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CONJUGATE GRADIENT METHOD FOR ELEMENTS OF NUCLEAR REACTOR ON SAFETY CONTROL

L. Aminu[1], J. O. Omolehin[2*], P. Dickson and Z. Onimisi[4]
1.Federal College of Fisheries and Marine technology, Victoria Island, Lagos
2.Department of Mathematical Sciences, Federal University Lokoja
3.University de Dschang, Western Cameroon
4.Department of Mechanical Engineering Technology, Kogi State Polytechnic, Lokoja, Nigeria.

ABSTRACT
Nuclear technology is a scientist venture that is used for the development of mankind. The accident of that venture can be devastating and catastrophic. This paper considers the safety aspect of it. Mathematical approach is used to structure the safety. Specifically, Conjugate Gradient Method (CGM) is used as the modeling algorithm for the elements of energy equations associated with the reactor of nuclear rod. It is proved that a reactor can be programed for optimal performance with minimum accident if the theoretical and the numerical processes of CGM are employed.

1. INTRODUCTION
As the nation of the world seek to meet the increasing demands for energy which lead to increases in environmental pollution from the burning of coal, oil and natural gas. The use of fossil fuels for transportation, generating electricity, heat and industrial production account for 85 percent [1] of the world's energy consumption. The environmental consequences of this heavy reliance on fossil fuel are only being fully realized. Sulphurdioxide emissions are said to cause acid rain. Nitrous oxide are said to cause smog. Particles in the air, from the burning of coal and oil, cause all manners of human lung ailments. The scientific community now believes that emissions of carbon dioxide, resulting from the burning of fossil fuels, is the leading contributor to global warming. Accordingly, the leaders of almost every nation in world met in Kyoto, Japan in December 1997 to establish aggressive limits to future use of fossils fuels. In spite of these concerns, fossil fuels are necessary to meet the world's energy demand. How long can the planet's environment continue to withstand the pollutant load caused by the emissions from these fossil sources? The answer is not certain, but the leaders of the world concluded in Kyoto that dramatic action is necessary even without having all the scientific data because the consequences of being wrong are too severe. Improvements in every efficiency, conservation and decrease in the use of fossil fuels will all be required if there is any hope of achieving the aggressive targets established by the political leaders. It is also necessary to develop non-carbon alternatives for energy production. Solar, wind and hydro-power are often mentioned for electric generation as they have been for many years. One of the sources of energy that has

*Corresponding Author

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provided many nations of the world with vast amount of electric power. The United States depends on nuclear energy for 20percent of its electricity. France, Japan, Germany, Korea, Taiwan, Sweden, Iran to name but a few, also have high reliance on nuclear energy [2]. The expanded role for nuclear power of many nations in their energy portfolios is driven by concerns about global warming, growth in energy demand and relative costs of alternative energy sources. In 2008, 435 nuclear reactors in 30 countries provided 16percent of the world's electricity. In January 2009, 43 reactors were under construction in 11 countries, with several hundred more projected to come on line globally by 2030 [3].

2. NUCLEAR REACTOR PROCESS

Nuclear reactors produce energy through a controlled fission chain reaction. While most reactions generate electric power, some can also produce plutonium for weapons and reactor fuel. Power reactors use the heat from fission to produce stream, which turns turbines to generate electricity. In this respect, they are similar to plants fuelled by coal and natural gas. The components common to all nuclear reactors include a fuel assembly, control rods, a coolant, a pressure vessel, a containment structure and an external cooling facility.

