing to movement through a fully enclosing fluid. The drag force is written as, [7]

$$F \quad \frac{1}{2}\rho A C_D v^2 \tag{2}$$

where A is the orthographic projection of the control rod on a plane perpendicular to the direction of motion and C_D – the drag coefficient. As the velocity of the control rod increases, the resisting drag force also increases. The differential eq. (1) is rearranged as follows

$$\int_0^v \frac{\mathrm{d}v}{(m \quad \rho V)\mathrm{g} \quad \frac{1}{2}\rho A C_D v^2} \quad \frac{1}{m}\int_0^t \mathrm{d}t \tag{3}$$

Solving this differential equation, the velocity becomes

$$v \quad \sqrt{\frac{(m \quad \rho V)\mathrm{g}}{\frac{1}{2}\rho A C_D}} \tanh t \frac{\sqrt{(m \quad \rho V)\mathrm{g}\frac{1}{2}\rho A C_D}}{m} \tag{4}$$

Equation (4) is the analytical solution of the terminal velocity, which considers the weight, buoyancy and drag forces. The control rod accelerates until the gravitational force balances the resistance forces created by the fluid. At this time, the control rod has reached its maximum kinetic energy and consequently its terminal velocity. Since the acceleration here is zero, the terminal velocity is then [7]

$$v_{\mathrm{ter}} \quad \sqrt{\frac{(m \quad \rho V)\mathrm{g}}{\frac{1}{2}\rho A C_D}} \tag{5}$$

where v_{ter} is the terminal velocity.

Calculation of impact force

The dynamic energy of a falling object at the impact moment can be calculated as [8]

$$E_{\mathrm{De}} \quad F_{\mathrm{w}} h \quad mgh \tag{6}$$

where F_{W} is the force due to gravity, g – the acceleration of gravity, and h – the falling height.

The impact force can be expressed as [8]

$$F_{\max} \quad 2\,mgh / \mathrm{S} \tag{7}$$

where S [m] is the deformation slow-down distance.

Dynamic buckling analysis

The equation of motion for lateral displacement y (x, t) from the initial shape $y_0(x)$ is

$$EI\frac{\partial^4 y}{\partial x^4} \quad P(t)\frac{\partial^2}{\partial x^2}(y \quad y_0) \quad \rho A\frac{\partial^2 y}{\partial t^2} \quad 0 \tag{8}$$

where E is Young's modulus, I – the moment of inertia of the bar section, EI – the bending stiffness, ρ – the mass density, ρA – the linear density, and x and t – the axial coordinate and time, respectively [9].

After dividing through by EI, it is convenient to introduce the parameters

$$k^2 \quad \frac{P}{EI} \quad r^2 A \quad \frac{I}{A} \quad c^2 \quad \frac{E}{\rho} \tag{9}$$

The first two parameters have already appeared in the static buckling problem. The new parameter c, which appeared because of the dynamic inertia term, is the wave speed of the axial stress waves in the bar. When these quantities are used the equation of motion (8) becomes [9]

$$\frac{\partial^4 y}{\partial x^4} \quad k^2\frac{\partial^2 y}{\partial x^2} \quad \frac{1}{r^2 c^2}\frac{\partial^2 y}{\partial t^2} \quad k^2\frac{\partial^2 y_0}{\partial x^2} \tag{10}$$

$$P_{\mathrm{cr}} \quad \frac{\pi^2 EI}{L^2} \tag{11}$$

where P_{cr} [GPa] is the critical load, modulus of elasticity, I – the moment of inertia, and L – the length of the rod [10].

$$I \quad \frac{\pi}{64}d^2 \tag{12}$$

where d is the rod diameter [10].

RESULTS AND DISCUSSION

Figure 4(a) and 4(b) shows the ABAQUS 3-D model of the control rod. The ABAQUS/ CAE, software has its own drawing entity which is capable of drawing the model in a 3-D mode, and also has a mesh tool to mesh the model with an adequate mesh model.

Figure 5 shows the buckling deformation at minimum impact force 755.73 N produced by ABAQUS/CAE. By considering the mass of the control plate set, M, falling from the top of the core moving at a height, d, under the influence of the gravity on top of the lower part of the control mechanism causing an impact force, F, this force causes a buckling deflection to the rod as seen in fig. 5 and subsequently the rod shall? breaks down. The impact force for operating conditions should be less than 755.73 N to eliminate the possibility of rod buckling.

Figure 6 depicts the von Mises stress at a minimum impact force, 755.73 N calculated by the ABAQUS/CAE release 6-14-5. The results showed that there is a minimum stress affected on the upper part of the control rod with the value of 6.345 MPa

Von Mises stress at maximum impact force has been calculated by using the ABAQUS/CAE release 6.14-5 as shown in fig. 7. The first part of the control rod, whose length is 1198 mm and diameter is 10 mm was subjected to 90 MPa as a maximum stress when the impact force reached up to 6625 N.

