THORIUM REACTOR AND ITS APPLICATIONS

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THORIUM REACTOR AND ITS APPLICATIONS

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ABSTRACT

M. Sc. Thesis

THORIUM REACTOR AND ITS APPLICATION

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Institute of Graduate Programs
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In this thesis, we try to get a general idea about the Thorium reactor fourth-generation and suggest a suitable solution for many nuclear reactor problems starting from energy cost, safety, friendly environment and minimising weapons of mass destruction products. Because there is no need for fertilization of Uranium and no Plutonium generated in the fuel cycle, it's impossible to create any nuclear weapons starting from a Thorium reactor. The medical isotope Ac-225 is generated by a Thorium reactor and can be separated by the Bismuth element used for cancer diseases. This technology provides a great ability to create biological smart bombs targeting infected tissue with no harm to healthy cells inside the human body.

Keywords **:** Fourth-generation reactor, design, Thorium, Uranium, medical, electricity, chain reaction, chemical processes, fuel salts.

Science Code : 91708

ÖZET

Yüksek Lisans Tezi

TORYUM REAKTÖRÜ VE UYGULAMASI

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Bu tez çalışmasında, dördüncü nesil toryum reaktör hakkında genel bir bilgi edinmeye ve enerji maliyeti, güvenlik, çevre dostu ve kitle imha silahları ürünlerini en aza indirgemek gibi birçok nükleer reaktör sorununa uygun bir çözüm önermeye çalıştık. Uranyumun zenginleştirmesine gerek olmadan ve yakıt döngüsünde üretilen plütonyum olmadan bir toryum reaktöründen başlayarak herhangi bir nükleer silah yaratmak imkansızdır. Medikal radyoizotop Ac-225, bir toryum reaktörü tarafından üretilir ve kanser hastalıkları için kullanılan bizmut elementine ayrılabilir. Bu teknoloji, insan vücudundaki sağlıklı hücrelere zarar vermeden enfekte dokuları hedef alan biyolojik akıllı bombalar oluşturmak için büyük bir olanak sağlar.

Anahtar kelimeler: Dördüncü nesil reaktör, tasarım, toryum, uranyum, medikal, elektrik, zincirleme reaksiyon, kimyasal prosesler, yakıt tuzları.

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SYMBOLS AND ABBREVIATIONS INDEX

SYMBOLS

$°C$: Celsius

σ : standard deviation

n : neutron

γ : gamma radiation

α : alpha particle

p : proton

f : fission

K_{eff} : efficiency factor

σ : microscopic cross-section area

N : number of nuclei's

v : velocity

∅ : neutron flux

∇ : the second derivative

Ω′ : other direction

Ω : direction

ψ : angular flux of neutrons

E′ : energy in other direction

r : position

E : energy

t : time

s : surface

a : homogenous thickness

L : diffusion length

D : monoenergetic neutrons

PNL : non-leakage probability

a, b, c, h ,r : dimensions of the heart

D : diffusion

S : neutron source

β : delay neutrons

λ : effective decay constant

X_{avg} : average distance

l : lifetime

Q_{ext} : isotropic neutron source

Λ : neutron generation time

ηc : cooling efficiency

ABBREVIATIONS

HP : High Pressure

MP : Mid Pressure

LP : Low Pressure

G : Generator

C : Compressor

T : Turbine

R : Reactor

LWRs : Light Water Reactors

HWRs : Heavy Water Reactors

LET : Linear Energy Transition

MR : Moderating Ratio

MeV : Mega electron-volt

HX : Heat Exchanger

IHX : Intermediate Heat Exchanger

MSR : Molten Salt Reactor

T_c : Cooling Temperature

T_h : Heating Temperature

CCGT : Combined Cycle Gas Turbine

^{135}Xe : Xenon

^{233}U : Uranium

^{235}U : Uranium

^{238}U : Uranium

^{239}Pu : Plutonium

^{232}Th : Thorium

^{229}Th : Thorium

^{233}Pa : Protactinium

^{232}Pa : Protactinium

^{225}Ra : Radium

^{225}Ac : Actinium

^{221}Fr : Franicum

^{217}At : Astatine

^{209}Bi : Bismuth

^{213}Bi : Bismuth

^{209}TI : Thallium

^{213}Po : Polonium

^{209}Pb : Lead

F : Fluorine

Li : Lithium

Be : Beryllium

UF_3 : Uranium trifluoride

UF_4 : Uranium tetrafluoride

Kr : Krypton

$NaNO_3$: Sodium Nitrate

KNO_3 : Potassium Nitrate

$NaNO_2$: Sodium Nitrite

HTS : High-throughput screening

$NaBF_4$: Sodium tetrafluoroborate

NaF : Sodium fluoride

Li_2CO_3 : Lithium carbonate

Na_2CO_3 : Sodium Carbonate

K_2CO_3 : Potassium Carbonate

LiF : Lithium Fluoride

NaF : Sodium Fluoride

KF : Potassium Fluoride

FLiNaK : Eutectic Alkaline Metal Fluoride Salt

BeF_2 : Beryllium difluoride

FLiBe : Molten Salt

Na : Sodium

LiF : Lithium Fluoride

H_20 : Water

ZrH_2 : Zirconium dihydride

D_20 : Deuterium Oxide

BeO : Beryllium Oxide

BeF_2 : Beryllium difluoride

Ni : Nickel

Mo : Molybdenum

Cr : Chromium

Fe : Iron

T : Titanium

ThF_4 : Thorium tetrafluoride

SiC : Silicon Carbide

CO_2 : Carbon dioxide

ThO : Thorium monoxide

HF : Hydrogen fluoride

NaF_2 : Sodium fluoride

MgF_2 : Magnesium fluoride

NaK : Sodium–potassium alloy

H_2 : Hydrogen

O_2 : Dioxygen

ThF_6 : Thorium hexafluoride

UF_6 : Uranium hexafluoride

F_2 : Fluorine

^{177}Lu : Lutetium

PART 1

INTRODUCTION

1.1. WHY THORIUM REACTOR IS IMPORTANT?

Most nuclear power plants at this time worked in light or heavy water reactors referred to as (LWRs or HWRs) where they are have many problems and difficulties which are given:

- Recycling fuel every 1 – 3 years because of low fissile breeding where these reactors worked with ^{235}U and ^{238}U which produce ^{239}Pu as waste that could be used for nuclear weapons as row material.
- The temperature usually bordered thermal efficiency less than 35% with the high-pressure cooling system may be led to pressure vessel failure or steam pressure explosion accident like Chornobyl.
- Radioactivity is a very high need to large secure limitations with high waste in disposal in addition to melting fuel dangerous and high core heat after an accident like Fukushima.
- Radiation effects on fuel life with high potential Hydrogen generated during accidents.
- ^{135}Xe (Xenon) isotope problems generated in core and fuel cycle utile > 2% of Uranium potential energy and produce a large amount of radioactive waste which needs high core and fuel access and careful power control.

A Thorium reactor can solve all of these problems because it is dealing with molten salt instead of water where molten salt can be cooled, heated, and operated with low pressure with less radioactive chemical waste and operation temperature limited by compatibility and structural materials [1] the fuel cycle consists of ^{232}Th as a fertile and ^{233}U fissile as shown in equation (1.1) [2].

$$n + {}^{232}Th \rightarrow {}^{233}Th \xrightarrow[24\ min]{\beta-} {}^{233}Pa \xrightarrow[2.4\ d]{\beta-} {}^{233}U \left[{}^{232}Th\ (n,\gamma + 2\beta-)\ {}^{233}U\right] \quad (1.1)$$

Is means Thorium as a fertile can be changed to ^{233}Pa by absorption of neutron and beta decay. this isotope has a half-life of 24 min transformed by second beta decay to ^{233}U as a fissile isotope .in some times ^{233}Pa takes a second direction as shown in equation (1.2) [2].

$$^{233}Pa + fast\ n \rightarrow {}^{232}Pa + n + n\ \left[{}^{233}Pa\ (n,2n)\ {}^{232}Pa\right] \quad (1.2)$$

This reaction is considered undesirable because the production of ^{232}U has a decay chain reaction emitting 2.6 MeV gamma-ray which makes the fuel cycle hard to handle so we should remove ProtActinium from the blanket of the heart to prevent (n,2n) reaction to keep the cycle closed between Thorium and Uranium without undesirable isotopes.

1.2. THORIUM REACTOR ADVANTAGES

1.2.1. Fuel Cycle

^{232}Th and ^{233}U breeder fuel cycles have advantages over ^{239}Pu and ^{238}U. Firstly, Thorium is four-time abundant in the earth's crust than Uranium and has a 100% ability to convert into fissile Uranium-233 when it is very hard in the case of Uranium-238 and Plutonium-239 [3]. Besides that breeding is possible in fast and slow neutrons the regeneration factor is η means the number of neutrons emitted per neutron absorbed needed to be at least 2.2 when it is equal to 2.24 in Uranium-233 in the case of thermal neutrons and 2.30 in fast typical spectrum .in Plutonium case these numbers are 2.1 and 2.45 which means needed to fast neutron spectrum, in addition, the delayed neutron fraction β=0.0026 in Uranium-233 when it is equal to 0.0020 the large difference make core control fuel cycle easier inside the heart of Thorium reactor then Plutonium fuel cycle [4] Figure (1.1).

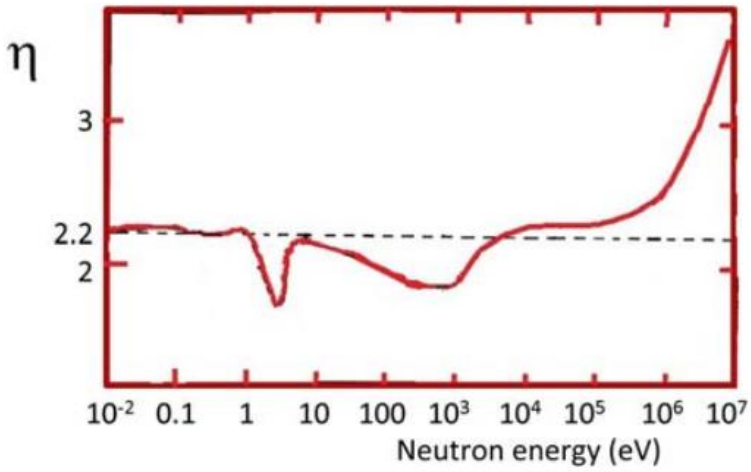


Figure 1.1. Deference of η with Neutron energy for ^{233}U.

The liquid fuel consists of two fluids the first one is fissile ^{233}U pass throw the core of the column and the second one is fertile ^{232}Th passing throw the blanket of the column .this column is made of graphite as a moderator that works on limited Neutrons speed to ensure absorption by Thorium-232 in the blanket .there fluids are contained Fluorides or Chlorides in an environment of FLiBe salt as a coolant [5] as shown in Figure (1.2).

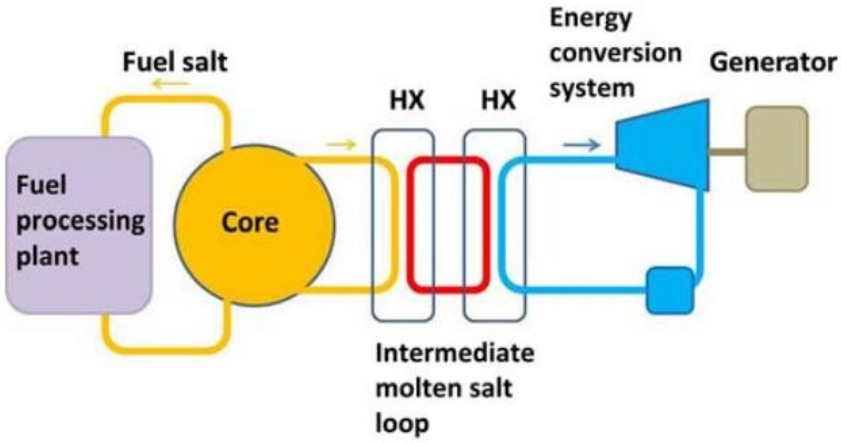


Figure 1.2. Simple fuel cycle in Thorium reactor [5].

The general idea from Figure (1.2) is that the molten fuel cycle inside the reactor shows the concept of how we can generate thermal and electrical power by transferring heat throw to heat exchanger loops and fuel treatment plant which we will discuss deeply in Part 3 for one column show Figure (1.3) and whole reactor.

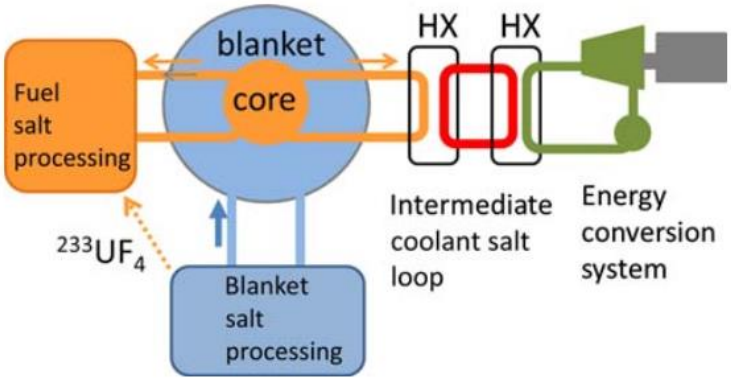


Figure 1.3. Fuel cycle in one column [5].

1.2.2. Safety

Thorium reactor in concept depends on liquid molten salts fuel so it is already in the molten phase so there is no danger of melting fuel issues and the ability to continuous refuelling from a far distance (by internet) which means less core reactivity that makes heart control easier and safer with ability to remove undesirable fission products continuously like Protactinium-233 and radioactive Cesium-137 which it could be used for another application with the ability to remove nobble gasses like Xenon and Krypton easily avoiding Chornobyl issues in other hand Thorium reactor works with low pressure so there is no need to huge containment domes and calculations for high-pressure vessels issues in addition of no concern for clade leak fission products so no need for cladding with Zirconium in hot water which caused to generate Hydrogen and explosions like Fukushima. Secondly, core overheating could melt the drain plug so the molten core drained into massive coolant tanks with a low solidification range to trap radioactivity so low core emission after shutdown and no need to use control rods because Fluorides and Chlorides salts are stable in high radiation fields with boiling degree is 1400 °C so no boiling will accrue [5].

1.2.3. Economy

Thorium reactors in principle depend on low pressure and high heat capacity led to low expensive core design without huge containment buildings because no heavy or light water uses these properties making it easy for shipping and underground

construction beside the core reactor could work with high temperatures 700 °C and electrical generation efficiency 44% or more compared 33% for LWRs and HWRs, in addition, there is no need to manufacturing fuel pellets or core control rods and precise core structure so no need to continuous leak test for fuel in core pins and easily refuelling without shutdown instead of the fuel lifetime is not limited by radiation damage all of these properties made Thorium reactor suitable economically to produce low-cost power with low price pills and give a huge effect on the economic system [5].

