NUCLEAR REACTOR
vs.
BIOLOGICAL REACTOR

--- A COMPARATIVE STUDY

(CFA EXERCISE)

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BT04B047

PROBLEM STATEMENT:

In this project, I propose to undertake a comparative study of Biological Reactors vs. Nuclear Reactors (focusing on nuclear fission reactors). Both reactors are industrially very important to the nation due to their unique role.

Nuclear Reactors have been recognized for their crucial role in generation of electricity and heat for domestic and industrial heating.

Biological Reactors have found extensive applications in pharmaceutical, biotechnology and water treatment industries. The products of the Biological Reactors maybe in the form of biomass, extracellular product (growth associated protein) etc.

In this study, I have hypothesized a model for energy generation in nuclear reactors taking cue from the biomass generation model in Biological Reactors.

Also, I have undertaken to qualitatively bring out the various similarities and differences in a nuclear reactor and Biological Reactor, both in principle and practice.

ACKNOWLEDGEMENT:

I wish to sincerely thank Professor G K SuraishKumar for giving us this exercise. It has been a learning experience and helped me unravel my creativity.

CONTENTS:

Introduction

Nuclear Fission reactor is based on the inherent property of the radioactive decay of unstable nuclei. (Instability of the nuclei is determined by the unequal number of neutrons and protons in the nucleus.)

Two main processes by which unstable nuclei decay are:

- Alpha decay: in this case the unstable nuclei emit an alpha particle reducing its proton number Z as well as Neutron number N by 2, thus, the ratio N/Z remains the same. It can be represented as below:

  $^{A}_{Z}X$ ----> $^{A-4}_{Z-2}Y$ + $^{4}_{2}He$

  PARENT NUCLEUS DAUGHTER NUCLEUS

- Beta decay: in this case either a neutron is converted to a proton or a proton is converted to a neutron, thus the N/Z ratio remains unaltered.

  $^{A}_{Z}X$ ----> $^{A}_{Z+1}Y$ + β^{-}

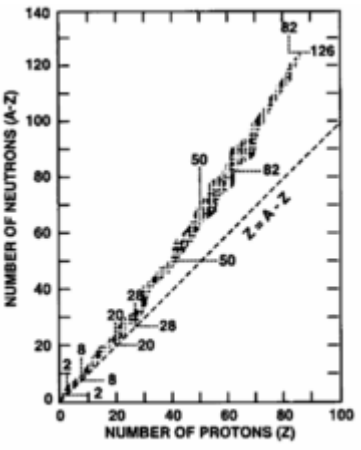


Figure 1

The kinetics of disintegration is explained by the laws of radioactive decay.If there are N radioactive nuclei at an instant t. thus,

$$dN = -\lambda N\, dt \qquad \text{……..(1)}$$

solving, we get,

$$N = N_o\, e^{-\lambda dt} \qquad \text{……..(2)}$$

where N_o is the number of active nuclei at t=0, λ is the rate decay.

Some other parameters defined for the above are:
Half-life period, $t_{1/2} = 0.693/\lambda$
Average life, $\tau = 1/\lambda$

In contrast, Biological Reactor is based on the property of cells to divide and reproduce. The rate of microbial growth is characterized by the net specific growth rate (μ), as given below:

$$dX = \mu x\, dt \qquad \text{……..(3)}$$

thus, solving,

$$X = X_o\, e^{\mu t} \qquad \text{……..(4)}$$

Some other parameters defined for the above are:
Doubling time, $t_d = 0.693/\mu$

Fuel: Uranium vs. carbon

In case of nuclear fission reactors, Uranium U_{235} is used as the fission material. Natural Uranium deposits contain about 99.3% of U_{238} and 0.7% of U_{235}.

A Biological Reactor may also refer to a device or system meant to grow cells or tissues in the context of cell culture. Traditionally bacteria, yeast or fungi cultures have been used, but animal and plant cultures can also be used. The cultures can be aerobic or anaerobic. Organism growing in Biological Reactor may be suspended or immobilized.
The medium needs to be rich in carbon substrate, dissolved oxygen (for aerobic cultures) and other nutrients (depending on the specific culture).

Source: Enriched Uranium vs. Inoculum

Natural uranium consists mostly of the ^{238}U isotope, with about 0.72 % by weight as ^{235}U, the only isotope existing in nature in any appreciable amount that is fissionable by thermal neutrons. Thus uranium needs to be enriched, i.e. the uranium 235 content is increased through the process of isotope separation.

Enriched uranium is a critical component for nuclear power generation.

Similarly, the inoculum used for cell culture in Biological Reactor is a crucial element. The age of inoculum has a strong effect on the lag phase. Thus, before introducing the inoculum to the Biological Reactor, it is grown in batch culture to minimize the lag phase and thus obtain maximum productivity.

Product: Energy vs. Bio-product

In the nuclear reactor, the byproduct is the energy harnessed from the fission reaction which is further used for generation of electricity or otherwise. In the nuclear reactor there occurs a mass defect when the fission reaction takes place, and it is this lose of mass which is converted into energy by the use of the equation $E=mc^2$, whereas in case of Biological Reactor, the product is in the form of biomass or extracellular product etc.