Thermal reactors operate on the principle that uranium-235 undergoes fission more readily with slow neutrons than with fast ones. Light water$()OH_2$, heavy water $()OD_2$, and carbon in the form of graphite are the most common moderators. Since slow neutron reactors are highly efficient in producing fission in uranium-235, they use fuel assemblies containing either natural uranium (0.7percent U-235) or slightly enriched uranium (0.9 to 2percent U-235) fuel. Rods composed of neutron absorbing materials such as cadmium or boron are inserted into the fuel assembly. The position of these control rods in the reactor core determines the rate of the fission chain reaction. The coolant is a liquid or gas that removes the heat from the core and produces stream to drive the turbines. In reactors using either light water or heavy water, the coolant also serves as the moderator. Reactors employing gaseous coolants $()HeorCO_2$ use graphite as the moderator. The pressure, made of heavy-duty steel, holds the reactor core containing the fuel assembly, control rods, moderator and coolant. The containment structure, compose of thick concrete and steel, inhibits the release of radiation in case of an accident and also secure components of the reactor from potential intruders. Finally, the most obvious components of many nuclear power plants are the cooling towers, the external components, which provide cool water for condensing the stream to water recycling into the containment structure. Cooling towers are also employed with coal and natural gas plants[4].

3. TYPE OF THERMAL REACTORS

Most of the nuclear power plants in the world are water-moderated thermal reactors. They are categorized as either light water or heavy water reactors. Light water reactors use purified natural water $()OH_2$ as the coolant/moderator, while heavy water reactors employ heavy water deuterium oxide $()OD_2$. In light water reactors, the water is either pressured to keep it in superheated form (in a pressurized water reactor employ heavy water reactor, PWR) or allowed to vaporize, forming a mixture of water and stream (in boiling water reactor, BWR). In PWR, superheated water flowing through tubes in the reactor core transfers the heat generated by fission to a heat exchanger, which produces steam in a secondary loop to generate electricity. None of the water flowing through the reactor core leaves the containment structure.

Other thermal reactors are Boiling Water Reactor (BWR), Heavy Water Reactor (HWR), Gas Cooled Reactor, Pebble Bed Reactor and Fast Neutron Reactor.

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4. DIFFERENT TYPES OF NON-NUCLEAR ELECTRIC POWER PLANTS

We have different types of non-nuclear electric power generation. Some are Windmills, Hydro-electric power (falling water) plants, Fossil-fuels plant and Solar cell plants.

5. WIND-MILL PLANT

This plant is a device for tapping the energy of the wind by means of sails mounted on a rotating shafts. It is generally less reliable than the water power, but where water is deficient wind power is an attractive substitute. Wind-mill plant can be used in areas that suffer from draught or from a shortage of surface water and also in a low-lying area where rivers offer little energy. They were mostly used, converting the energy of the wind into mechanical energy for grinding grain, pumping water and drainage. They produced less energy for electricity[5].

6. HYDRO-ELECTRIC POWER

It is the electricity produced from generators driven by water turbines that convert the potential energy in falling or fast-flowing water to mechanical energy. They are usually located in dams that impound rivers; especially in areas with heavy rain fall and hilly or mountainous region. In generation, water is collected or stored at a higher elevation and led downward through large pipes or tunnels to a lower elevation. At the end of its passage down the pipes, the falling water causes turbines mechanical energy into electricity [6]. Although hydro-electric power plants are not hazardous as the fossil fuels, but it may not meet the electricity demand of a country as fossil fuels would. Also if there is not enough water impounded in reservoirs during the dry season, the falling water would not be enough to cause the turbine to turn to generate electricity.

7. FOSSIL-FUELS

The production of stream by fossil-fuels, produce the greatest amount of electrical energy compared to hydro-electric and wind-mills. Fossil-fuels are coal, petroleum, natural gas, oil shale, bitumen, tar sands and heavy oil. All contain carbon and were formed as a result of geologic processes acting on the remains of organic matter produced by photosynthesis. All fossil-fuels can be burned in air or with oxygen to provide heat. The heat may be utilized to produce steam to drive generators that can supply electricity [7]. The use of fossil-fuels is very hazardous to human health as a result of environmental pollutant from burning of the fuels.