Economic properties are given as

- Simplicity
- The capital cost of the plant
- Construction time-modular and factory built
- Plant lifetime
- Fuel cycle cost, availability
- Reliability, availability, maintainability
- Load following
- Investment risk and finance availability
- Plant staff size, training, availability
- Market proximity to the load centre
- Transmission grid capacity and stability
- Resources
- Natural hazards-seismic activity, fires, floods, wind storms, lightning.

1.2.4. Environment

Thorium element in nature is four-time abundant than Uranium so it could be covered all world's demands on nuclear fuel with the ability of recycling actinides (elements 89 – 103) in liquid fuel which cant be in LWRs and HWRs so low nuclear waste production secondly high efficiency to produce electrical power according to the high cooling system so less heat rejection to the environment Thorium reactor liquid fuel

produces 1% of nuclear waste with low radioactive isotopes can easily treated and non critically concerned [5].

Acceptances of Thorium reactor [5] are given as:

- Waste-chemical, radioactive
- Decommissioning
- International sales

Regulatory simplicity is given as:

- Regulations-stability, retrofitting, reporting requirements
- Lawsuits
- Safety
- Emergency planning-off-site evacuation plan required?
- Emissions
- Worker exposure
- Licensing-lifetime power plant license (licensing may be slow in countries with no MSR experience).

Public acceptance is given by:

- Public understanding
- Environmental regulations- cooling water, archaeological sites, protected species
- Waste heat
- Passive safety
- Emissions-toxic metals, chemicals, radioactivity
- Radwaste minimization, benign disposal
- Public concerns and perception
- Nonproliferation of nuclear weapons

1.3. THORIUM REACTOR DIFFICULTIES AND PROBLEMS

Thorium reactor has many challenges and difficulties we will mention them here but discuss them deeply and gave solutions in Part 3 for the following problems:

- The fuel flow out reactor continuous emit delayed neutron throw surrounding pipes and valves this emission neutron effect kinetic, dynamic and neutron noise in stationary and cause plumping radioactive so remote maintenance is required.
- Fusion product Tellurium-caused cracks inside the heart can be reduced by controlling UF_3/UF_4 ratio.
- Neutron irradiation cause helium accumulation to rise to ultimate tensile stress by radiation which is called radiation hardening decreasing ductility inside the column's heart so there is needed to provide carbon content or shield all vessels and pipes including the heart's columns.
- Corrosion problems in pipes, valves, pumps, and the core because of high temperature and salty environment.
- The tritium issue is a big problem produced by Li element absorption neutron to produce Tritium which affects on neutron economy [6].

PART 2

KINDS OF THORIUM REACTOR DESIGNS

2.1. MATERIALS

2.1.1. The Molten Salt

The molten salt is a chemical component produced by the chemical reaction between acids and alkalis where the results are salt and water the physical properties of molten salts which will be used in our reactor are transparent, liquid phase, low density close to water density, and low vapour pressure(0.5 MPa near to 5 atm) beside that it should be chemically stable and can dissolve all nuclear materials which needed in the heart of reactor since most salts have high melting temperature if leakage happened it will be solidified with no radioactive material and this is another benefit as a safety property in a Thorium reactor [7].

Figure 2.1. Chloride salt as an example.

These molten salts will be used as a coolant and reactor fuel and heat transfer medium as fuel the molten salt is Lithium Beryllium Fluoride (F-Li-Be) reacted chemically with fissile isotope as an ionic element which is ^{233}U produce UF_4 and fertile isotope in an ionic state which is ^{232}Th to produce ThF_4. These two salts are the main fuel reactor at the same time (F-Li-Be) works as heat transfer with heat exchangers and heart coolant liquid. When the fissile reaction occurs the liquid fuel temperature increases and can be exchanged with molten salt by pumping it throw the core and recycle it again this property give us high control on the core temperature in another hand the molten salt transfer heat to heat exchangers system loops for electrical generators turbines to star power plant operations [9]. Secondly, liquid Fluoride salts as a fuel and coolant have great properties because of their high thermochemical stability and considered high corrosion resistance, and the liquid phase of fuel gives the ability to remove all gases produced inside the heart of the reactor such as Xenon Xe-135 and Krypton's (Kr-85,87,88,89) which is highly radioactive and create high damages inside the core by pumping the liquid salts outside the core to gas releasing champers [8].

Table 2.1. Molten salts' physical-chemical properties in Sodium and 500 °C [10].

Elements / Molten salts	$NaNO_3$-KNO_3-$NaNO_2$ [HTS]	$NaBF_4$-NaF	Li_2CO_3-Na_2CO_3-K_2CO_3	LiF-NaF-KF [FLiNaK]	LiF-BeF_2 [FLiBe]	Na
Chemical composition (mol%)	7-44-49	92-8	41-36-23	46.5-11.5-42	66-34	–
Melting temperature (°C)	142	384	399	454	459	98
Volumetric heat capacity: C (J/m^{3}K) × 10^{-6}	2.79	2.82	3.49	4.01	4.80	1.05
Density: d (kg/m^3) × 10^3	1.79	1.87	2.02	2.17	2.05	0.83
Thermal conductivity: h (W/mK)	0.59	0.35	0.55	1.2	1.00	66.
Kinematic viscosity: k (m^2/s) × 10^6	2.26	0.8	11.8	4.2	7.44	0.29
Heat-transfer capability $(C/k)^{0.4} h^{0.6} \times 10^{-3}$	49.7	55.7	25.2	69.4	52.8	1.264
Heat-transfer per unit pump-power: $C^3/d \times 10^{-15}$	12.1	12.1	21	29.4	53.8	1.39

From Table (2.1), we conclude Fluoride molten salt (F-Li-Be) has given as

- Low pressure and low vapour pressure
- High boiling temperature
- High heat capacity
- Suitable viscosity
- Good(panel) number between 10 – 20 in range of 500 – 700 °C (thermal shock in high deference of temperatures changes)

2.1.2. Moderator (Graphite)

The fission and absorption reactions are very high cross-sections at low energy so the neutron emitted by the fissile reaction needs too many collisions with material to slow down the neutrons from (MeV) to thermal energy (0.025 eV). Here comes the moderator as an essential part of the reactor to keep nuclear reaction and the critical case continues and under control, many types of materials could be used as a moderator as shown in Table 2.2. But we choose graphite for the Thorium reactor because of its special properties.

Table 2.2. Possible moderators materials [11].

Material	A	N	Moderating ratio
Hydrogen	1	18	
H_2O		19	71
ZrH_2			27
Deuterium	2	24	
D_2O		34	5670
Lithium-7	7	67	11
^7LiF			21
Beryllium	9	84	164
BeO		101	217
BeF_2			86
Carbon	12	110	191
Oxygen	16	145	

As we can show from Table (2.2) a represents the atomic number and n is equal to an average number of collisions where moderating ratio MR is calculated by dividing slow-down power over the absorption cross-section [11].

$$MR = \frac{\varepsilon \sum_{s}}{\sum_{a}} \quad (2.1)$$

We can see carbon which is graphite has a high moderating ratio equal to 191 and a high rate of collision or neutron impacting equal to 110 is mean graphite as a moderator will be worked with high efficiency in the inflection of neutrons or slow down but there are limitations we should consider as

- Molten salt should not penetrate the graphite surface as is cause additional radiation inside the core and damages the fuel heart columns this issue can be solved by making the surface porosity less or equal to 1 micrometre.
- Xenon and Krypton gases should not be trapped in graphite because it has a large absorption cross-section which will affect on neutron economy inside the core and chain reaction efficiency so should be pebbled these gases is necessary.
- Heat removal from graphite is very important when it is heated by gamma-ray or neutron slowing down this heat must be evaluated with fuel heat to keep graphite expansion very low and exchange heat with coolant molten salt with high efficiency [12].

2.2. STRUCTURAL MATERIALS

When we are starting and thinking to build a Thorium reactor there are many requirements to choosing materials for construction with certain conditions we should mind the heat temperature for a long duration and strength at a high temperature elevated so the material should have high creep and fatigue resistance with good ductility after radiation secondly the most important property should take care is corrosion resistance that's because fuel and coolant are in liquid phase salts beside that low activation for waste disposal and minimum Tritium retention are required for designing reactor with no issues.

2.2.1. Superalloy (Hastelloy Nickel and Nickel-Based Alloy)

Hastelloy Ni alloy contains (Ni-Mo-Cr-Fe) composition as shown in Table (2.3) improves excellent performance to parts that are faced the salty environment so Hastelloy can be used in the reactor vessel, pipes, pump, and heat exchangers [13].

Table 2.3. Hastelloy composition [14].

Element	Hastelloy N (Haynes)[a]	Hastelloy N (ORNL spec.)	Modified Hastelloy N (with Nb)	Modified alloy (with Ti)
Nickel	71	Base	Base	Base
Molybdenum	16	15–18	11–13	11–13
Chromium	7	6–8	6–8	6–8
Iron	<5	<5	<0.1	<0.1
Manganese	<1	<1	0.15–0.25	0.15–0.25
Silicon	<1	<1	<0.1	<0.1
Phosphorus	<0.8	<0.015	<0.01	<0.01
Sulfur		<0.02	<0.01	<0.01
Boron		<0.01	<0.001	<0.001
Niobium		–	1–2	–
Titanium		–	–	<2

Hastelloy has good compatibility with salts containing Fluorides or Chlorides because halogens are thermodynamically stable with Nickel alloys [14]. Hastelloy has great properties against fast and thermal neutrons which did not affect metal because of its high ductility, creep resistance, and fatigue at high-temperature long time environments all of that made superalloy Hastelloy Nickel a suitable base material for manufacturing Thorium reactor parts [15].

Figure 2.2. Hastelloy [15].

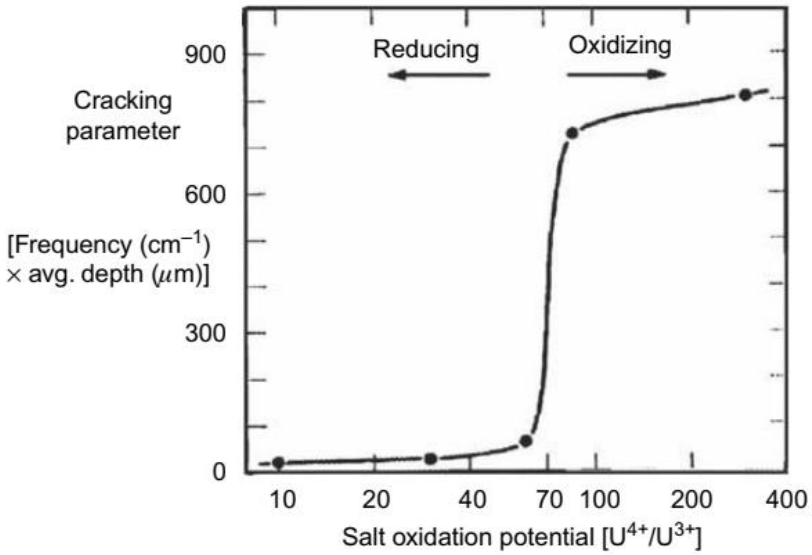


Figure 2.3. Hastelloy crack behavior [15].

2.3. DESCRIPTION AND DESIGN OF THORIUM REACTOR

Thorium reactor is the fourth generation of nuclear reactor differs from all kinds of reactors which are using solid fuel it depends completely on liquid fuel which is Thorium tetra-Fluoride as a fertile pass throw an outer stream of columns of heart or core called (blanket) and Uranium tetra-Fluoride as fissile pass throw an inner stream of columns (core) which made of graphite as moderator separate between two liquids with a certain thickness to slow down the neutrons and keep the chain reaction in critical care [16].

Secondly, there are three fluid loops stations the first one contains two stations (refresh fuel cycle and reprocess fuel cycle) for fuel recycling it works like a kidney purifying the fuel from gasses bubbles like (He - Xe – Kr) and isotopes with approximately has long half-life like ProtActinium which need 27 days to decay to ^{233}U this loop is very important it keep the fuel pure as possible. The second loop station is coolant salt which is composition is (F - Li- Be) salt entrance the heart as a cooling fluid exit with 700°C to the heat exchangers system to transport heat to another power generation loop so this loop works as heat removal from the heart and in same time heat transfer loop. Thirdly the safety heat removal loop which is underground consist of a group of drain tanks joints with the heart of the reactor by a thermal fuse when the heart heat

exceeds the normal limits (750 – 900°C) this fuse will meltdown and all fuel will pour inside these tanks to chill up and heat removing with no any radiation because of the absence of moderator from Figure(2.3) [17].

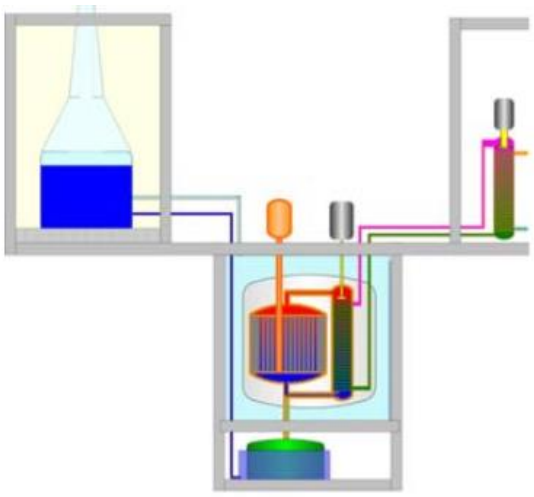


Figure 2.4. Safety drain tank and reactor properties.

Table 2.4. Reactor components.

Electrical capacity (MWe)	168
Thermal capacity (MWt)	395
Inlet/outlet temperatures of primary loop	600/700°C
Fuel salt (salt of primary loop)	$LiF\text{-}BeF_2\text{-}UF_4\text{-}ThF_4$
Salt of second loop	FNaBe
Moderator	Graphite
Structural material	Nickel-based alloy or surface-treated stainless steel
Main vessel size (D × H) (m)	5.2 × 6.0
Processing for fuel cycle	Online degassing (Xe, He, T), offline removing solid fission products
Residual heat removal	Passive residual heat removal system
Generator system	Open air Brayton cycle and Rankine cycle

The Thorium reactor's main parts are the heart which is the(core and blanket), chemical separation stations, and heat exchanging coolant cycle as we can see in this Figure (2.4).