In a typical fission event, a U-235 nucleus absorbs a thermal neutron, producing a compound nucleus U-236 in a highly excited state. It is *this* nucleus that actually undergoes fission, splitting into two fragments. These fragments, between them, emit two neutrons, leaving Xe-140 and Sr-94 as fission fragments. Thus, the overall fission equation for this event is:

$$^{235}U + n \rightarrow ^{236}U^{*} \rightarrow ^{140}Xe + ^{94}Sr + 2n + \mathbf{\Delta E}$$

The energy released as a result of one fission reaction is as calculated below (based on the binding energy curves). For heavy nuclides (mass about 240u), the mean biding energy per nucleon is about 7.6MeV. For middle-mass nuclides (mass about 120), it is about 8.5 MeV. This difference in total binding energy between a single large nucleus and two fragments (assumed to be equal) into which it may be split is :

$$\Delta E = 2(8.5^{\text{MeV}}/_{\text{u}})(\tfrac{1}{2})(200\text{u}) - (7.6^{\text{MeV}}/_{\text{u}})(200\text{u}) \approx 200\text{MeV}$$

Whereas in the Biological Reactor, the bio-product obtained by growing the cells is the desired product. Microbial products can be of three types:

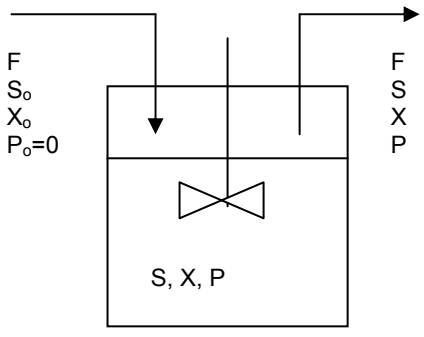
1. Growth associated products which are produced simultaneously with microbial growth.
   $q_P = (1/X)\ (dP/dt) = Y_{P/X} .\mu$
2. Non-growth associated product formation takes place during the stationary phase when growth rate is zero.the specific rate of product formation is constant.
   $q_P = \beta$ = constant
3. Mixed growth associated product formation which takes place during slow growth and stationary phases. In this case, specific rate of product formation is given by :
   $q_P = \alpha\ \mu + \beta$

Model: Proposed vs. Established

On the basis of mode of operation, a Biological Reactor may be classified as batch, fed batch or continuous (e.g. continuous stirred-tank reactor model).

Taking the case of a chemostat (which is one example of a Biological Reactor).Uniform vigorous mixing is assumed such that concentrations in any phase do not vary with position inside the reactor. The liquid effluent has been assumed to have same concentration as the reactor contents. The process is assumed isothermal at the desired temperature.

X= viable cell concentration in tank and effluent stream
X_o=viable cell concentration in feed stream
F=volumetric flow rate of feed and effluent streams
V=Volume
r_x=rate of cell formation, cells per unit time per unit volume



Employing cell balance:

$I + O + G - C = dA/dt$ (at steady state)

Rate of generation = Output rate

$$dt(XV) = F.X - F.X_o$$
$$dx/dt = F.X - F X_o$$

from (3) $\mu \times V = F.X - F X_o$

substituting Dilution rate, $D = F/V$

$$(\mu - D).X + D X_o = 0$$

if $X_o = 0$ (i.e. sterile inoculum) then, $\mu = D$

in this case, μ(specific growth rate) is the biological parameter whereas D(dilution rate) is the operational parameter.

Employing substrate balance:

$I + O + G - C = dA/dt$ (at steady state)

$$S.F = S_o.F - (V/Y_{X/S}).(dx/dt)$$

$$S = S_o + \mu. \frac{x\,V}{F.Y_{X/S}}$$

$$D(So - S) - \mu x/Y_{X/S}$$

Given $\mu = \frac{\mu_m S}{(S + Ks)}$

Thus, $x = Y_{X/S}\left(S_o - D\frac{K_s}{\mu_m - D}\right)$

Now, as the cell divides, one parent cell gives rise to two daughter cells (second generation), which further divide into two daughter cells each (third generation)
As is illustrated in the schematic below:

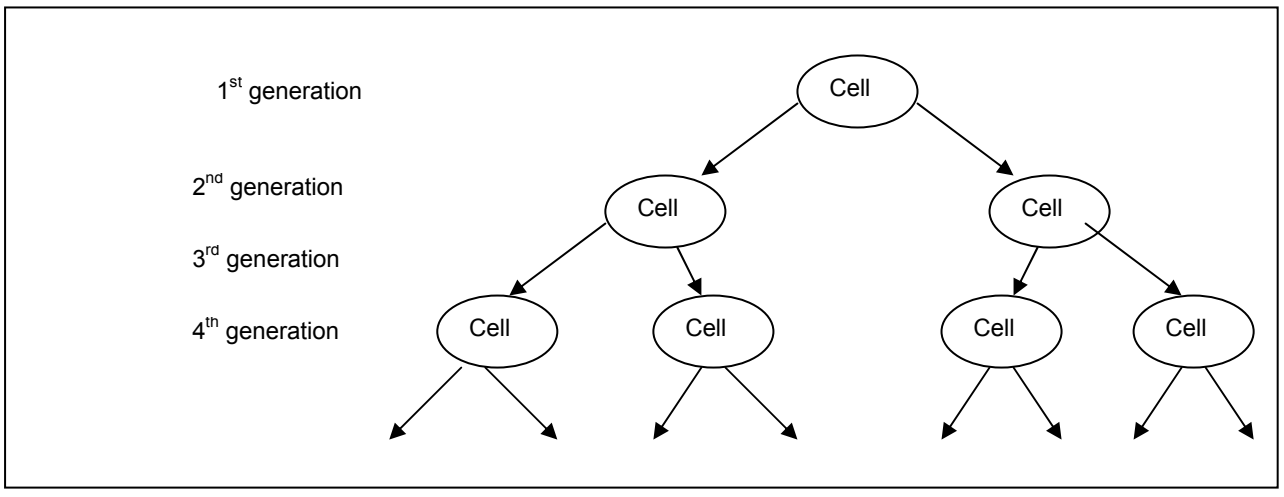


Figure 2: Schematic of cell division

Now, taking a look at the nuclear fission chain reaction as shown in the illustration below:

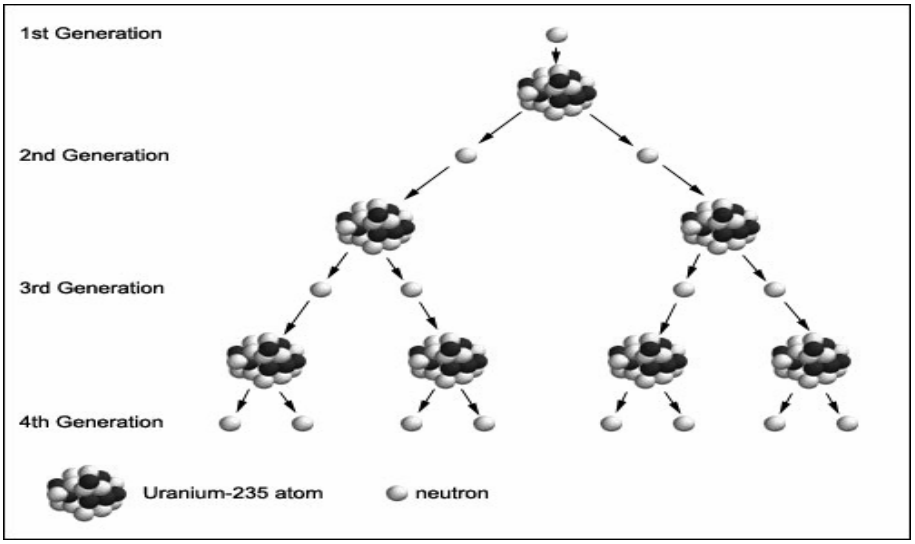


Figure 3

The figure 1 and 2 compel one to think the inherent *chain* nature in both the cases. In the case of cell proliferation, each cell divides into two leading to newer generation. And in case of nuclear fission reaction, each reaction gives rise to two neutrons which in turn lead to fission of one nucleus each.

Thus, it compels one to think of nuclear fission reactor model based on the lines of the model of a Biological Reactor.

In this the byproduct is not matter rather the energy produced in the reactions, which can be related to the number of neutrons, by the following proposed equation:

$$\ln (E/E_o) = (n*m) \ln k \qquad \text{[PROPOSED MODEL]}$$

based on the assumption that all the fissionable nuclei react with the incoming neutron to undergo fission with probability of one.

E = energy released after n cycles of reaction in MeV
E_o = energy released in one fission reaction in MeV
k = number of neutrons per reaction
m = no of fissionable chain reactions at any instant
n = cycles of reaction
N = n*m = total number of Uranium Nuclei.

Drawing analogy from the Biological Reactor model above,
k (number of neutrons per nuclear fission reaction) becomes the operational parameter, while the E_o (energy released per nuclear fission reaction) becomes my nuclear parameter.

Examples may be given of typical reaction products, such as:

U-235 + n ===> Ba-144 + Kr-90 + 2n + energy

U-235 + n ===> Ba-141 + Kr-92 + 3n + 170 MeV

U-235 + n ===> Te-139 + Zr-94 + 3n + 197 MeV

the values of k vary as 2 and 3 in the above two reactions.

the graph below shows other alternative forms in which U_{235} fission can occur, thus varying values of k.

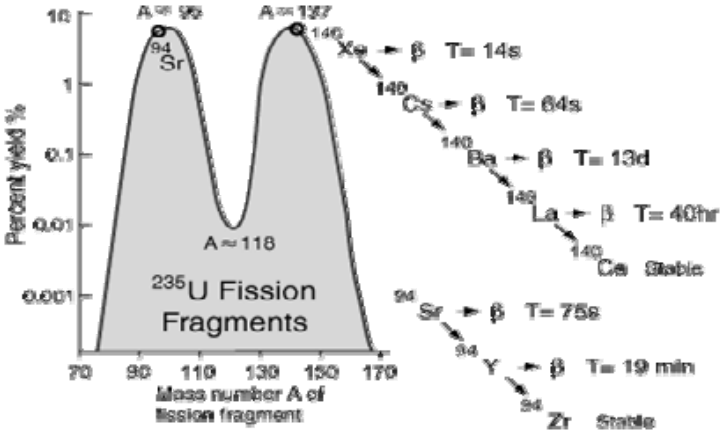
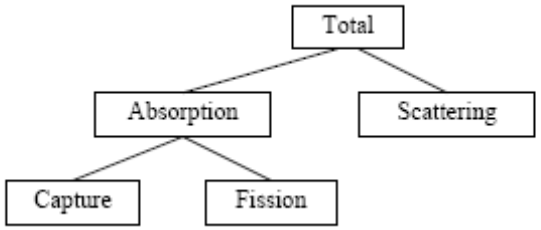


Figure 4

But in realistic terms the probability of the nuclei to undergo fission on interacting with neutron beam is not one. Rather it depends on the neutron cross-section.