8. SOLAR CELL PLANTS

This is the best plant that can only be conveniently used on satellites and space where the flow of energy out of the sun (the solar wind) can be harnessed without interference from the atmosphere or the rotation of the earth [8]. Although this type of non-nuclear power plant can also be used on earth, but cannot produce the desire electricity because of the changes in atmospheric conditions and rotation of the earth.

9. ADVANTAGES OF NUCLEAR PLANT OVER NON-NUCLEAR PLANT

All the non-nuclear power generation discussed above produced low electricity compared to the nuclear reactors. The nuclear reactor released a large amount of energy during the process of fission. Most of this energy released takes form of heat, which is used to produce steam. The steam drives a turbine, the mechanical energy of which is converted to electricity by a generator. The whole process takes place in a safety environment that is not hazardous to the human. The nuclear reactor eliminates most of the disadvantages of the non-nuclear energy by generating enough energy for consumption; does not emission of carbon which is very dangerous to the environment; does not involve burning of coal and oils that are the causes of all manners of lung ailments and also does not dependent on fossil-fuels.

10. SOME NUCLEAR ACCIDENTS

There were three major nuclear reactor accidents they are the three moles island in Pennsylvania, USA in 1979 [3], the Chernobyl RBMK in Soviet Union in 1986 [10] and Fukushima nuclear reactor accident in Tokyo,

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Japan in 2011 [11].
With the above analysis on nuclear accidents, nuclear technology is necessary for power generation if the safety concerns can be adequately addressed and that is why this work is purely devoted to the safety aspect and not to the weapons production. Power from the reactors produce energy in form of heat that releases steam to turn turbine to generate electricity, therefore it is necessary to find equations for rate of heat that can be used for the purpose of our work.

1. MAIN RESULT

a. NOMENCLATURE

The following nomenclatures are the elements of nuclear reactor

A = heat transfer area

C_j = concentration of species j

C_{jf} = feed concentration of species j

C_{js} = steady-state concentration of species j

C_P = constant-pressure heat capacity

$\overline{C}_{Pj}$ = partial molar heat capacity

C_{Ps} = heat capacity per volume

$\hat{C}_P$ = constant-pressure heat capacity per mass

$\hat{C}_V$ = constant-volume heat capacity per mass

ΔC_P = heat capacity change on reaction, $\Delta C_P = \sum_j V_j \overline{C}_{Pj}$

E = total energy

$\hat{E}$ = total energy per mass

$\overline{H}_j$ = partial molar enthalpy

$\hat{H}$ = enthalpy per mass

ΔH_{Ri} = enthalpy change on reaction, $\Delta H_{Ri} = \sum_j V_{ij} \overline{H}_j$

k_i = reaction rate constant for reaction i

k_m = reaction rate constant evaluated at mean temperature T_m

K_i = equilibrium constant for reaction i

$\hat{K}$ = kinetic energy per unit mass

m_k = total mass flow of stream k

n = reaction order

n_j = moles of species j, $V_R C_j$

n_r = number of reactions in the reaction network

n_s = number of species in the reaction network

P = pressure

P_j = partial pressure of component j

$P_{nj} = \left(\frac{\partial P}{\partial nj}\right) T, V_{nk}$

Q = volumetric flow rate

Q_f = feed volumetric flow rate

Q_r = heat transfer rate to reactor

r_i = reaction rate for ith reaction

R_j = production rate for jth species

t = time

T = temperature

T_a = temperature of heat transfer medium

T_m = mean temperature at which k is evaluated

U_o = overall heat transfer coefficient

$\hat{U}$ = internal energy per mass

v_k = velocity of stream k

V = reactor volume variable

V = reactor volume variable

$\dot{V}_j$ = partial molar volume of species j

V_R = reactor volume

ΔV_i = change in volume upon reaction $i, \sum_j V_{ij} \overline{V}_j$

W = rate work is done on the system

α = coefficient of expansion of the mixture, $\alpha = \left(\frac{1}{V}\right)\left(\frac{\partial V}{\partial T}\right)P, nj$