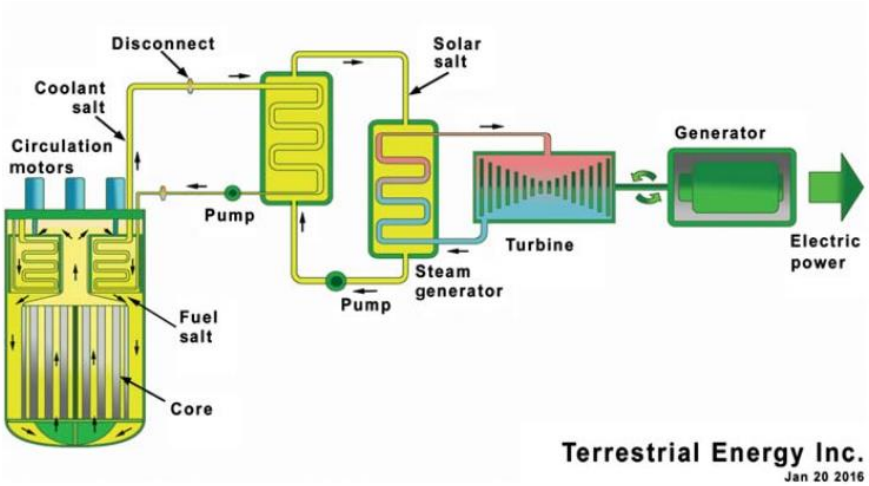


Figure 2.5. Sketch of Thorium reactor power plant.

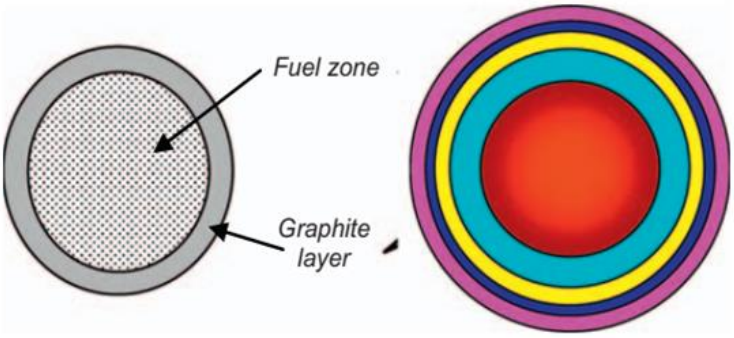
The main heat source and energy generation come from the heart by nuclear reaction between Thorium and Uranium as nuclear fuel salts. The core of the reactor contains two vassals the first one is internally made of graphite called the core which includes ^{233}U passage and the second one which is an outer surface made of Nickel (hast alloy) called a blanket which consists of ^{232}Th. These two vassals are connected by two chemical separation stations. the reaction starts when ^{232}Th absorbs a neutron that came originally from the fission reaction of ^{233}U according to these equations (2.2), (2.3) and (2.4) [18]:

$$^{232}Th + {}_{0}n^{1} \rightarrow {}^{233}Th + \gamma \text{ (neutron absorption)} \quad (2.2)$$

$$^{233}Th \rightarrow {}_{-1}\beta^{0} + {}^{233}Pa \text{ (beta decay } -\lambda = 22.3 \text{ min)} \quad (2.3)$$

$$^{233}Pa \rightarrow {}_{-1}\beta^{0} + {}^{233}U \text{ (beta decay } -\lambda = 27 \text{ days)} \quad (2.4)$$

As the main design, there are several suggestions. However, some ideas use two vessels for the core and blanket shown in Figure 2.6. or use columns for the core contained by a vessel as a blanket as we can see in Figure (2.9) a,b,c,d.



	(^{233}U+Th)O_2kernel (500 μm) diameter
	Pyrolitic graphite (90 μm) thick
	Inner dense carbon (30 μm) thick
	Silicon carbide (30 μm) thick
	Outer dense carbon (50 μm) thick

Figure 2.6. Column layers materials.

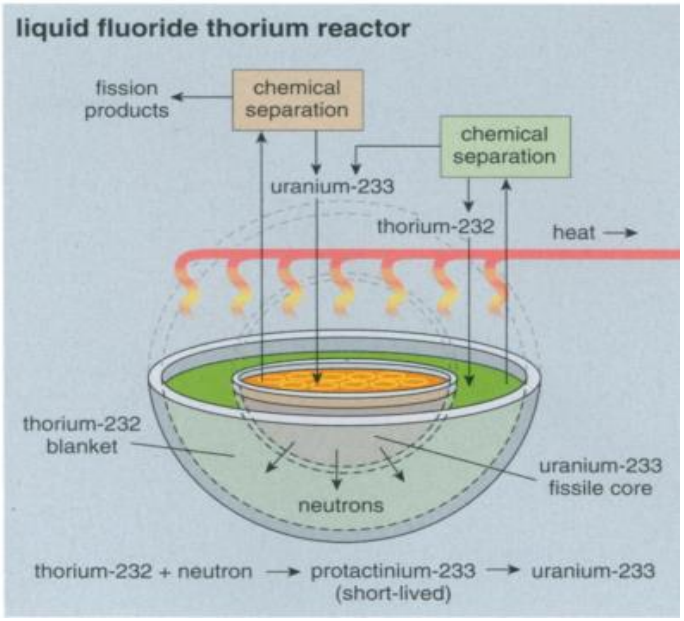


Figure 2.7. Front view cross-section for the main fuel column.

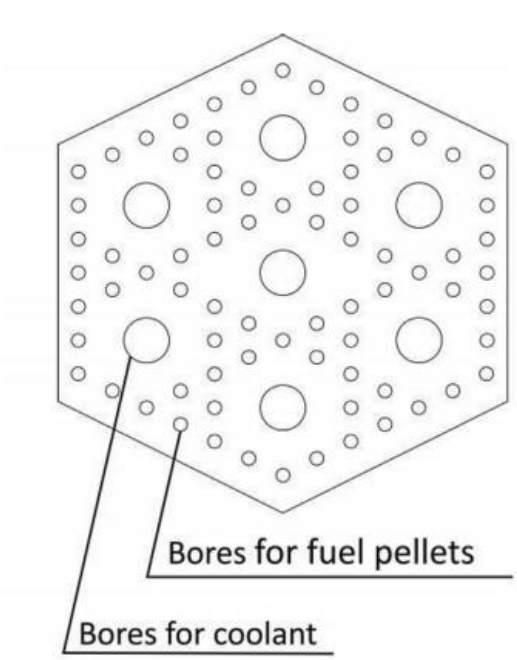


Figure 2.8. Fuel and coolant salt streams inside the column.

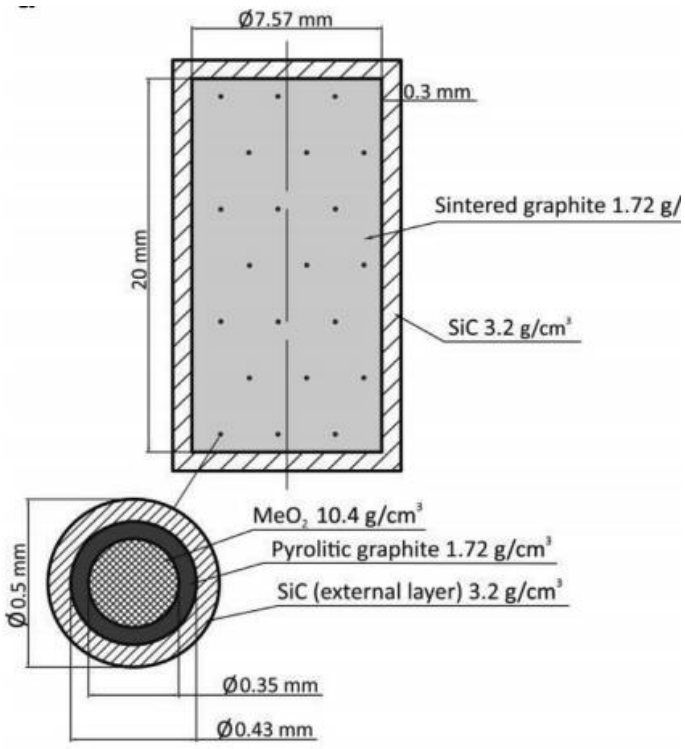


Figure 2.9. Column dimensions.

2.4. MECHANISM

When fissile ^{233}U passes throw the core the scattered neutrons will decay throw the liquid salt fuel some of them will penetrate the graphite with low velocity under the effect of graphite as a moderator to be absorbed by fertile ^{232}Th to create ProtActinium isotope and gamma-ray in form of heat in this time we need to separate ProtActinium from the blanket using first recycling station to send it to decay tank for 27.5 days some of it will decay to ^{233}U we can use it as fresh fuel inside the core the other part will take a different nuclear direction chain reaction decays by two alpha decay to create ^{225}Ac isotope used in medical applications. the remaining ^{233}Pa isotope generated by positive beta decay like actinides and lanthanides could be recycled for industrial applications or sent to waste storage. while ^{233}U inside the core fissile a neutron by beta decay changed to ^{232}Th should be separated by the recycling fuel process which is the second station loop to reuse it as fresh fuel inside the blanket [19].

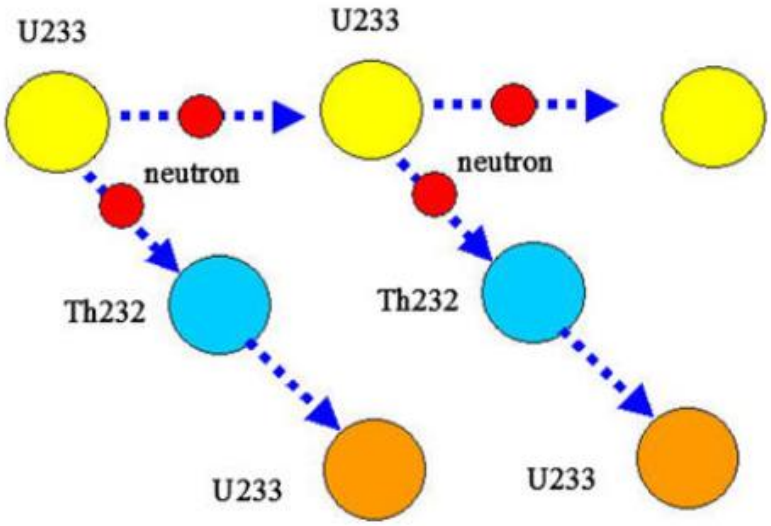


Figure 2.10. Beta decay for U-233.

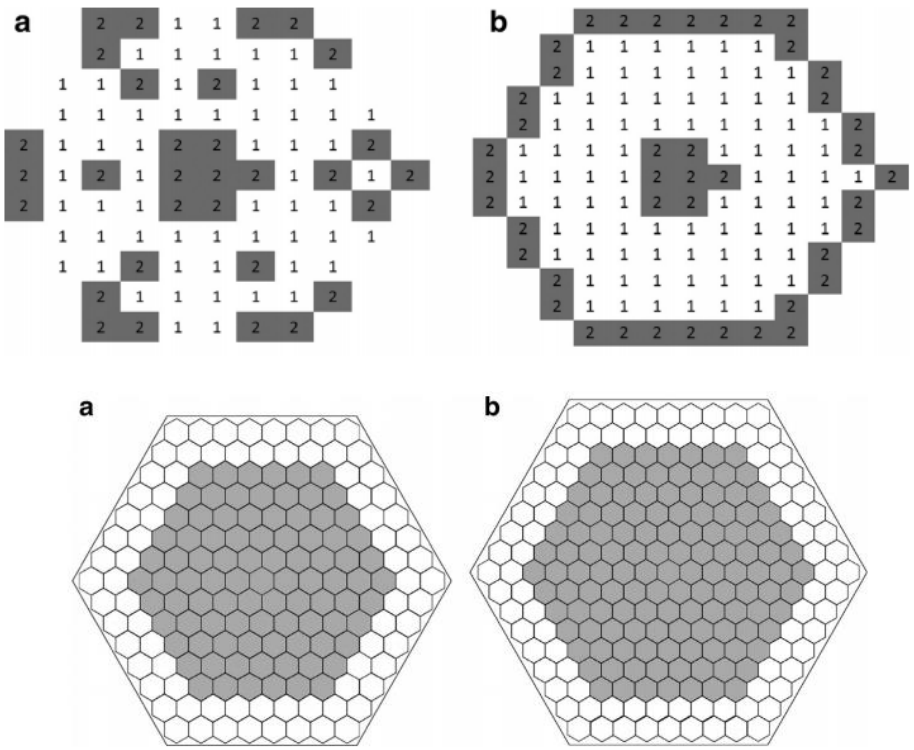


Figure 2.11. Core reactor configuration [20].

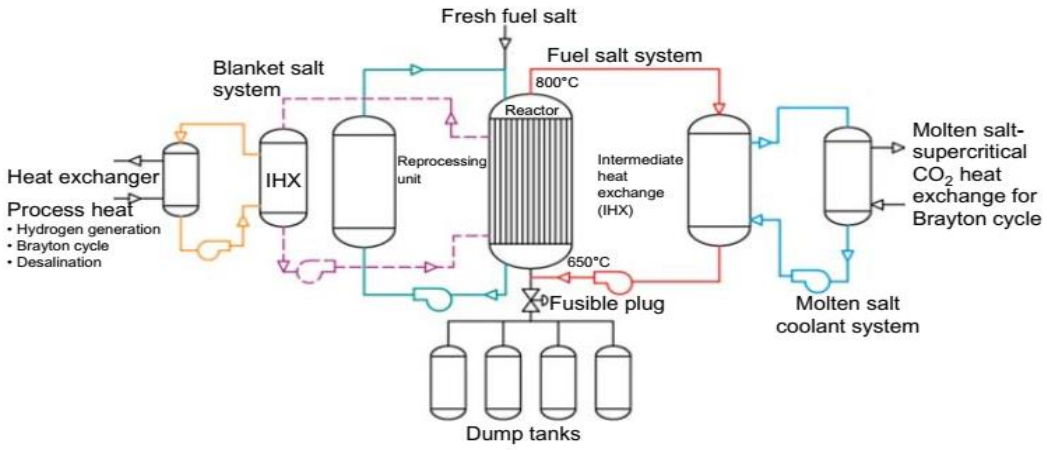


Figure 2.12. Thorium reactor sketch [21].

2.5. CHEMICAL PROCESSES (KIDNEY)

These stations are most important to keep the reactor in continuous operation and are divided into two stations first one is the fresh fuel cycle which deals with the primary fuel loop to remove fissile products that may be poisoning the fuel salt with undesirable products and neutrons. the second one is reprocessing fuel cycle which deals with a

secondary fuel loop to remove gasses and other side productions and keep the results salt in maximum purity to reuse it as nuclear fuel in the primary loop again these two stations include many chemical reactions in many stages to reach the required results [22].