The neutron can react with the nuclide in the following ways.

Cross-section Hierarchy



The *microscopic cross section* (σ) is a property of a given nuclide; σ is defined as the probability per nucleus that a neutron in the beam will interact with the nucleus; this probability is expressed in terms of an equivalent area that the neutron "sees."

$$\sigma_t = \sigma_a + \sigma_s = \sigma_s + (\sigma_c + \sigma_f) \text{ where } \sigma_c = \sigma_f$$

The mean free path is $\lambda = 1/\Sigma$. The microscopic cross section is measured in units of barns (b): 1 barn equals 10^{-24} cm^2 = 10^{-28} m^2.

The *macroscopic cross section* (Σ) takes into account the number of those nuclides present

$$\Sigma = N\sigma \ [\text{cm}^{-1}] \qquad \text{where N = total number of nuclei.}$$

$$\Sigma_t = \Sigma_a + \Sigma_s = \Sigma_s + (\Sigma_c + \Sigma_f)$$

Thus, the above equation can be modified as

$$\ln (E/E_o) = (n*m*\sigma_f) \ \ln k$$
$$2 . \ln (E/E_o) = (n*m*\sigma_a) \ln k$$

<u>1/*v* Law</u>

For very low neutron energies, many absorption cross sections are 1/*v* due to the fact the nuclear force between the target nucleus and the neutron has a longer time to interact

$$\sigma_a \propto 1/v \propto 1/\sqrt{KE} \propto 1/\sqrt{T}$$

where KE = kinetic energy of the colliding neutron

Thus,

$$\ln (E/E_o) \propto \sigma_a \propto 1/\sqrt{KE}$$

Thus, in the nuclear reactor, the kinetic energy of the colliding neutrons is important in determining the number of fissionable nuclei, which in turn determines the amount of energy generated. Studies have been undertaken to map the cross section of the neutron vs. the energy of the neutron (as shown below).

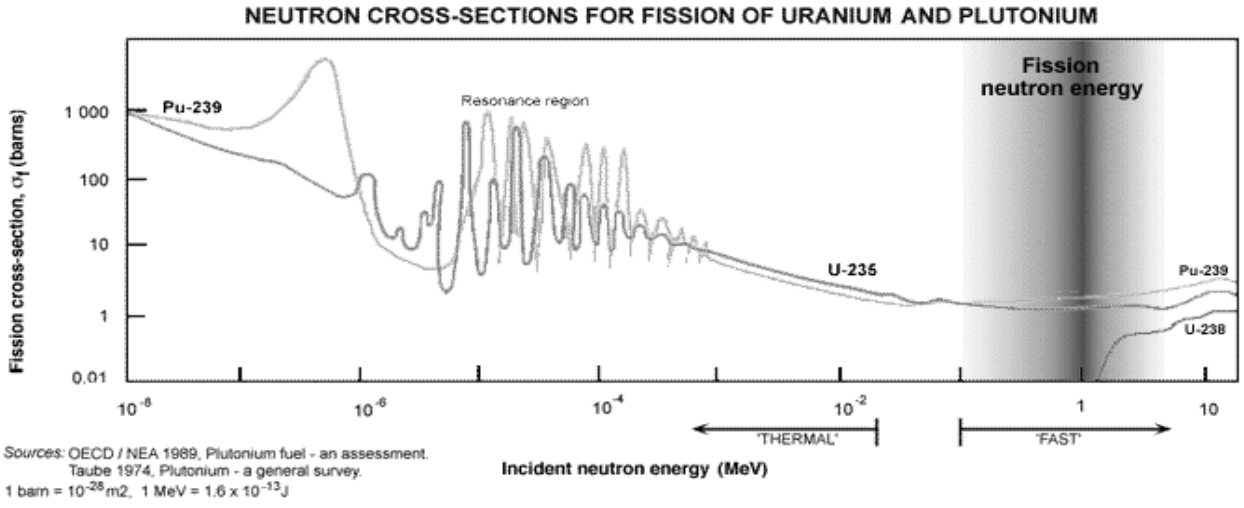


Figure 5

Conservation: Energy vs. Material

In case of Biological Reactors, material balances (for substrate as well as cell mass) have been employed, while in case of nuclear reactors, it is energy conservation which has gained impetus.
To illustrate the principle of energy balance in nuclear fission, we take the following example:

The energy set free by the fission of $^{236}_{92}U$ amounts to 19 billions of kilojoules per mol uranium. This gain in energy is counter-balanced by the loss of a small quantity of matter (mass defect), matter which is transformed into energy.