τ = reactor residence time, $\tau = V_R / Q_f$

V_{ij} = stoichiometric coefficient for species j in reaction i

$\overline{V}_j = \sum_j V_{ij}$

ρ = mass density

ρ_k = mass density of stream k

b. THE ENERGY BALANCE FOR REACTORS

The following results, which are to be used in our control operator in our CGM were obtained through energy balance equation and were arranged in terms of rate of heats of the reactors (i.e. batch, continuous stirred tank, semi batch and plug flow). See [15].

$$Q_{11} = \frac{dU}{dt} - W_s - W_b \qquad (12.1)$$

$$Q_{12} = \frac{dU}{dt} + p\frac{dV_R}{dt} \qquad (12.2)$$

$$Q_{13} = \frac{dH}{dt} - V_R\frac{dP}{dt} \qquad (12.3)$$

$$Q_{14} = V_{R\rho}\hat{C}_P\frac{dT}{dt} - \alpha TV_R\frac{dP}{dt} + \sum_j \overline{H}_j\frac{dn_j}{dt} \qquad (12.4)$$

$$Q_{15} = V_{R\rho}\hat{C}_P\frac{dT}{dt} - \alpha TV_R\frac{dP}{dt} + \sum_i \Delta H_{Ri} r_i V_R \qquad (12.5)$$

$$Q_{16} = V_{R\rho}\hat{C}_P\frac{dT}{dt} + \sum_i \Delta H_{Ri} r_i V_R \qquad (12.6)$$

$$Q_{21} = \Delta H_R r V_R \qquad (12.7)$$

$$Q_{22} = \Delta H_R k C_A^2 V_R \qquad (12.8)$$

$$Q_{23} = V_{R\rho}\hat{C}_V\frac{dT}{dt} + \sum_i\left[\Delta H_{Ri} - \alpha TV_R\sum_j V_{ij}\left(\frac{\partial P}{dn_j}\right)_{T,V,n_k}\right] r_i V_R \qquad (12.9)$$

$$Q_{24} = V_{R\rho}\hat{C}_V\frac{dT}{dt} + \sum_i\left(\Delta H_{Ri} - RT\overline{V}_i\right) r_i V_R \qquad (12.10)$$

$$Q_{25} = \frac{dU}{dt} - Q_{f\rho f}\hat{H}_f + Q_\rho\hat{H} - W_s - W_b \qquad (12.11)$$

$$Q_{26} = \frac{dU}{dt} + P\frac{dV_R}{dt} - Q_{f\rho f}\hat{H}_f + Q_\rho\hat{H} \qquad (12.12)$$

$$Q_{31} = \frac{dH}{dt} - V_R\frac{dP}{dt} - Q_{f\rho f}\hat{H}_f + Q_\rho\hat{H} \qquad (12.13)$$

$$Q_{32} = V_{R\rho}\hat{C}_P\frac{dT}{dt} - \alpha TV_R\frac{dP}{dt} + \sum_j \overline{H}_j\frac{dn_j}{dt} - Q_{f\rho f}\hat{H}_f + Q_\rho\hat{H} \qquad (12.14)$$

$$Q_{33} = V_{R\rho}\hat{C}_P\frac{dT}{dt} - \alpha TV_R\frac{dP}{dt} + \sum_i \Delta H_{Ri} r_i V_R + \sum_i C_{jf}Q_f\left(\overline{H}_{jf} - \overline{H}_j\right) \qquad (12.15)$$

$$Q_{34} = V_{R\rho}\hat{C}_P\frac{dT}{dt} + \sum_i \Delta H_{Ri} r_i V_R + \sum_i C_{jf}Q_f\left(\overline{H}_{jf} - \overline{H}_j\right) \qquad (12.16)$$

$$Q_{35} = V_{R\rho}\hat{C}_P\frac{dT}{dt} + \sum_i\left(\Delta H_{Ri} - \alpha TV_R\sum_j V_{ij}P_{nj}\right) r_i V_R - \sum_i C_{jf}Q_f\left(\overline{H}_{jf} - \overline{H}_j\right) - \alpha TV_R\sum_j P_{nj}\left(C_{jf}Q_f - C_jQ\right)$$