2.5.1. Fresh Fuel Cycle

Starting from Uranium Oxide to generate the main fuel salt which is Uranium tetraFluoride as shown in this chemical reaction:

$$UO_2 + 4HF \rightarrow UF_4 + 2H_2O \quad (2.5)$$

Fluoric acid work as a reduction agent that reacts with Oxygen in an exothermic reaction to give Uranium tetra-Fluoride in a liquid phase and at 500 °C we use it as the main fissile fuel in the heart (core stream).

In the same principle the Thorium tetra-Fluoride can be generated as shown in this chemical reaction :

$$ThO_2 + 4HF \rightarrow ThF_4 + 2H_2O \quad (2.6)$$

It is an exothermal reaction under 500 – 600°C heat-generating given as Thorium tetra-Fluoride salt in the liquid phase which will use as fertile fuel in the heart (blanket stream) [23].

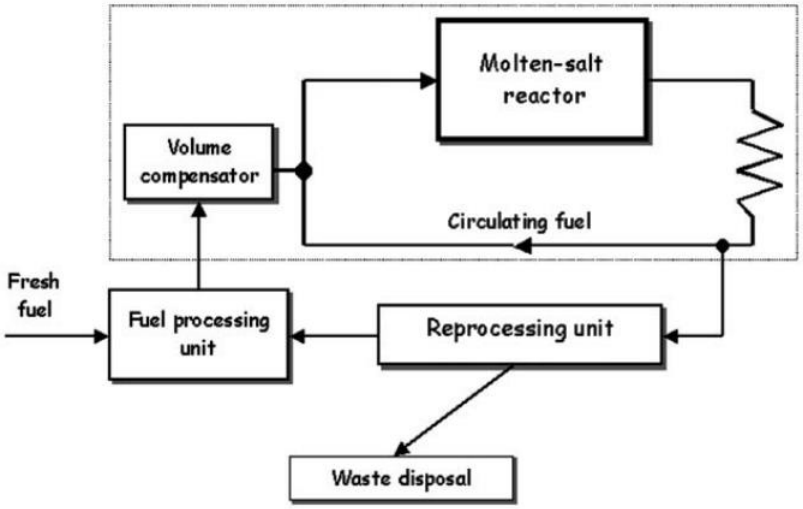


Figure 2.13. Fresh fuel cycle diagram [24].

2.5.2. Reprocess Fuel Cycle

This station is highly important to keep the reactor in steady-state condition and working for the longest time we need high-purity fuel inside the heart so this station helps us to remove fissile products which have a long half lifetime like Protactinium reaches 27days and will decay to ^{233}U that we can use it as main fissile fuel in the core this process help as to avoid poisons neutrons which effects on neutrons economy inside the heart the second important property that we can remove actinides like Krypton and Xenon which dissolved in liquid salts by chemical separation[24] in another hand the chain reaction inside the heart divided into three nuclear reactions alpha decay, negative beta decay and positive beta decay the negative beta decay is the main reaction:

$$^{232}Th + {}_{0}n^{1} \rightarrow {}^{233}Th + \gamma \text{ (Neutron absorption)} \quad (2.2)$$

$$^{233}\text{Th} \rightarrow {}_{-1}\beta^{0} + {}^{233}\text{Pa} \text{ (beta decay } -\lambda = 22.3 \text{ min)} \quad (2.3)$$

$$^{233}\text{Pa} \rightarrow {}_{-1}\beta^{0} + {}^{233}\text{U} \text{ (beta decay } -\lambda = 27 \text{ days)} \quad (2.4)$$

We need to remain the heart chain reaction under these conditions but while nuclear chain reaction energy can not be expectable and unknown so positive beta decay and alpha decay accurse. Positive beta decay gives a positive nucleus.

$$^{233}U - 1\beta^{+} = {}^{232}Th\ (fissile) \tag{2.7}$$

Will react with negative nuclei came from a negative beta reaction to give us energy in form of heat so we can neglect neutron economy effecting because heat generation can replace our losses but alpha decay we should concern because the new component that results we should separate in this station. the most wanted is Actinium-225 as a medical isotope.

$$^{233}U + \alpha\ decay \rightarrow {}^{232}Th + \alpha\ decay \rightarrow {}^{225}Ra + \beta\ decay \rightarrow {}^{225}Ac \tag{2.8}$$

The other unwanted results are Uranium hexafluoride and Thorium hexafluoride in the gas phase we can be separated by the gas tank inside this circuit and react with Oxygen as shown in this equation:

$$UF_6+O_2 = UF_4 + H_2O \quad ThF_6+O_2 = ThF_4+H_2O \tag{2.9}$$

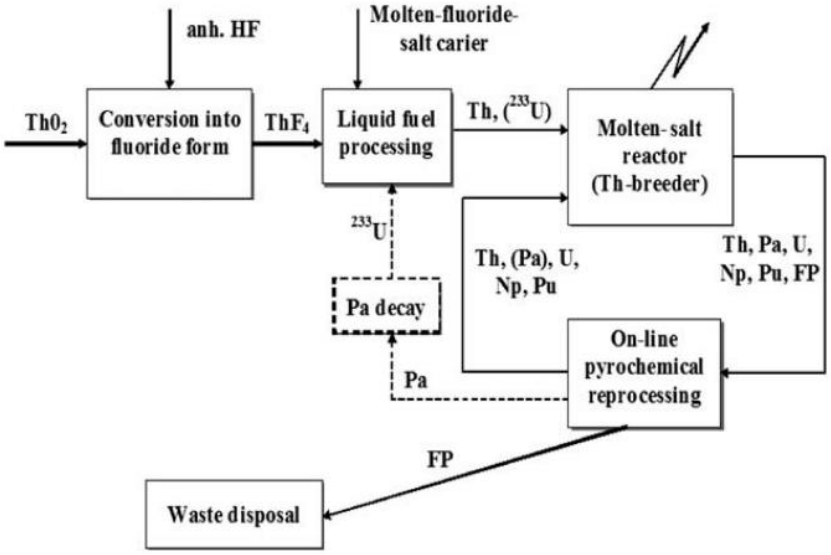


Figure 2.14. Recycle fuel process diagram [24].

2.5.3. Chemical Separation Processes

- Gases extractions: In this process, we can separate gases generated inside the heart this method depends on Henry's law principle which is compared to inert partial gas pressure in atmospheric pressure in this process we can remove all neutrons poison gases such as ^{135}Xe and ^{85}Kr which has low solubility inside liquid salts and high consuming of neutrons in the presence of another gas like (He) has different partial pressure the dissolved gases will leave the liquid molten salt and could be removed successfully these process limitations are bubble size, temperature, and gas pressure[25].
- Fused salt volatilization: This process help us to separate the most undesirable elements developed inside fuel salts in the core or mantel at same time it is including two stages first one is improving Fluoride bubbles inside the reactor heart it reacts with dissolved components and fissile products such as Nobelium, Molybdenum, and Technetium in addition of our fuel salt to create Uranium hexafluoride and Thorium hexafluoride in the gas phase under high temperature 500 – 600°C which operation temperature of the heart [26] the second stage is staring when the liquid mixture pumped to recycle fuel process to start chemical separation using two beds of NaF_2 at 400°C and MgF_2 at 100°C using NaK as a coolant [25]. This property give us the ability to remove all undesirable products and let Thorium hexafluoride and Uranium hexafluoride frozen in the chemical chamber to reduction by H_2 to produce Fluoride acid or oxidized by O_2 to produce water and pure Thorium tetra-Fluoride and Uranium tetra-Fluoride.

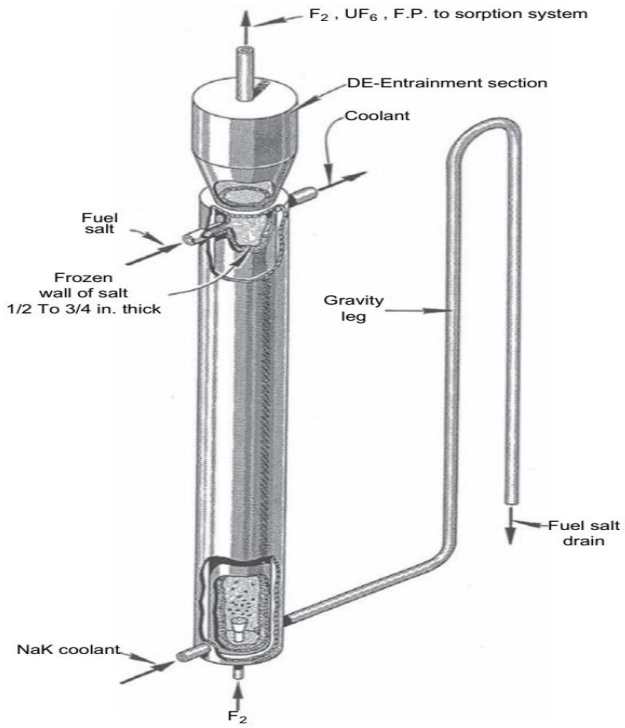


Figure 2.15. Fluoride bubbling process.

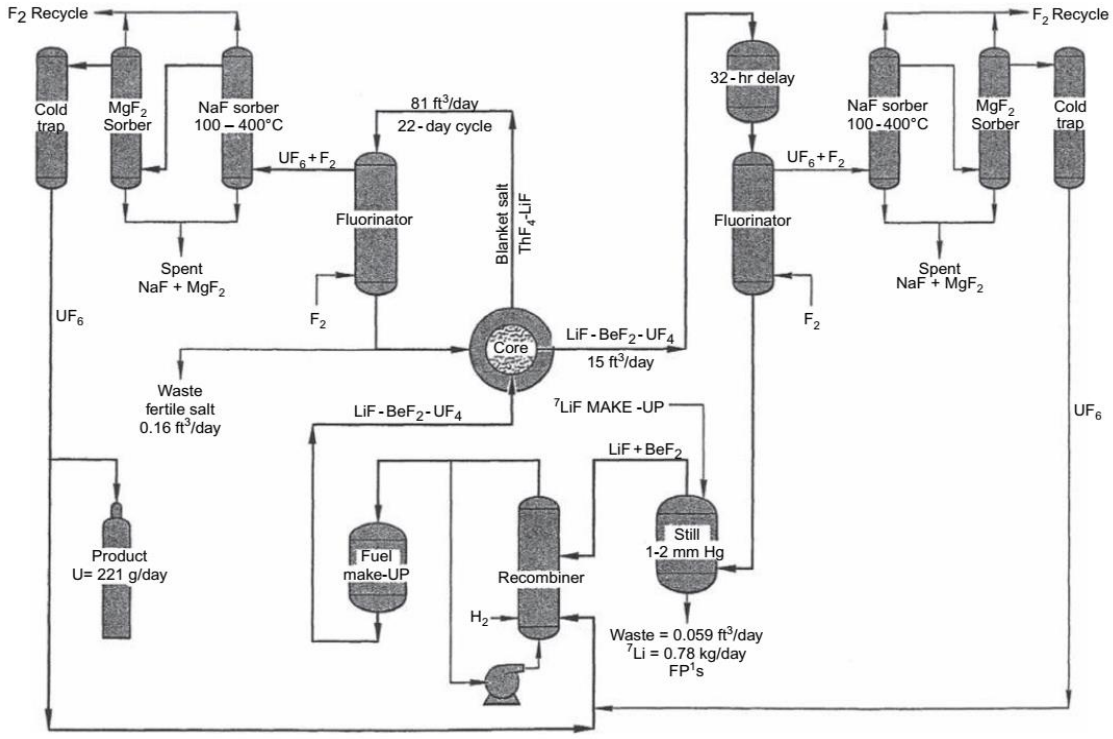


Figure 2.16. Sketch of Recycling fuel and chemical separation .

- Molten salt liquid metal extraction: this process is applied to clean up our fuel salt from lanthanides like rare earth and fission products and remove ProtActinium in the first stage by using liquid Bismuth bath reduction in a multi-stages extraction system [4]. The main principle of this process is the low melting temperature of Bismuth 271°C immiscible in a halides mixture with a low vapour pressure at 500 – 700 °C with suitable solubility of Thorium and Uranium in this degree adequate for this application where extraction reduction of molten salts and liquid metals can be represented by this relation:

$$MX_n + nLi\ (Bi) \leftrightarrow M(Bi) + nLiX \qquad (2.10)$$

Where MX is a metal halide that reacts with the Lithium Bismuth phase to produce M(Bi) metal Bismuth phase with Lithium halide [27].

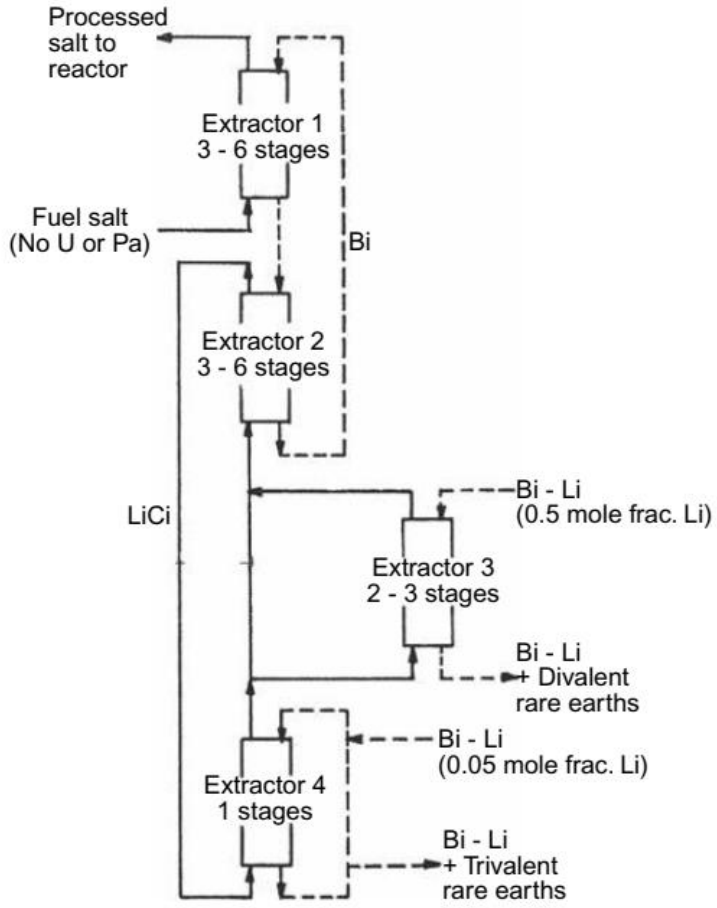


Figure 2.17. Molten salt liquid metal extraction for Bi-Li.