Mass defect: 1°/o (1000 g of $^{236}_{92}U$ yield 999 g of fragments)
The energy set free is calculated according to Einstein's Relation: $E = m \cdot c^2$

$E = 1\ g \cdot 9 \cdot 10^{16}\ m^2 \cdot s^2 = 8.1 \cdot 10^{10}$ kJ for (initially) one kilogram of $^{236}_{92}U$

$= 19.1 \cdot 10^{9}$ kJ for (initially) one mol of $^{236}_{92}U$

Energy Considerations:

In the case of nuclear reactors, energy stored in the reactants is consumed as:

$$P.E._{neutron} + K.E._{neutron} + P.E._{U\text{-}nucleus} \rightarrow P.E._{fragments} + K.E._{Fragments} + n^* K.E._{neutron} + n * P.E._{neutron} + \Delta E$$

where n=number of neutrons.

In the case on Biological Reactors, substrate may be consumed as:

$$\Delta S = \Delta S_{\text{assimilation into biomass}} + \Delta S_{\text{growth energy}} + \Delta S_{\text{maintenance energy}} + \Delta S_{\text{assimilated into an extracellular product}}$$

Factors and control

Factors affecting cell growth in Biological Reactor are:

- Nutritional factors (Minimal Medium): availability of carbon, nitrogen, sulfur, phosphorus, trace elements, and, in some cases, vitamins.
- Physical Factors: pH, temperature, oxygen concentration, moisture, osmotic pressure, radiation

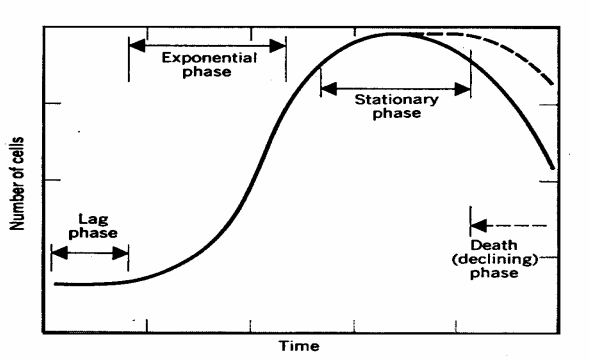


Figure 6: Phases in cell growth

The stationary phase as depicted in the accompanying figure is usually due to substrate exhaustion, or oxygen exhaustion in case of aerobic microorganisms.
The rate of specific growth is determined by the dilution factor, as proved earlier.

For a chain reaction of nuclear fission, such as that of uranium-235, is to sustain itself, then at least one neutron from each fission must strike another U-235 nucleus and cause a fission. If this condition is just met, then the reaction is said to be "critical" and will continue. The mass of fissile material required to achieve this critical condition is said to be a critical mass. The critical mass depends upon the concentration of U-235 nuclei in the fuel material as well as its geometry.

Critical Mass vs. Minimal Medium

The critical mass requirements of the nuclear reactor determine the feasibility of the fission reaction at any instant. Just as the nutritional requirement of minimal medium is important for the growth of the cell culture, the presence of critical mass is important for the sustainability of the reactor.

Plant design

NUCLEAR FISSION REACTOR

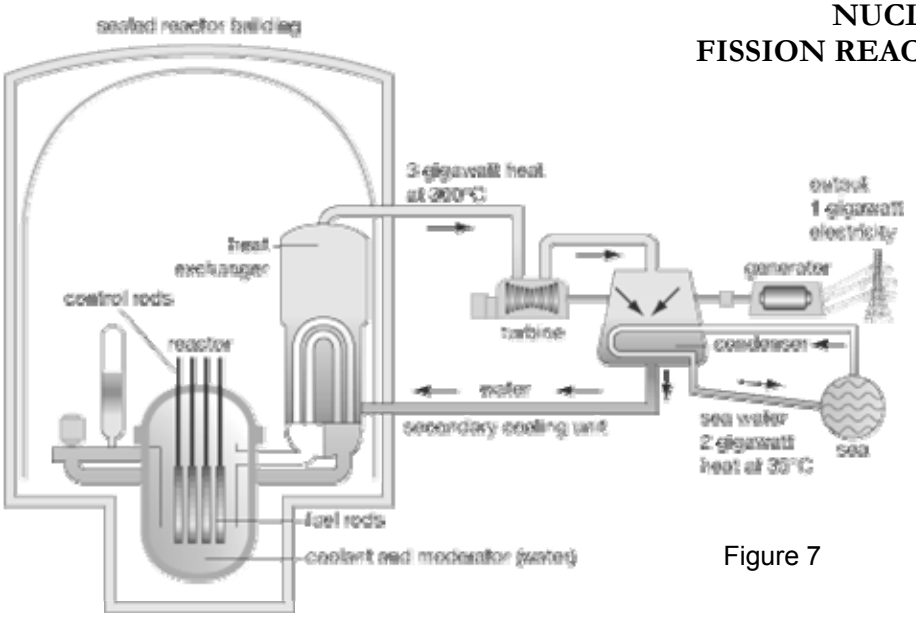


Figure 7

Uranium is taken in the form of cylindrical rods arranged in a regular pattern in the active reactor core. The volume in the core is filled with material as heavy water (D_2O), graphite, beryllium, which is called as the moderator. The moderator slows down the neutron to thermal energies. The geometry of the core is such that 2.5 neutrons are released (on an average) per fission reaction, of which 1 neutron used to trigger the next fission reaction and the remaining are lost without any fission. The reaction is thus sustained at a constant rate.