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(12.17)

$$Q_{36} = V_{R\rho}\overset{\therefore}{C}_P\frac{dT}{dt} + \sum_i\left(\Delta H_{Ri} - RT\overline{V}_i\right)r_iV_R - \sum_i C_{jf}Q_f\left(\overline{H}_{jf} - \overline{H}_j\right) - RT\sum_j P_{nj}\left(C_{jf}Q_f - C_jQ\right)$$

(12.18)

$$Q_{41} = \sum_i \Delta H_{Ri}r_iV_R - Q_{f\rho f}\overset{\therefore}{C}_P\left(\overline{T}_f - \overline{T}\right) \tag{12.19}$$

$$Q_{42} = Q_{f\rho}\overset{\therefore}{C}_P\,\Delta T \tag{12.20}$$

$$Q_{43} = \frac{dU}{dt} - Q_{f\rho f}\overset{\therefore}{H}_f - W_s - W_b \tag{12.21}$$

$$Q_{44} = \frac{dU}{dt} + p\frac{dV_R}{dt} - Q_{f\rho f}\overset{\therefore}{H}_f \tag{12.22}$$

$$Q_{45} = \frac{dH}{dt} - V_R\frac{dP}{dt} - Q_{f\rho f}\overset{\therefore}{H}_f \tag{12.23}$$

$$Q_{46} = V_{R\rho}\overset{\therefore}{C}_P\frac{dT}{dt} - \alpha TV_R\frac{dP}{dt} + \sum_j\overline{H}_j\frac{dn_j}{dt} - Q_{f\rho f}\overset{\therefore}{H}_f \tag{12.24}$$

$$Q_{51} = V_{R\rho}\overset{\therefore}{C}_P\frac{dT}{dt} - \alpha TV_R\frac{dP}{dt} + \sum_i\Delta H_{Ri}r_iV_R - \sum_i C_{jf}Q_f\left(\overline{H}_{jf} - \overline{H}_j\right) \tag{12.25}$$

$$Q_{52} = V_{R\rho}\overset{\therefore}{C}_P\frac{dT}{dt} + \sum_i\Delta H_{Ri}r_iV_R - \sum_i C_{jf}Q_f\left(\overline{H}_{jf} - \overline{H}_j\right) \tag{12.26}$$

$$Q_{53} = V_{R\rho}\overset{\therefore}{C}_P\frac{dT}{dt} + \sum_i\Delta H_{Ri}r_iV_R - Q_{f\rho f}\overset{\therefore}{C}_P\left(\overline{T}_f - \overline{T}\right) \tag{12.27}$$

$$Q_{54} = Q_\rho\overset{\therefore}{C}_P\frac{dT}{dV} + Q(1 - \alpha T)\frac{dP}{dV} + \sum_i\Delta H_{Ri}r_i \tag{12.28}$$

$$Q_{55} = Q_\rho\overset{\therefore}{C}_P\frac{dT}{dV} + \sum_i\Delta H_{Ri}r_i \tag{12.29}$$

$$Q_{56} = Q_\rho\overset{\therefore}{C}_P\frac{dT}{dV} + Q\frac{dP}{dV} + \sum_i\Delta H_{Ri}r_i \tag{12.30}$$

$$Q_{61} = -\frac{k(T)}{1 + k(T)\tau}C_{Af}\Delta H_R \qquad \text{where } k(T) = k_m e^{-E\left(\frac{1}{T} - \frac{1}{T_m}\right)} \tag{12.31}$$