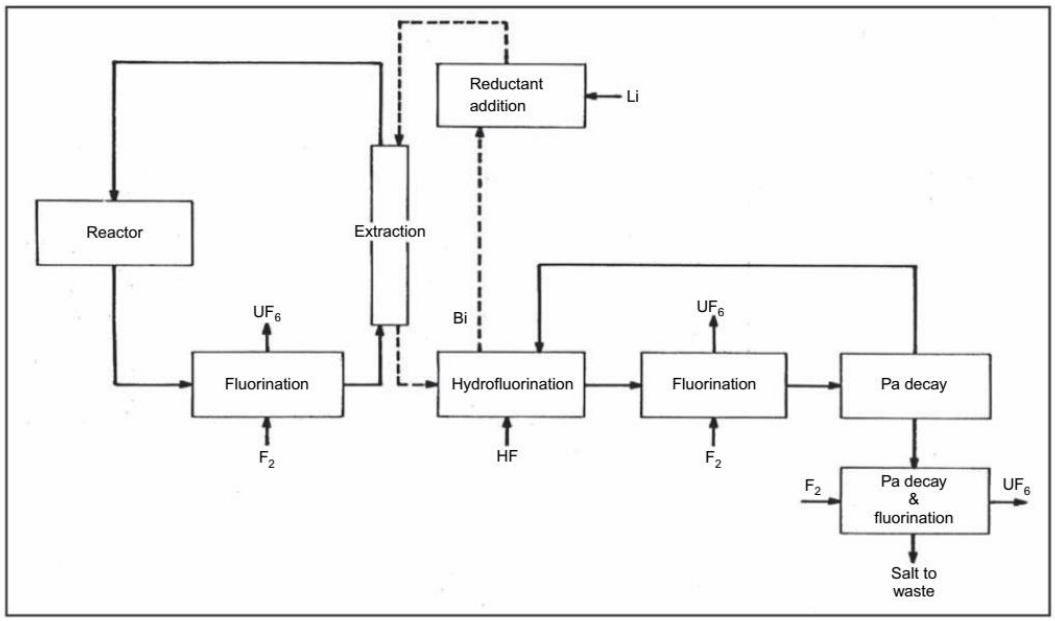


Figure 2.18. Molten salt liquid metal extraction for Pa-Bi.

The Protactinium Bismuth phase is most important for medical application when some Protactinium suffering from alpha decay to give Actinium-225 combined with Bismuth. Where Bismuth is considered an antibody-friendly element inside the human body that's mean human antibody will be armed with alpha decay particle directed to infected tissues with different kinds of cancers as we mentioned in chapter four of this thesis.

- Electrochemical separation process: In this process is secondary separation for rare earth elements like Thorium and Uranium in addition to our cooling liquid salts (Lithium Fluoride, Beryllium Fluoride, and Nickel eutectic phase) may be affected by nuclear reactions and produce different kinds of fissile products we can separate these undesirable elements according to its viscosity, electrical conductivity, low melting point, and electrochemical stability at 456°C [28].

- Vacuum distillation: This process is used to purify coolant liquid salts which are Lithium and Beryllium Fluoride at 1200°C.

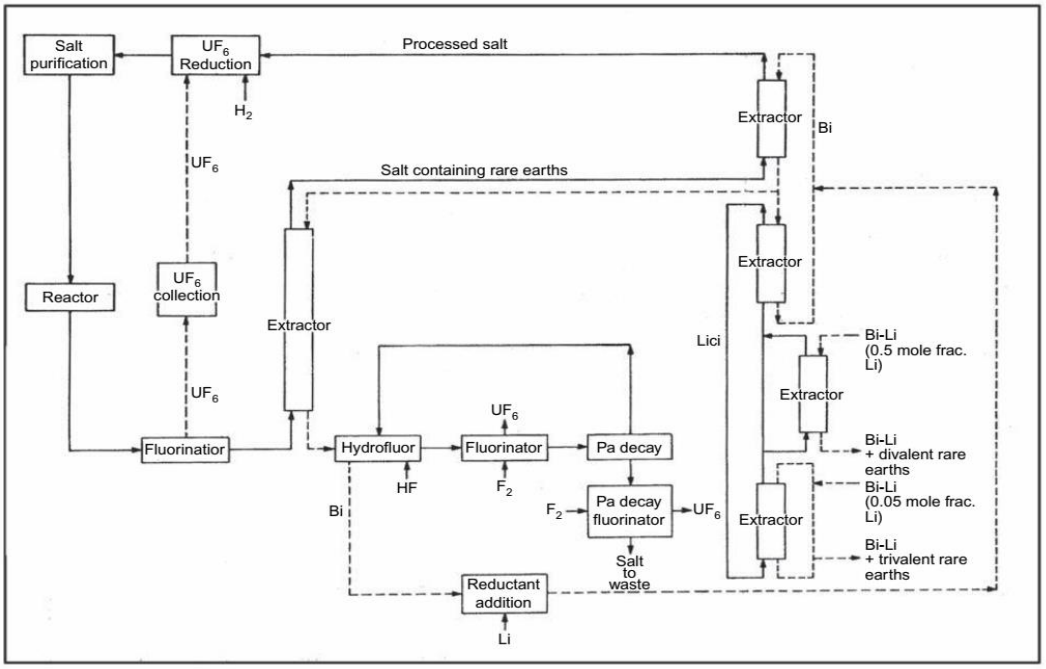


Figure 2.19. Sketch of the Recycling fuel process.

2.5.4. Safety and Radioactivity

Thorium fourth generation reactor has many differences then low or heavy water reactors in principle it deals with ^{233}U as fissile and ^{232}Th as fertile materials with graphite structural columns as a moderator while low and heavy water reactors use ^{233}U enriched by 5% to 20% of ^{235}U isotope as high fissile and ^{238}U or ^{239}Pu as a fertile material which has a great neutrons spontaneous generation causing high nuclear chain reaction releasing very high energy in form of heat sufficient to start a nuclear explosion if we can not control on critical conditions of the reactor so if enrichment increased to 80% or 90% of ^{235}U isotope in addition of Tritium and Hydrogen isotope generated from heavy water which is used as a moderator when absorbing a neutron that's led to the ability to manufacturing nuclear weapon while all of these elements are avoided in Thorium reactor in another word it is very hard or can say impossibly to start manufacturing nuclear weapon using Thorium reactor [29]. But we should not forget the high level of gamma radiation caused by the ^{228}U isotope which is stable as the ^{228}Th isotope's half-life is 1.8 years resulting from alpha decay of ^{232}Th reaches 2.6 MeV we should be separated from fuel salt as we mentioned before in kidney parts the other radioactive isotope is the ^{232}U results from ^{233}Pa beta decay half life 1.3 days can

be separated easily because short half-life then the rest ^{233}Pa half life 27.5 days in addition of that all radioactive isotopes actinides such as Neptunium, Americium and Curium can be recycled to fabricate a new fuel as we can see in Figure 2.20.

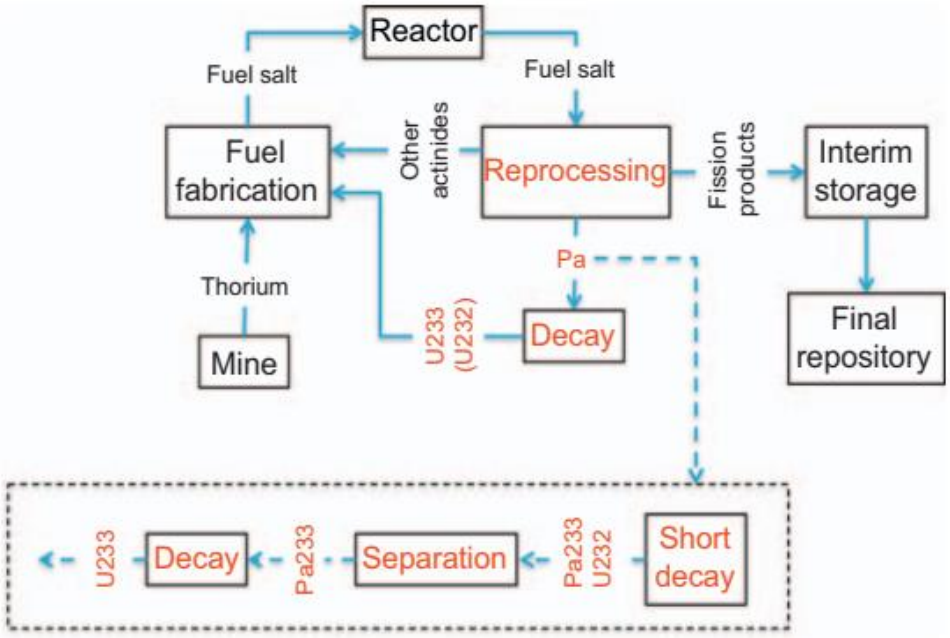


Figure 2.20. Sketch of radioactive elements separation.

2.6. PART REVIEW

From all the above Thorium reactor's main concept is nuclear-molten fuel salt gives us the ability to choose the suitable design can select between a multi-column core heart or vessel core heart according to chemical process complexity and power generate needed as we can see in Figure (2.14) and Figure (2.15). The operation process starts from preparing the fissile and fertile fuel in high purity concentration and keeps it as possible in this case by chemical processes facility during the chain reaction and continuous separation of harmful and advantageous isotopes to keep the main fuel reaction in good conditions with the ability to recycle the fuel and secondary products.

We should mention the complexity of this kind of reactor as a disadvantage but when we considered the power generation in low cost and high level of safety with 1% of pollution products that makes us reconsider all power generation methods, especially when knowing the increase in global energy demand besides the global warming and

pollution of Carbon-di-Oxide results from fossil fuel which is the main reason of climate change and environmental deterioration.

On other hand, there is the ability to develop this kind of reactor to create many applications like medicine, seawater desalination, air space engines, submarines, and Thorium battery so for all of these Thorium reactors, the fourth generation is a promised technology could give humanity a good life and reduce many presents problems.

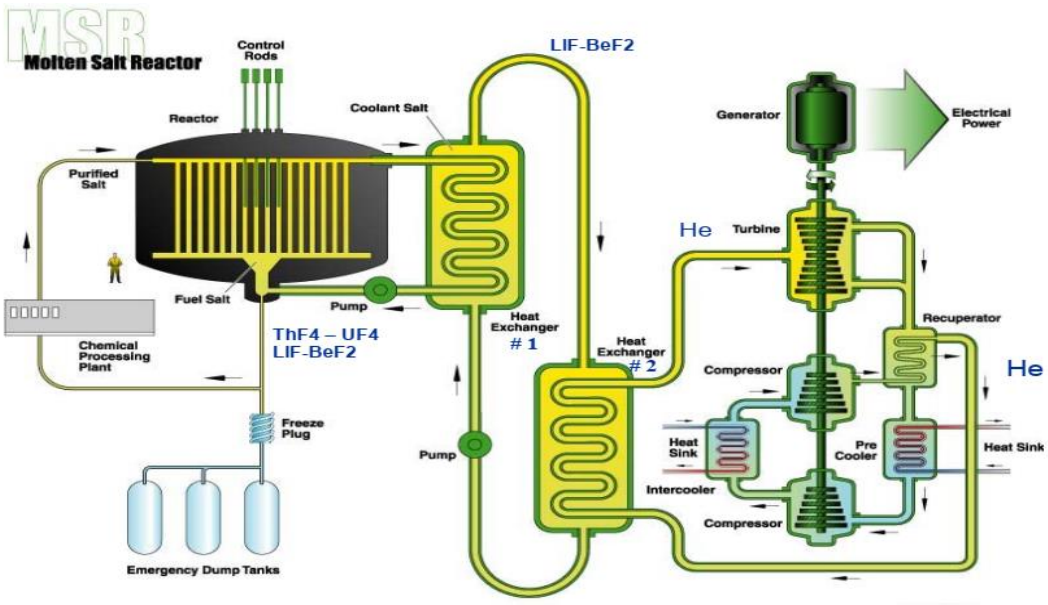


Figure 2.21. Multi-column core reactor.

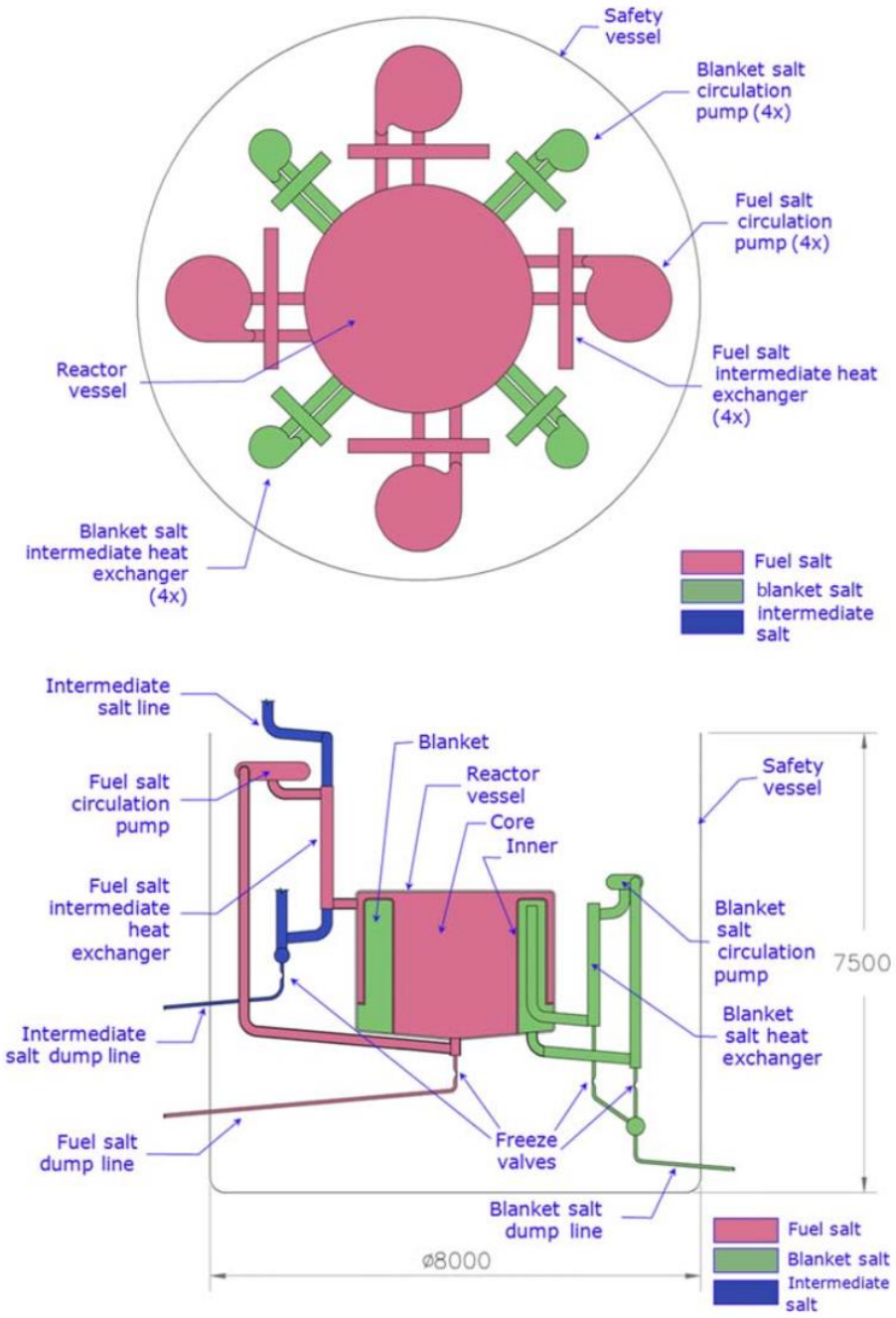


Figure 2.22. Vessel core reactor.