If the rate of loss of neutrons is decreased further, the fission rate will keep on increasing which may lead to explosion. And if the rate of loss of neutrons is increased, the fission rate will decrease, and ultimately the chain will stop this is fine tuned by the use of control rods, which are made of cadmium, which is a good neutron absorber.

Also, coolant liquid such as water at high pressure or molten sodium is passed through the reactor core. This heat is used to prepare steam from water. This steam is used to run steam turbines to and thus electricity is generated.

CHEMOSTAT

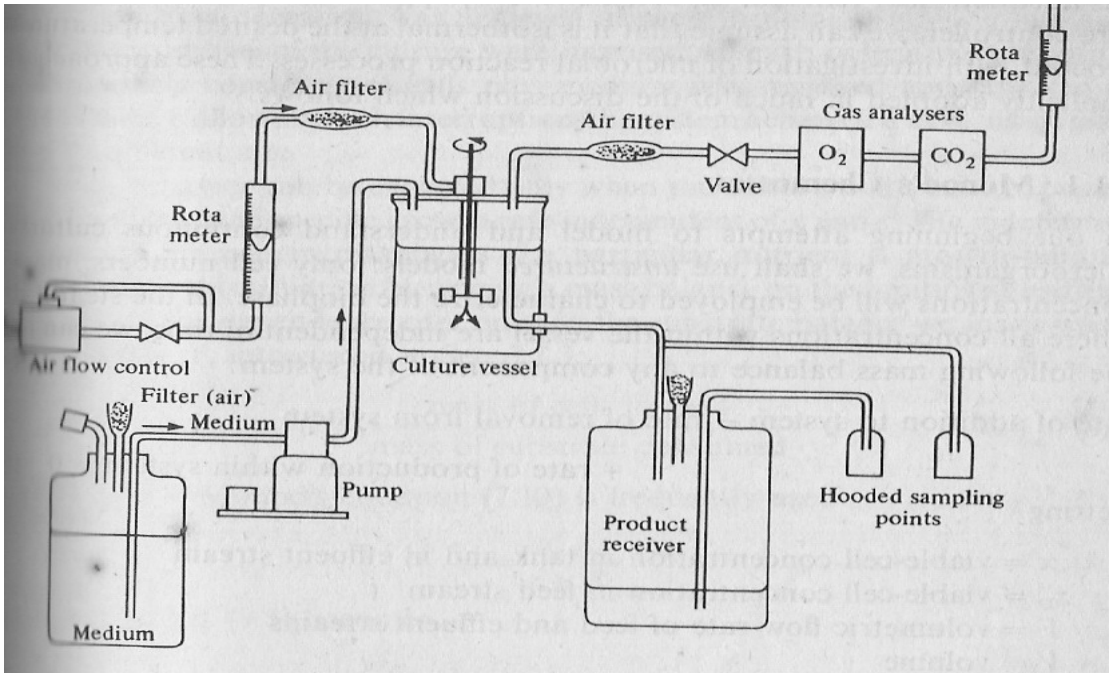


Figure 8

The above is a diagram of a completely mixed continuous stirred tank reactor (CSTR or chemostat). As the above figure suggests, the microorganisms are cultured in the culture vessel, and the product is collected in the product receiver. The mixing is buy means of an impeller, rising gas bubbles or both. We assume that the mixing is so vigorous that each phase of the vessel contents is of uniform composition. Thus, the liquid effluent has same composition as the reactor contents. Oxygen is aerated through the air filter to maintain the required levels of Dissolved Oxygen (DO).

Probes:

Dissolved Oxygen (DO) Probes are an essential part of Chemostats especially when growing an aerobic culture. It helps us keep a tab on the dissolved oxygen values in the medium, and thus help us decide the amount of oxygen to be aerated into the medium. There can be three cases:

Rate of oygen suppy < Rate of oxygen consumption by cells	DO decreases
Rate of oygen suppy > Rate of oxygen consumption by cells	DO increases
Rate of oygen suppy = Rate of oxygen consumption by cells	DO critical

In nuclear reactors, current research is going on developing a new approach to continuously monitor the health of nuclear reactors. This technology is being referred to as "Nondestructive Evaluation (NDE)". By providing the ability to peer inside critical pipes and structures without having to destroy them, NDE has become essential to the nuclear power industry. This system will provide continuous monitoring so that deviations from normal operation can be detected immediately, and problems can be addressed before they become serious. Moreover, on-line monitoring is done remotely, greatly reducing exposure levels of maintenance workers.

Suggestions for similar online sensors for Biological Reactors

- Sterilisable(heat and pressure resistant)
- Low adhesion to bacterial cells and other fouling species(like proteins)
- Leak proof; mechanically robust
- Stable signal over long periods of time.