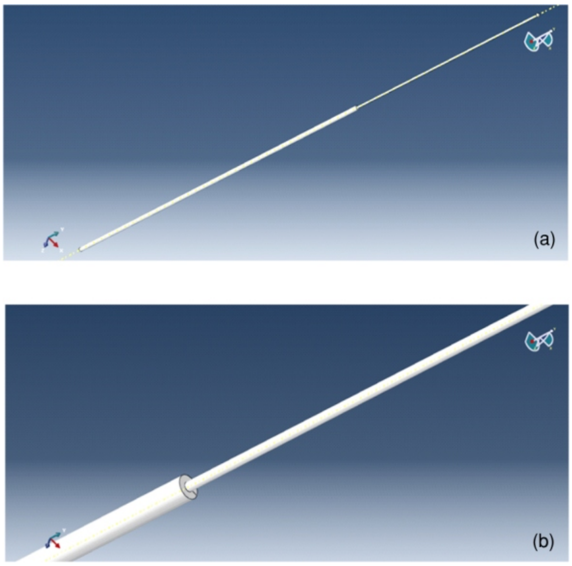

Figure 4. The ABAQUS 3-D control rod model

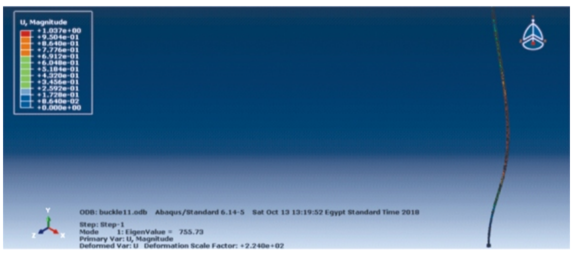

Figure 5. The ABAQUS buckling deformation at impact force F = 755.73 N

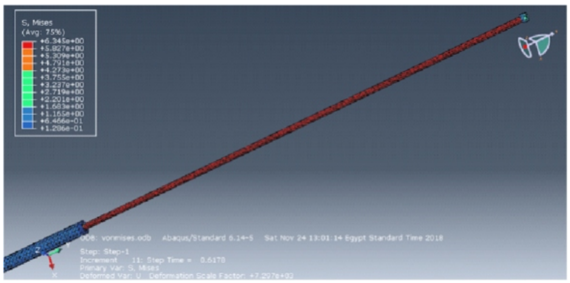

Figure 6. Von Mises stress at critical impact force F = 755.73 N

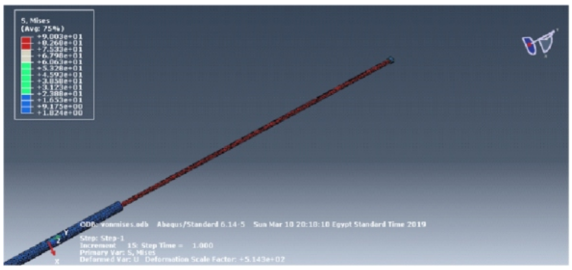

Figure 7. Von Mises stress at maximum impact force F = 6625 N

Figure 8 illustrates the relation between the control rod position and its velocity during the motion processes of the control rod in the reactor core from the top position to the bottom position. At the beginning of the rod drop, the gravity strong, so the rod is accelerating gradually from the stopping state overcoming the drag force and the buoyancy force. As the rod drops, its acceleration increases with time, subsequently increasing its velocity. The calculations showed that the control rod reached the bottom of the reactor core after travelling a distance equal to 0.8 m within the drop time of 0.41 s and the terminal drop velocity was 3.8 ms^{-1}.

Figure 9 shows the maximum impact force, which was produced at the impact moment, which was equal to 6625 N till the run number (51) which was associated to the scram time 0.5 s.