PART 3

EQUATIONS OF FUEL CYCLING

3.1. THORIUM REACTOR PHYSICS

The most important concept to understand how a Thorium reactor works and its limitations we need to know the physical properties and operations such as fuel composition changes during burning up, neutron interaction with matter, nuclear fission, multiplication factor, neutron spectrum, transport and diffusion equation of neutron, kinetic equation, and critical equation. All of these factors should be understood very well before starting design and choosing materials to solve problems and issues of operating, critical situations, design needs …. *etc.*

3.1.1. Neutron Interaction with Matter

There are two kinds of reactions are scattering and absorption a scattering reaction is an exchange of energy between two colliding particles and the Neutron still free after interaction while in a capture reaction the neutron retained inside nuclei producing a new isotope .there are many types of capture reactions such as

- Gamma radiation (n, γ)
- Alpha particle injection (n, α)
- Proton injection (n, p)
- Fission (n, f)

When a neutron is captured inside nuclei its kinetic energy and binding energy will be transferred to it and made it in an excited energy state part of this energy transferred to a neutron may be emitted leaving nuclei with low exiting energy this reaction is called inelastic scattering which happened in high energy neutrons another possibility

the neutron scattered by the nuclei without change in internal energy in this case called elastic scattering could occur in all kinds of neutron energy because income energy divided between scattered neutron and recoil nuclei.

Collision

Absorption is by

- Fission [(n,f) reaction]
- Capture [(n, gamma ray) reaction] (n,p) and (n, alpha) reactions

Scattering is by

- Elastic scattering [(n,n) reaction]
- Inelastic scattering [(n,n") reaction] (n,2n) reaction

3.1.2. Chain Reaction Factor

When nuclei like ^{233}U absorb neutrons the excited nuclei break up into two fission products and release high energy 1 MeV neutrons .these neutrons will be absorbed by another fissile nuclei's in this case we can say that a chain reaction started so the factor K_{eff} measured the number of neutrons emitted to several neutrons absorbed .when it is equal 1 that's mean the chain reaction will stop because of many neutrons will not be absorbed by leakage out of the core .so must be $K_{eff} > 1$, in this case, the core will be in supercritical condition and high rate of neutron production may lead high heat and expulsion the reactor .to solve this challenge we need high absorption material to keep the heart under control here ^{232}Th come as high-efficiency absorption to complete the chain reaction with high capability control the heart and keep reactor working with high efficiency [30].

$$K\infty = \frac{neutron\ produced\ in\ one\ generation}{neutron\ absorbed\ in\ preceding\ generation} = \frac{rate\ of\ neutron\ production}{rate\ of\ neutron\ absorbtion} \qquad (3.1)$$

$$K_{eff} = \frac{rate\ of\ neutron\ production}{rate\ of\ neutron\ absorbed + neutron\ leakage} \quad (3.2)$$

3.1.3. Cross-Section Area and Reaction Rate

The microscopic cross-section area (σ) is a particular reaction applied to single nuclei when the targeted material is many nuclei per unit volume (n) :

$$\sum = n\sigma \ldots(\text{m-1}) \quad (3.3)$$

when we have a mixture of materials and different cross-section areas:

$$\sum = n1\ \sigma1 + n2\ \sigma2 + ni\ \sigma i \quad (3.4)$$

Where n1, n2 ….atc depend on the component mixture, atomic weight, and densities.

3.1.4. Reaction Rate

$$\text{Reaction rate} = \sum nv \text{ interaction m-3s-1} \quad (3.5)$$

In this equation (n) represent the density of neutrons and (v) the velocity so this expression gives a reaction rate in one second for 1 m^3 of material. the neutron flux defines as produced neutron density in velocity.

$$\emptyset = nv \text{ neutrons m-2s-1} \quad (3.6)$$

So the reaction rate could be considered as:

$$\text{Reaction rate} = \sum \emptyset \text{ interaction m-3s-1} \quad (3.7)$$

The microscopic and macroscopic cross-sections could be defined by adding expressions. σ_a for absorption, σ_f for fission, σ_s for scattering, and σ_t for total cross-section.[30].

3.2. NEUTRON ENERGY DISTRIBUTION

Fission neutrons have average energy equal to 2 MeV depending on neutron speed which is near 20000 Km/s where fission happened with low neutron energy as shown in Figure (3.1)and Figure (3.2).

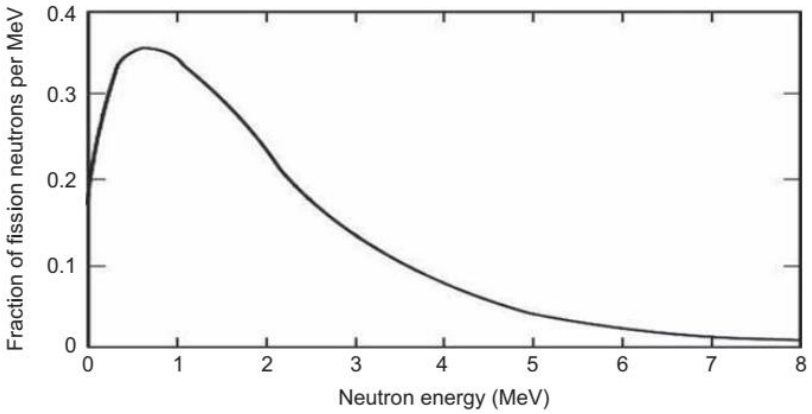


Figure 3.1. Fission neutron and energy [30].

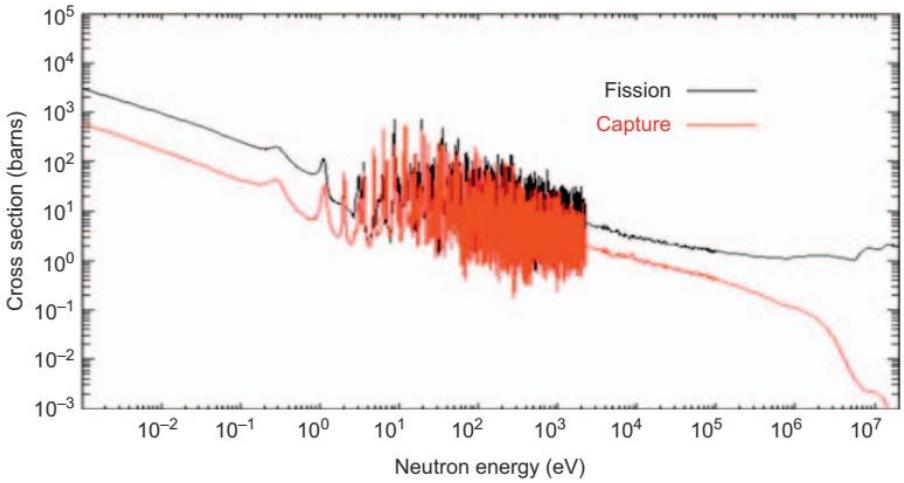


Figure 3.2. Fission probability with energy [30].

Since the fission cross-section needs low energy so we should need a moderator to slow down neutrons the lightweight moderators are recommended like Carbon and Hydrogen in a Thorium reactor we will use graphite as a moderator because of the high recoil by graphite nuclei will absorb the energy of neutrons inside the core and slow it down what are we needed to increase fission reaction.

3.2.1. Neutron Transportation and Diffusion (Boltzman Equation)

$$\frac{1}{v}\frac{\partial}{\partial t}\psi\ (\mathrm{r,E,\Omega,t}) + \sum\ t\ (\mathrm{r,E})\ \psi\ (\mathrm{r,E,\Omega,t}) + \Omega\nabla\psi\ (\mathrm{r,\ E,\ \Omega,\ t})$$
$$= \int_0^{\infty} d\mathrm{E}' \int_0^{4\pi} d\Omega' \sum_s\ (\mathrm{r,\ E}' \rightarrow \mathrm{E,\ \Omega}'.\ \Omega)\ \psi\ (\mathrm{r,\ E}',\ \Omega',\mathrm{t}) +$$
$$\frac{X(E)}{4\pi}\left[\int_0^{\infty} dE'v(E')\sum_f\ (\underline{r}, E')\emptyset(\underline{r}, E', t\right] + \frac{1}{4\pi}\,\mathrm{Qext(r,E,t)} \qquad (3.8)$$

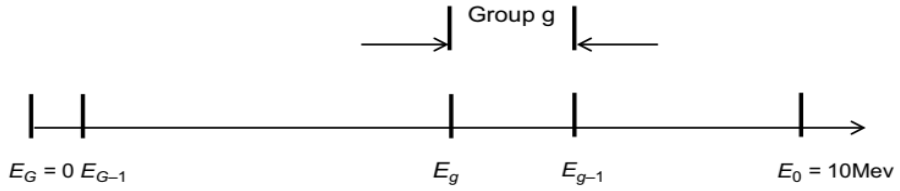
Fission reaction is a heat generation reaction dependent on neutron flux distribution that could be calculated from the above equation where Ψ(*r, E, Ω,t*) Angular flux of neutrons at position r with energy E moving in direction Ω at time t. Ψ(*r, E′, Ω′, t*) Angular flux of neutrons at position r with energy E moving in direction Ω′ at time t, φ (*r, E,t*) Scalar flux at position r and neutron energy E at time t defined as limited integration from 0 to 4π for this expression(ΩΨ)d where (*r, E′, Ω, t, Σt, E*) total macroscopic cross-section for all interactions of energy E at r, Σf, E and the macroscopic fission cross-section, Σs (*r, E′→! E, Ω′, Ω*) Scattering macroscopic cross-section with neutrons of energy E' moving in the direction Ω_0 to neutrons of energy E and into the direction Ω at position r, Q(*r, E,t*) Isotropic neutron source at r of neutrons of energy E at time t; χ(E)Fission neutron energy spectrum. All expressions are defined as energy E in position R in direction Ω at time t per unit volume per second [31].

3.2.2. Neutron Energy

$$\psi\ (\mathrm{r,E,\ \Omega}) = \psi\ (\mathrm{r,\ \Omega})\mathrm{f(E)}\ \ [31] \qquad (3.9)$$

The energy of neutron limitation is between (10 – 0.01) MeV where f(E) neutron energy flux when we multiply this equation with Boltzman equation with considered angular flux, cross-section area for each energy level, the small interval of energy range, angle, space, and time we get this equation:

$$\Omega.\ \nabla\ \psi\mathrm{g(r,\ \Omega)} + \sum_{t.g}\ (r).\psi(\mathrm{r.\ \Omega}) = \sum_{g'=1}^{G}\ \int_0^{4\pi}\ d\Omega'\ \sum_{sg'\rightarrow g}\ (r, \Omega' \rightarrow \Omega)\ \psi g'(\mathrm{r,}$$
$$\Omega') + \frac{x}{4\pi}\sum_{g'=1}^{G}\ v\sum_{fg'}\ (r)\emptyset g'(\mathrm{r}) + \mathrm{Sg\ (r,\ \Omega\ )} \qquad (3.10)$$



3.2.3. Approximation For One Group Energy

From the equation above we can calculate monoenergetic neutron and the equation become :

$\Omega.\nabla\psi$ (r, Ω)+$\sum$ t (r) ψ (r, Ω)=$\int_0^{4\pi}$ $d\ \Omega'\sum_s$ (r, Ω′ → Ω) ψ(r, Ω′)+$\frac{1}{4\pi}$

v$\sum_f$ (r) ∅(r)+(r , Ω) [31] (3.11)

3.2.4. Fuel Burnup Equations

In these calculations, we considered all reactions and composition changes with fissile or absorb chain reactions and isotope production.