Operational Parameter: Height of Fuel Rods vs. Critical Dilution factor

In the nuclear fission reactor, the reaction is controlled by the number of neutrons at any instant, for every neutron can initiate one reaction and availability of uranium substrate. The rate of generation of energy in this case is determined by the number of neutrons available. The number of neutrons can be limited by the use of control rods in the nuclear reactor. Control rods are essentially neutron absorbers made up to cadmium. The height of the control rods inserted into the reactor core is responsible for the rate of neutrons available for fission, and thus the rate of fission of the uranium (substrate). If the control rods are pulled out completely, the reaction will become uncontrolled, as every fission reaction will produce a maximum of three neutrons. If the control rods are partially in, the per neutron count will be two or one, thus slowing down the rate of fission reaction. When the control rods arte inserted fully, the reactor will come to a stop as all the neutrons available will be absorbed.

This has been illustrated in the following graph on a qualitative basis:

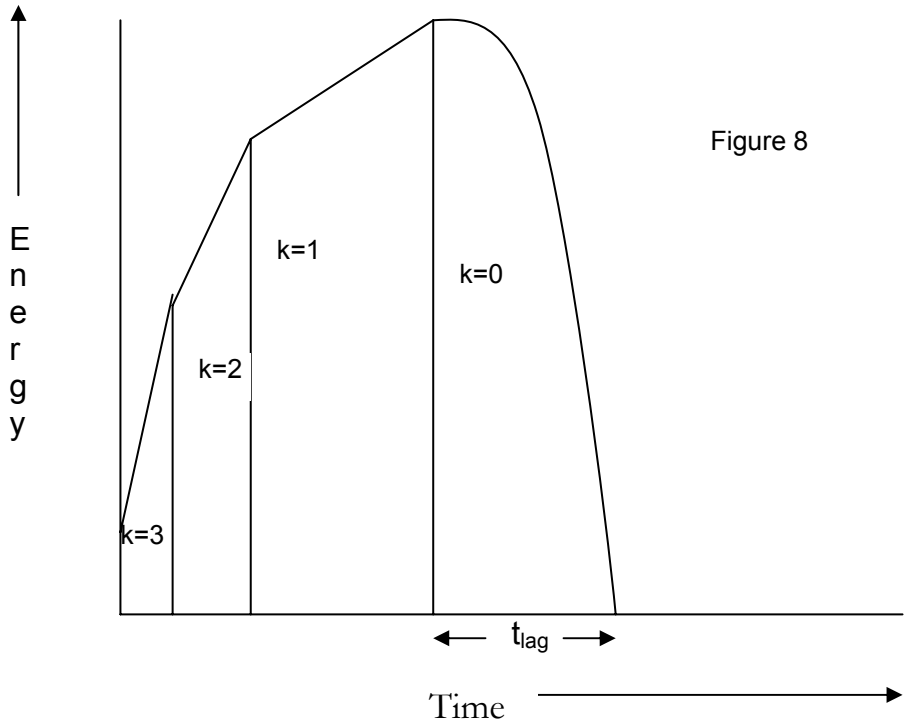


Figure 8

The area under the graph represents the various time periods during which number of neutrons vary from k=3 to k=0 i.e. from the reaction being uncontrollable to the end of the reaction. This is directly determined by the height of the fuel rods in the reactor core (as explained above).

Whereas in chemostat, critical dilution is the operational parameter. $D = D_c$ define the washout condition in case of the chemostat, as is illustrated in the diagram below:

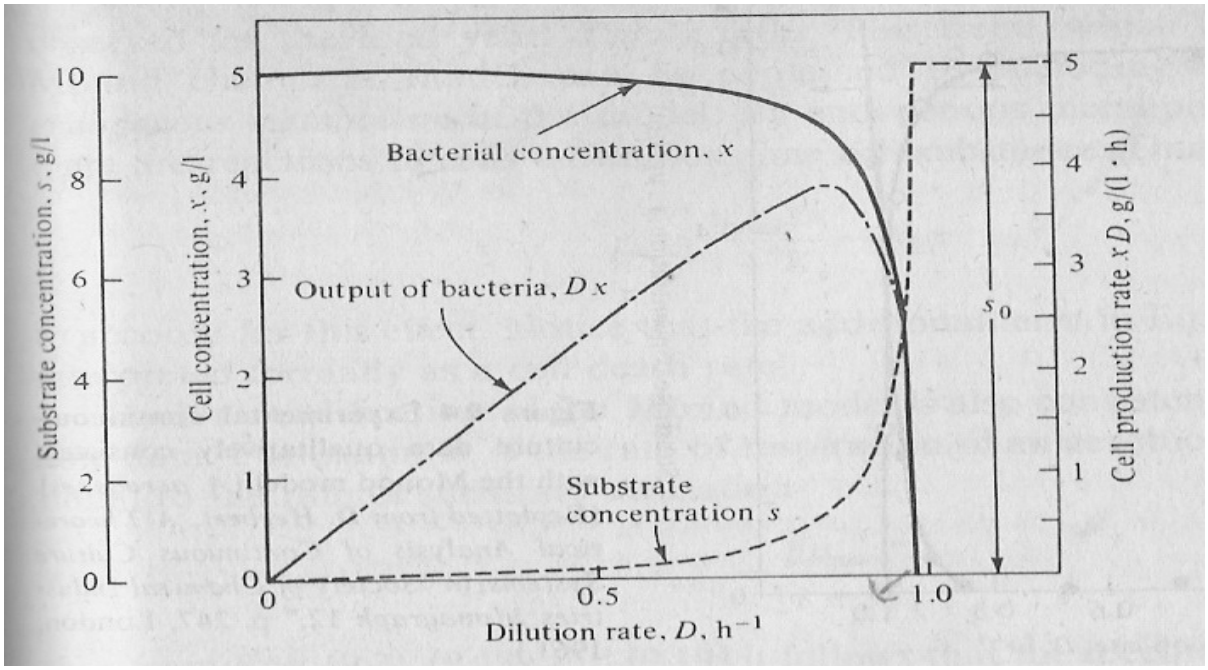


Figure 9

Productivity: energy production vs. biomass production

Chemostat productivity can be calculated as follows:

Chemostat productivity, $R = \frac{\text{Amount of cells produced}}{\text{Volume - time}}$

$$R = \frac{\Delta x}{\Delta t \,.\, V}$$

$$R = \frac{\mu \,.x\,.\, V}{V}$$

$$R = \mu .\, x$$

$$R = x.\, D = D.\, x = Y_{X/S}\left(\frac{S_o - D\, K_s}{\mu_m - D}\right)$$

maximize R w.r.t D to find the maximum productivity;
thus, we get,

$$D_{max.} = \mu_m \{1 - \sqrt{\left(\frac{Ks}{K_s + S}\right)}\}$$

Now, to find cell concentration when $D = D_{max.}$

$$X_{max.} = Y_{x/s}$$

$$X_{max.} = Y_{x/s} [\, (S + K_s) - \sqrt{K_s}(K_s + S)\,]$$

When Ks << S

$$X_{max.} = Y_{x/s} [\, S - \sqrt{(K_s \,.\, S)}\,]$$

$$X_{max.} = Y_{x/s} \,.\, S$$

Thus, $R_{max} = X_{max} \,.\, D_{max.}$

$$\boxed{R_{max.} = Y_{x/s}.\, S \,.\, \mu_m}$$

On the above basis, expression for nuclear productivity can be hypothesized,

Nuclear Productivity, $N = \frac{\text{Amount of energy produced in MeV}}{\text{No. of fissionable Uranium nuclei}}$

[PROPOSED MODEL]

(Substituting from $2 \ln (E/E_o) = (n*m*\sigma_a) \ln k$)

$$N = \frac{E_o\, k^{nm\sigma a/2}}{n * m}$$

Productivity will be maximum when all the fissionable nuclei undergo fission coming in contact with the neutron i.e. $\sigma_a = 1$

$$N_{max} = \frac{E_o\, k^{nm}}{n * m}$$

Waste:

While nuclear reactor is synonymous with its waste generation, Biological Reactors are being recognized for their role as waste treatment plants. (Not the nuclear waste!)

In the nuclear reactor, waste is generated is form of:

- Uranium enrichment process (as described in the above sections) generates radioactive waste.
- Fossil fuel emissions as carbon dioxide, sulfur dioxide or nitrogen oxides are associated with fuel mining as well as transport to nuclear plant
- Use of large quantities water for steam production and cooling disturbs the ecosystem of source.
- Discharge of water which is non-radioactive but has heavy metal pollutants and high temperature
- Radioactive waste is generated as the fission products and the vessels in which the reaction takes place.
- Local land contamination by toxic byproducts.

An overview of Biological Waste Treatment

- Waste material generated in society can be categorized as: industrial waste, domestic waste and agricultural waste
- The major waste treatment strategies used are :physical treatment, chemical treatment and biological treatment
- The use of Biological Reactors in Biological treatment is unparallel.
- Biological waste treatment employs mixed culture of organisms depending on the nature of the waste. The treatment maybe aerobic or anaerobic. The details of waste treatment will not be discussed here.

Closing Statement

Based on the study of the Nuclear reactors and Biological Reactors, I have tried to summarize it in the following table:

FEATURE	**NUCLEAR REACTOR**	**BIOLOGICAL REACTOR**
FUEL	Uranium 235	Carbon substrate (Minimal medium)
PRODUCT	Energy	Biomass/extracellular Product(protein)
PRINCIPLE OF CONSERVATION	Mass- Energy conservation	Material balance
FACTORS AFFECTING PRODUCT	-critical mass -no. of neutrons per fission reaction. -Control rods -Moderator(water)	-nutritional parameters (minimal medium) -physical parameters
OPERATIONAL PARAMETER	Dilution Rate (D)	Height of Fuel Rods
PRODUCTIVITY	Amount of energy produced/no. of fissionable nuclei	Amount of cells produced/Volume-time

The idea behind undertaking this study is to try and incorporate the variations from nuclear reactors to biological reactors and vice-versa, as both are industrially important sectors. The underlying principle is to exploit the given resource to obtain products of our need, which maybe electricity, proteins, biomass, etc.
There are certain overlapping areas where borrowing ideas from the other may turn out useful, be it plant design, transport of fuel, controlling the reaction, recycling, etc.

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