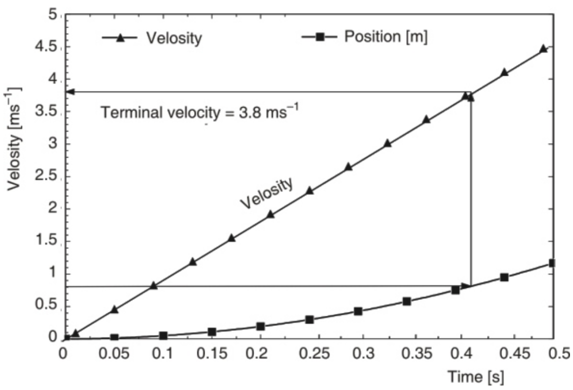

Figure 8. Control rod drop for 0.5 seconds, solution time

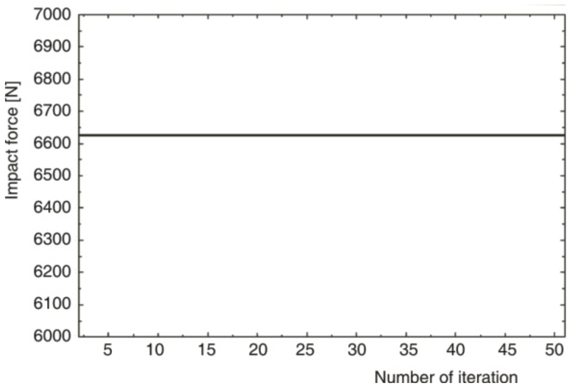

Figure 9. The maximum impact force history

CONCLUSIONS

The control rod drop analysis has not previously been assessed for the ETRR-2 reactor. In this study, the drop of the control rod is predicted in a theoretical way by developing a computer code with the engineering equation solver package to predict the terminal drop velocity of the control rod at the reactor core bottom. The control rod travels from the top of the core to the bottom of the core for a distance of 0.8 m with velocity of 3.8 ms^{-1} in a drop time of 0.41 s. The ABAQUS/CAE release (version) 6.14-5 is used to predict the von Mises stresses. The produced stresses are 6.345 MPa at an impact force of 755.37 N and 16.34 MPa at a maximum impact force of 6625 N. A critical buckling deformation force of 783.69 N is predicted by multiplying the U-magnitude of (1.037) by the eigenvalue of (755.73). The impact force for operating conditions should be less than 755.73 N to eliminate the possibility of rod buckling, and the drop time should be not less than 400 ms. The recommendation for solving of the presented problem could be summarized as follows

The material of the control rod could be changed to another material which has a high stiffness in order to resist the failure probability.

The shock absorber of the control rod must be checked from the design point of view to minimize the impact force generated from the scram.

The material of the control rod and shock absorber of other similar research reactors should be considered.

The reactor operators have to follow the correct operating instructions to avoid the repeated undesirable scram and have to investigate the reasons.

ACKNOWLEDGMENT

The authors appreciate the support from the nuclear research center during the conducting of this work.

AUTHORS' CONTRIBUTIONS

Both authors have made the same contribution to model the problem and analysis of the results. The manuscript was prepared and written by Adel Alyan.

REFERENCES

[1] Frederic, S., *et al*., Analysis of Control Rod Drop Accidents for the Canadian SCWR Using Coupled 3-Dimensional Neutron Kinetics and Thermal Hydraulics, *Science and Technology of Nuclear Installations,* (2018), pp. 1-17
[2] Daogang, L., *et al*., R&D on a Nonlinear Dynamics Analysis Code for the Drop Time of the Control Rod, *Science and Technology of Nuclear Installations,* (2017), pp. 1-6
[3] Zuokang, L., *et al*., Control Rod Drop Dynamic Analysis in the TMSR – SF1 Based on Numerical Simulation and Experiment, *Nuclear Engineering and Design, 322* (2017), Oct., pp. 131-137
[4] Yoon, K. H., *et al*., Control Rod Drop Analysis by Finite Element Method Using Fluid-Structure Interaction for a Pressurized Water Reactor Power Plant, *Nuclear Engineering and Design, 239* (2009), 10, pp. 1857-1861
[5] ***, Safety Analysis Report (SAR) of ETRR-2, Cairo, June 2003
[6] ***, Code on the Safety of Nuclear Research Reactors: Design, IAEA Safety Series 35-S1, 1992
[7] Kim, H-J., *et al*., Drop Impact Analysis of Plate- Type Fuel Assembly in Research Reactor, *Nuclear Engineering and Technology, 46* (2014), 4, pp. 529-540
[8] ***, https://www.engineeringtoolbox.com/impact-force-d_1780.html
[9] Lindberg, H. E., Little Book of Dynamic Buckling, September, 2003
[10] Gere, J. M., Mechanics of Materials, 6^{th} ed., Thomson Learning, IncInc., USA, 2004

Received on August 26, 2019
Accepted on December 31, 2019

Адел АЛИАН, Хешам ЕЛКАТИБ

НУМЕРИЧКО ИСТРАЖИВАЊЕ ДЕФОРМАЦИЈЕ СИСТЕМА КОНТРОЛНЕ ШИПКЕ ТОКОМ СЦЕНАРИЈА ПАДА ШИПКЕ У ТИПИЧНОМ РЕАКТОРУ ЗА ИСПИТИВАЊЕ МАТЕРИЈАЛА

Анализа пада контролне шипке веома је важна за анализу сигурности, те је приказан математички модел контролне шипке реактора ETRR-2. Развијен је рачунарски програм компаније Engineering Equation Solver за испитивање силе удара и коначне брзине пада шипке. Такође, деформациони напони извијања симулирани су коришћењем комерцијалног софтвера, ABAQUS/CAE верзија 6.14-5. Овај рад описује теоријске резултате потребне за постизање фон Мисесовог напрезања при највећој ударној сили током пада контролне шипке. Предвиђено је брзина контролне шипке након што је достигла дно језгра од 3.8 ms^{-1}, после пада који је трајао 0.41 секунду до дна реактора. Резултати су показали да су максимална и минимална фон Мисесова напрезања 90 MPa и 6.345 MPa при максималној и минималној ударој сили од 6625 N и 755.73 N.

Кључне речи: контролна шипка, ударна сила, измештање, MTR истраживачки реактор