Criticality equation: that's mean K_{eff} =1

To simplify the case of monoenergetic neutrons with diffusion approximate for homogenous infinite thickness which is symbolled a=1 in x-direction we get as [31]

$K_{eff}= \frac{(neutron\ source\ rate)}{loss\ rate\ by\ scattering+loss\ rate\ by\ absorption})=\frac{(v\sum_f \quad \emptyset)}{(D\nabla\emptyset-\sum_a \quad \emptyset)}$ (3.12a)

or

$D\nabla 2\emptyset - \sum_a \quad \emptyset = 0$ (3.12b)

We define this as a diffusion length $L^2= \frac{D}{\sum \quad a}$then :

$\nabla 2\emptyset - \frac{1}{L^2}\emptyset + \frac{v\sum_f}{Keff\sum_a}.\emptyset = 0$ [31] (3.13)

Where $K\infty > 1$ there are no critical conditions under these parameters so the equation will be :

$\nabla 2\ \emptyset - \frac{1}{L^2}(1- \frac{K\infty}{Keff})\ \emptyset = 0$ [31] (3.14)

So it can be written as

$\nabla 2\ \emptyset + B2\ \emptyset = 0$ where $B2= \frac{1}{L^2}(\frac{K\infty}{Keff} - 1)$ and $B2 > 0$ the solution will be :

$\emptyset\ (X)= A\ sin\ sin\ (Bx)\ + C(Bx)$ [31] (3.15)

as we can see the equation of original diffusion is a second-order differential equation so we need two boundaries to find variables A and C. otherwise we set the origin point of coordinates as the centre of the reactor that's mean the flux is symmetrical around the centre plan so one boundary condition is the flux in one direction where the other boundary is zero

$\emptyset(\pm\frac{a}{2}) = 0$

We will assume the thickness of the reactor is (a) so :

$\frac{B}{2}a = (2n+1)\frac{\pi}{2}$. [31]

The general solution of the flux will give as [31]

$\emptyset\ (X)= \sum_i\ Ai\ cos\ cos\ [\ (2n+1)\frac{\pi}{2}x\ ] > 0$ (3.16)

The fundamental mode equation because of higher mode die out and vibration of the string remains so the solution is given

$\emptyset$ (X)= C $cos\ cos$ ($\frac{\pi}{a}$ x)

We can calculate the variable C from other conditions. as we can see the solution can be determined when all conditions are satisfied so

B =$\frac{\pi}{a}$

B2 = $\frac{1}{L^2}$ ($\frac{K\infty}{Keff}$ -1)

K_{eff} = $\frac{K\infty}{1+L^2B^2}$ [31]

For non-leakage probability K_{eff}= $K\infty$ .P_{NL} so the solution for geometric buckling is given in this equation :

P_{NL} = $\frac{1}{1+L^2B^2}$ and B^2 = ($\frac{\pi}{a}$)^2

When reactor dimensions(size, thickness, and infinite slab reactor) are known the $K\infty$ and L^2 are known too so the geometric buckling can be calculated :

Where reactors critical is K_{eff}= 1 .so that $1 + L^2B^2 = K\infty$ this lead to B2 = $\frac{K\infty-1}{L^2}$

and a = πL L $\sqrt{\frac{1}{K\infty-1}}$ .For sphere design: B^2 =$\frac{\pi}{R}$.

for cylindrical B^2 =($\frac{\pi}{H}$)^2 +($\frac{2.405}{R}$)^2 and for rectangular design

B^2 = ($\frac{\pi}{a}$)^2+($\frac{\pi}{b}$)^2+ ($\frac{\pi}{c}$)^2 .[31] (3.17)

All these calculations assumed that all materials were in the homogenous case and neglecting multi regions flux inside the reactor was continuous of neutron flux boundary conditions .in reality the reactor is in three-dimension nonhomogenous material the solution must be in numerical analysis.

3.3. KINETIC EQUATION

To keep the reactor power constant we should keep it in critical case however to change its power we should change effective multiplication so we need to know Thorium reactor energy changed by understanding the kinetic equation which depends on the diffusion equation in case of no fuel flow:

$$D \nabla^2 \phi - \sum_a \phi + S = \frac{dh}{dt} \quad [31] \qquad (3.18)$$

Where S represents neutron source given as :

$$S = K\infty \sum_a \phi (1 - \beta) + \lambda C \quad [31]$$

The first relation shows the prompt-neutron contribution and the second relation shows delayed neutron contribution. In a nuclear fission reaction, some neutrons delay into six groups but to simplify the equation we considered it to be like one group so that (β) presents delay neutrons then(1–β)represent prompt neutrons, and(λ) is the effective decay constant, and (C) is the atomic density.

$$D \nabla^2 \phi - \sum_a \phi + K\infty \sum_a \phi (1 - \beta) + \lambda C = \frac{dn}{dt} \quad [31]$$

In this expression neutron, flux and precursor are related to time and space so we can replace $B^2\varphi$ which is mean geometrical buckling.

Where

$$\phi = NV \frac{D}{\sum_a} = L^2$$

$$v\sum_a [- \frac{DB^2}{\sum_a} - 1 + K\infty (1- \beta)] .n + \lambda C = v\sum_a [- L^2 B^2 - 1 + K\infty (1- \beta)].n + \lambda C$$

$$= v\sum_a [1+ L^2 B^2 \left(\frac{K\infty (1-\beta}{1+L^2 B^2} - 1\right)] + \lambda C = \frac{dn}{dt} \quad [31] \qquad (3.19)$$

This equation can be simplified by replacing these parameters:

$$l = \frac{1}{v\sum_a \quad (1+L^2 B^2)}$$

This is known as finite medium prompt-neutron lifetime because the average distance that neutrons run without leaking from the medium is expressed as:

$$X_{avg} = \frac{1}{\sum_a \quad (1+L^2 B^2)}$$

Thus, the lifetime could be given by dividing the distance by the neutron speed (v) Substituting the following relation:

$$K_{eff} = \frac{K\infty}{1+L^2 B^2}$$

finally the following relation results [31]

$$\frac{Keff\,(1-\beta)-1}{l}.n + \lambda C = \frac{dn}{dt} \qquad (3.20)$$

Or it can be written as

$$\frac{\frac{(1-\beta)-1}{Keff}}{\frac{l}{Keff}} n + \lambda C = \frac{\frac{(1-1}{Keff)-\beta}}{\frac{l}{Keff}} n + \lambda C = \frac{\rho-\beta}{\frac{l}{Keff}} n + \lambda C = \frac{dn}{dt} \quad [31] \qquad (3.21)$$

where

$$\rho = \frac{(Keff-1)}{Keff} \approx 1 - K_{eff}.$$

The growth of precursors is estimated from this relation :

$$\frac{dC}{dt} = \beta\, K\infty \sum_a \quad \emptyset - \lambda C$$

Using the expression of the $K\infty v\sum_a = \frac{Keff}{l}$ so the following relation is obtained

$$\frac{dC}{dt} = Keff \ \frac{\beta}{l} \text{ n} - \lambda \text{C}$$

These equations are simplified by defining neutron generation time as:

$$\Lambda = \frac{l}{Keff}$$

Then the final kinetic equations are expressed as:

$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} \text{ n} + \lambda \text{C}$$

$$\frac{dC}{dt} = \frac{\beta}{\Lambda} \text{ n} - \lambda \text{C} \qquad (3.22)$$

PART 4

APPLICATIONS

4.1. ACTINIUM-225 MEDICINE APPLICATION

Actinium isotope which is given as a side product came from a reactors heart collected by chemical cycles inside kidneys (Part 2) can produce alpha particles by alpha decay chain reaction capable of targeting cancer cells with different sizes and diameters because of its special properties :

- Low toxicity against normal cells and healthy tissue
- High linear energy cause high damage in each alpha decay
- Short half-life reaches 10 day
- Each alpha decay produces 4 alpha particles

These properties made Actinium suitable to cure different kinds of cancers like blood or prostate cancer. This cure technique depends on mixing different kinds of antibodies (peptides-IgGs antibodies- small molecules) solute with Actinium-225 particles making them high toxicity .when injecting the patient with this solute these toxic antibodies will attack damaged tissue by cancer cells carrying Actinium molecules which decay alpha particles with high energy targeting cancer cells nucleus[32]. This radiochemical property could not find in beta decay therapy, especially in (linear energy transition) LET which reaches 100 keV/μm causing huge cracks in the DNA of the targeting cell in addition to alpha particle diameter compared with beta particle diameter considered high that's mean high concentrate of alpha particles in the depth of two cells or more on tissue with low range of decay compared with beta particles led to low toxicity on health cells with high effect on cancer cells regardless Oxygen concentration and cell cycle position [33].

4.1.1. Ac-225 Chain Decay

The Actinium half-life is 10 days its chain reaction shown in Figure 1 ends with ^{209}Bi including 4 rounds of alpha decays and 2 rounds of beta decay with a different range of energy emissions depending on chemical daughters as shown in Tables (4.1) and (4.2).

Table 4.1. Alpha decay series.

Element	Half-life	Decay	Energy	Name
^{225}Ac	-	α	6 MeV	Actinium
^{221}Fr	10 d	α	6 MeV	Francium
^{217}At	4.8 m	α	7 MeV	Astatine
^{213}Bi	32.3 ms	α	444 Kv	Bismuth
^{209}Tl	45.6 m	α	440 Kv	Thallium

Starting from Bismuth we have two rounds of beta decay and end with Bismuth-209 which is considered good and healthy for the immune system.

Table 4.2. Beta-decay series.

Element	Half-life	Decay	Energy	Daughter	Half-life	Energy	Name
^{213}Bi	45.6 m	β−	659 Kev	^{213}Po	4.2 μs	8 MeV	Polonium
^{209}Tl	3.20 m	β−	198 Kev	^{209}Pb	3.25 h	198 Kev	Lead

When Bismuth decay to Thallium and Polonium all mount of Polonium by alpha decay change to lead which by beta decay reaches stability as Bismuth-209 is considered a healthy element inside the patient body Figure (4.1) [34].

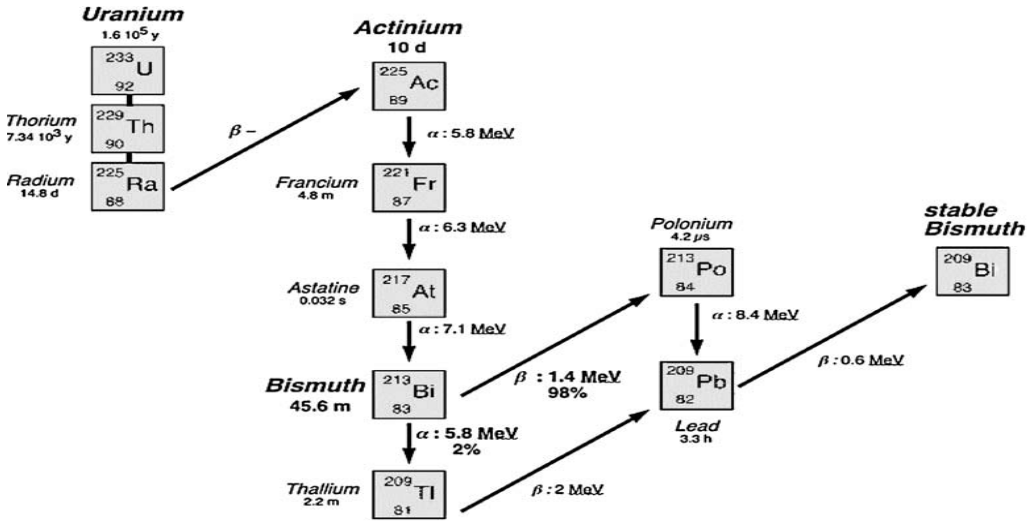


Figure 4.1. Actinium decay and its chemical daughters.

4.1.2. Animal Trails

These experiments were done on normal mice infected with different kinds of cancers by injecting them with Sodium striates mixed with Actinium-225 with an amount of 1080 nCi and PH 6.5 (^{225}Ac) for each one. After 5 hours was killed and collected its boons, leavers, urea, and tumours were. After one day when samples reach secular equilibrium we get these results in Table (4.3):

Table 4.3. The concentrations for 1 m molars (Ac-225) inside animal organs.

Dosage	Boons	Leaver	Urea	Tumour	Blood
1080 nCi	1.2%	5.7%	16.8%	3.5%	0.06%

We can notice that high concentration in tumour tissue shows the effect of Actinium combination with antibodies is well directed to tumour cells in another hand high concentration in leaver and urea shows body resistance to toxicity and the ability to remove dosage effect gradually.

When we repeat this experiment with 1350 nCi dosage and 6.5 PH (^{225}Ac) on mice who had colon cancer and sacrifice them after 15 hours we find concentration rises in boon, leaver, spleen, Digestive, bone marrow, and the kidneys. After many trials (1 day, 2 days … 52 days) and sacrifice time, we can say that any organs that showed a

high concentration of Actinium had acellular necrosis which improve changes in tissues and only 0.17 % of ^{225}Ac deposited inside leaver and bone marrow, in other words, the body gets to ride out toxicity by urea or Actinium ends as Bismuth [35]. The most important factor in this therapy is connecting the antibody (immunoglobulin carrier) and Actinium-225 molecules and keeping this combination during daughter generation for good penetration to tumour tissue for both solid or separated cancers. the second fact is choosing the right antibody as a carrier like (DOTA-LgGs) to keep Actinium daughters inside damaged cells and prevent toxicity in healthy cells [36].

Table 4.4. Combination with antibodies [36].

Comparison of the cytotoxicity in vitro of ^{225}Ac- versus ^{213}Bi-antibody constructs.

Antibody	^{225}Ac construct ED_{50} (pCi/mL)	^{213}Bi construct ED_{50} (pCi/mL)	Cancer	Cell type
HuM195	8	-	AML	HL60
HuM195	-	200,000	AML	HL60
B4	60	-	B-NHL	Daudi
B4	-	280,000	B-NHL	Daudi
J591	90	-	Prostate Carcinoma	LNCaP
J591	-	220,000	Prostate Carcinoma	LNCaP
3F8	100	-	Neuroblastoma	NMB7
Herceptin	150	-	Breast Carcinoma	BT-474
Herceptin	1300	-	Ovarian Carcinoma	SKOV3-NMP2

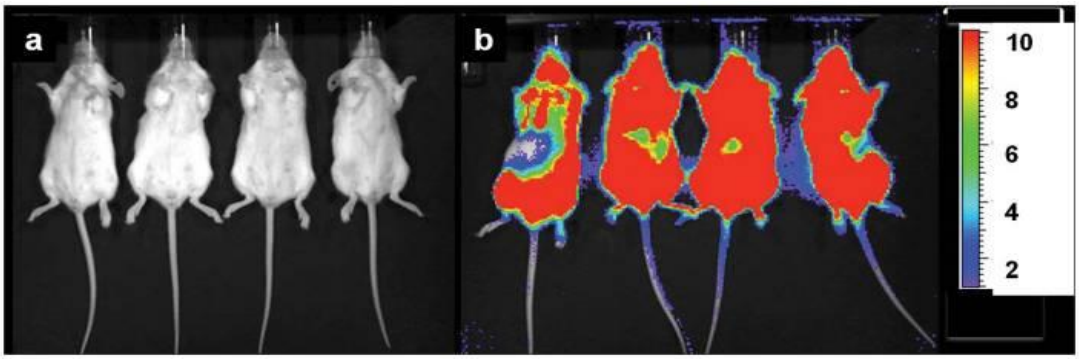


Figure 4.2. Pictures have taken on day 17 after treatment with [Ac-225] DOTA-B4 [5].

Figure (4.2) shows different kinds of antibody constructions combined with Actinium isotope depending on cancer types in several organs proving an ability to cure many samples depending on dosage amount and time of injection.

In a monkeys trial, we find the DOTA-HuM-195 antibody reacts with Actinium-225 which is closest to human antibodies injected with 370 kBq\kg dosages 45% of blood clarify from toxicity and Bismuth daughters in 12 weeks but after it gets anaemia and kidney failure with high to keratinize because of toxicity so correct amount of injection will be the limitation of successes so when trying 185 kBq\kg dosages tried on monkeys gives a great result it could survive for 13 weeks with a low concentration of ^{209}Bi reaches to 0.02 % and after 19 weeks it was mercy killed to collect results what shows 99% of curing of cancer .for human trials this search suggest 28 kBq\kg as a beginning injection to keep low toxicity and operation under control [37].