$$Q_{62} = \frac{C_{ps}}{\tau}\left(T - T_f\right) \tag{12.32}$$

$$Q_{63} = \frac{2}{R}U^{\circ}\left(T_a - T\right) \tag{12.33}$$

$$Q_{64} = U^{\circ}\,2\pi R\Delta_z\left(T_a - T\right) \tag{12.34}$$

$$Q_{65} = K_1\left(C_A - \frac{1}{K_1}\left(C_{Af} - C_A\right)\right)\Delta H_RV_R - Q_{f\rho}\overset{\therefore}{C}_P\left(T_f - T\right) \tag{12.35}$$

$$Q_{66} = \frac{d}{dV}\left(Q_\rho\overset{\therefore}{H}\right) \tag{12.36}$$

If the above thirty-six parametric equations and nuclear tokens can be used for the structure model for the construction of nuclear reactors, then the safety will be maximized and disaster minimized. This will later be structured into mathematical model in form of quadratic functional. The model will be solved using Conjugate Gradient Method algorithm, with MATLAB as support software.

In particular, we shall use the following quadratic functional for further work.

$$f(X) = f_0 + \langle a, X \rangle_H + \frac{1}{2}\langle X, AX \rangle_H$$

where $X \in \Re^6$ *i.e.* $X = (x_1 x_2 x_3 x_4 x_5 x_6)^T, a = (111111)^T, f_0 = 1$ *and*

$$A = \begin{pmatrix} Q_{11} & Q_{12} & Q_{13} & Q_{14} & Q_{15} & Q_{16} \\ Q_{21} & Q_{22} & Q_{23} & Q_{24} & Q_{25} & Q_{26} \\ Q_{31} & Q_{32} & Q_{33} & Q_{34} & Q_{35} & Q_{36} \\ Q_{41} & Q_{42} & Q_{43} & Q_{44} & Q_{45} & Q_{46} \\ Q_{51} & Q_{52} & Q_{53} & Q_{54} & Q_{55} & Q_{56} \\ Q_{61} & Q_{62} & Q_{63} & Q_{64} & Q_{65} & Q_{66} \end{pmatrix}$$

Where Q_{ij} are the rate of heat of the reactors, and $i, j = 1,2,3,4,5,6$

Example 1.

Minimize

$$F(x) = 1 + x_1 + x_2 + x_3 + x_4 + x_5 + x_6 \frac{1}{2}x_1^2 + x_1x_3 + x_1x_4 + x_1x_5 + x_2x_3 + 2x_2x_4 + x_2x_5 + x_2x_6 + x_3x_4 + x_3x_5$$
$$+ x_3x_6 + x_4x_5 + 2x_2^2 + \frac{3}{2}x_3^2 + x_5^2 + x_6^2$$

$$A = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 0 \\ 1 & 4 & 1 & 2 & 1 & 1 \\ 1 & 1 & 3 & 1 & 1 & 1 \\ 1 & 2 & 1 & 2 & 1 & 0 \\ 0 & 1 & 1 & 1 & 4 & 1 \\ 1 & 1 & 1 & 0 & 1 & 2 \end{pmatrix}$$

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Table 1: Numerical Example

N	MV	OBJ	NITR
6	$x_1 = -0.8465$, $x_2 = -0.4135$, $x_3 = -0.0906$, $x_4 = -0.3425$, $x_5 = -0.1614$, $x_6 = -0.1645$	0.23	2

PARAMETER DESCRIPTION OF TABLE 1

N=the dimension of the vector x

x = the minimizing vector

OBJF = the minimum value of the objective functional

NITR = the number of iterations for the convergence of CGM for a particular problem

ANALYSISI OF TABLE 1.

It can be seen in Table 1. That the method converges in the second iteration. The implication is that if the elements of the reactor are well structured, according to the capacity N, we would achieve optimal result. Observe that N is the size of the reactor.

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