4.1.3. Other Medicine Applications of Actinium-225

- Targeting peptides and small molecules.
- Carbon nanotube constructs.
- Metallofullerene carriers.
- Liposomal carriers.

4.1.4. Reaction of Actinium with cancer cells

Actinium isotope could be produced from Thorium reactor heart as a side effect product and can be a powerful element in many medical applications, especially as a chemical cure for almost kinds of cancer because its dependent on combined with antibodies inside the bloodstream which are concentrated in tumour tissue where alpha decay chain started these particles has low penetration ability for two or more cells worked like a bomb inside nuclei DNA led to destroying cancer cells in short time with minimum effect on healthy cells. the second advantage of this process is high molarity inside infected tissue results from antibody attack brings Actinium and its daughters and toxicity could be removed easily because the chain reaction ends with Bismuth-209 isotopes in a short time which is considered a friendly element inside the human body otherwise beta decay particles have more powerful penetration ability then alpha particles that are mean damaging all cells without guidance like alpha particles which directed by antibodies as we side before Figure (4.2).

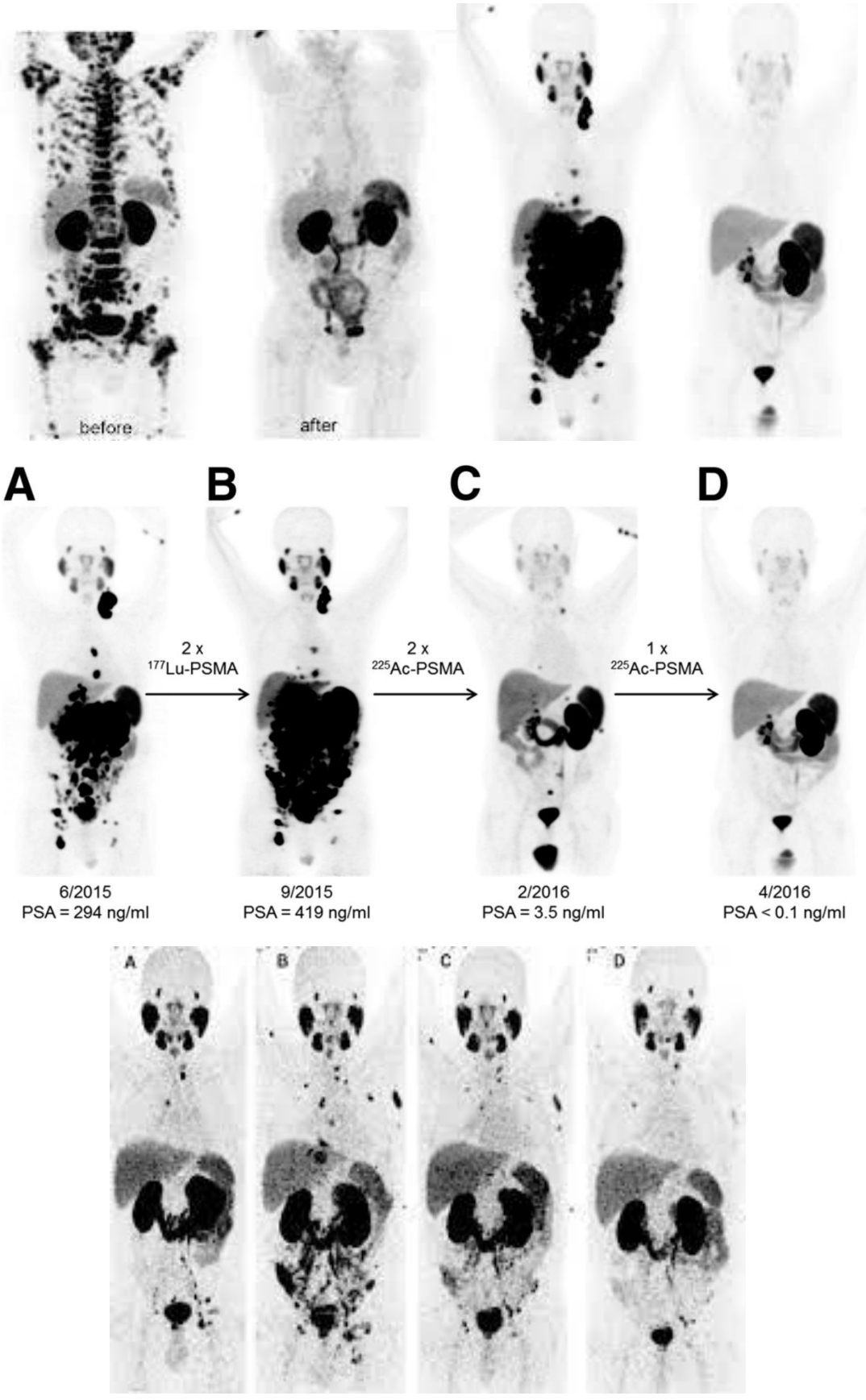


Figure 4.3. Actinium effects on cancer and toxic removal.

4.2. ELECTRICAL POWER PRODUCTION

Thorium reactor as a heat source is considered an important and high-efficiency source to provide rotation force for different kinds of turbines so we can use it to produce electricity with low price and permanently .according to Carnot efficiency equation[38]:

$$\eta c = 1 - \frac{Tc}{Th} \quad (4.1)$$

We find that turbine efficiency is always low than Carnot, where T_C and T_h are coolant temperatures and leaving temperature in kelvin wherein worldwide power transformation depends on this principle so needed to raise efficiency by using different fluids, providing heat transfer inside the turbine cycle with low losses in heat in the same time high capability to remove superheated from the heart of reactor and matching turbines characteristics. And the characteristics are given

- Safe
- Efficient- thermodynamically, financially, and in the use of all resources
- Reliable High availability
- Robust-fault tolerant
- Low maintenance and easy to maintain
- Cheap-low first cost
- Diversity of supply-multiple vendors
- Flexible-load following, ramping. peaking Scalable works well in a range of sizes
- Adaptable-can be upgraded/updated
- Compatible with the nuclear island
- Environmentally benign during all stages of its life cycle

There are many heat engine cycles in use that are different in properties, advantages, and, disadvantages which are listed below.

- Steam turbine (Rankine cycle)
- Helium Brayton cycle
- Combined cycle, Brayton and Rankine together (CCGT)
- Supercritical CO_2
- Unusual cycles
- Binary Mercury/steam
- Boiling Aluminum Chloride
- Air-breathing hybrid CCGT
- Air-breathing open cycle Brayton

We will discuss the helium Bryton cycle and CO_2 supercritical because:

- Low corrosion problems.
- High-efficiency power heat transfer.
- Chemical lethargy and easily provided at a cheap price.
- Helium could be provided from the reactor heart as an unwanted element so it is two in one option.
- CO_2 gas has a high molecule weight and high superheated degree which means high cooling and high rotation power force.

4.2.1. Helium Bryton Cycle

Helium Bryton cycle close-loop could use high coolant temperature reaches 900°C with 54% efficiency with three stages of recuperation coolant stations when T_c reaches 100°C Carton efficiency reaches 68% when turbine blades should be more than normal gas or steam turbines.

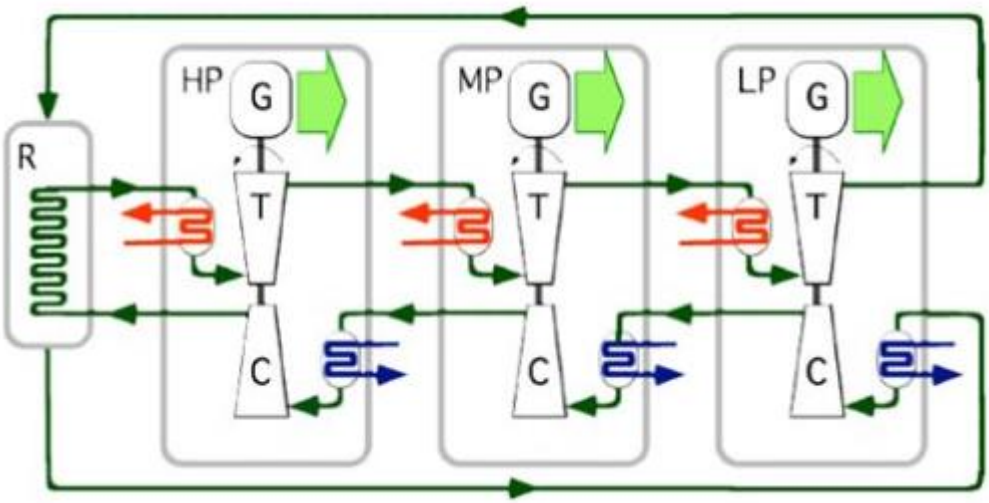


Figure 4.4. Flow diagram for (He) Bryton cycle [39].

The hot pressured Helium reaches 18 MPa and a temperature of 650°C interring turbines in point 1 and rotates compressors and electrical generator when gas expansion happened inside turbine heat remain will be removed by recuperating points 2 and 3 to preheat gas interring intermediate heat exchanger (IHX) and gas-cooled in a heat exchanger (HX) in points 3 and 4 it is compressed in three stations with cooling between each stage to get more compression as shown in Figure (4.4).

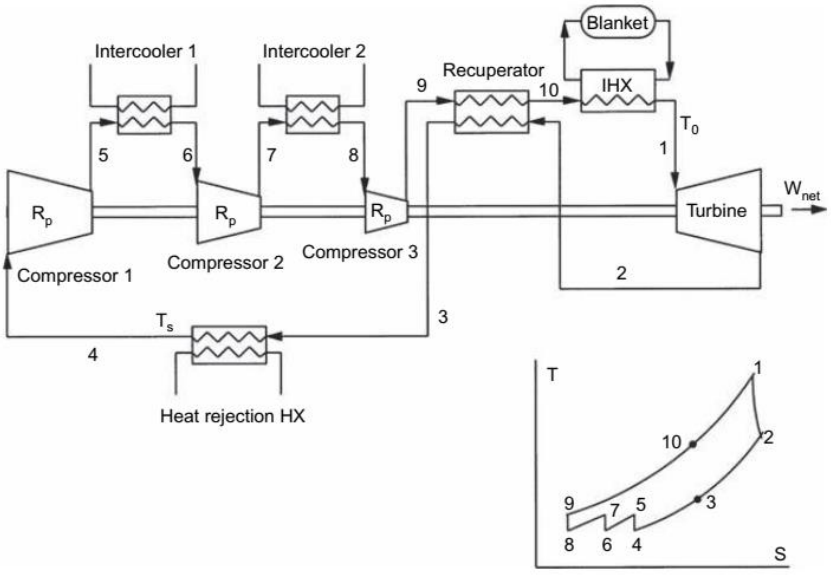


Figure 4.5. Helium high-pressure Bryton cycle, intercooler recuperate and heat exchanger [40].

Recuperation in points 9 and 10 will exchange heat with the reactor when the heat reaches 650 °C and pressure 18.5 MPa Carnot efficiency will be [38]:

$$\eta\, x = \frac{(T10 - T9)}{T2 - T9)} \qquad (4.2)$$

Where 96% thermal conversion to electrical power Carnot efficiency is 46% while when T_c is equal to 100 °C we find efficiency 60% [40].

Helium Bryton cycle closed system has many properties some of them are useful like the high range of heat exchanging from 650 °C to 100 °C which means a great cooling rate from the heart of the reactor which we needed to keep the heart under control in the same time 60% of electrical power heat conversion efficiency considered very good rate in addition helium as a gas chemically lethargy so no corrosion problems or undesirable reactions in the same time this system deals with high pressure reaches to 10 – 15 MPa so we need to select our materials carefully to prevent any accidents of leakage and this system need high-frequency turbines more than 60 Hz [41].

4.2.3. CO_2 Supercritical Bryton Cycle

In this cycle when pressure is triple point the fluid will no longer consider liquid or gas CO_2 supercritical cycle temperature starts from 550 °C to 800 °C and high pressure from 12 to 20 MPa with efficiency reaching 37% [42].

CO_2 interring turbine in points 5 and 6 which drive electrical generator and compressor shaft. the fluid compressed in points (1,2,8,3) to (12 -20 MPa) and the precooled and recuperated would improve thermodynamic efficiency when highly compressed fluid heated by the heart of the reactor in points 4 and 5 which is recycled to the turbine and needed good recuperate and low-temperature heat sink equal to 10 °C.

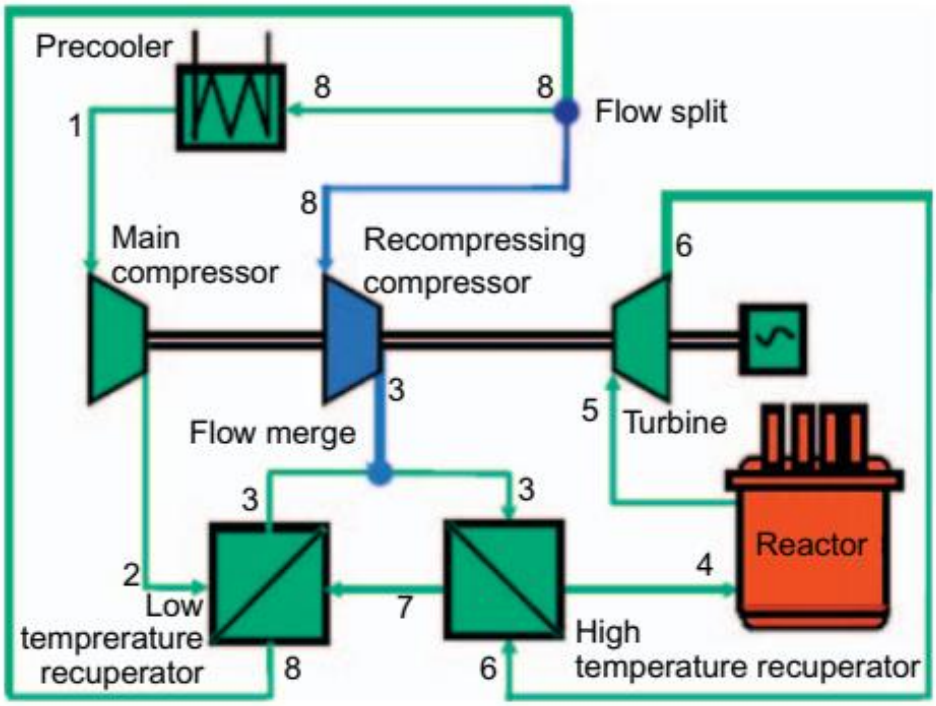


Figure 4.6. CO_2 supercritical system [41].

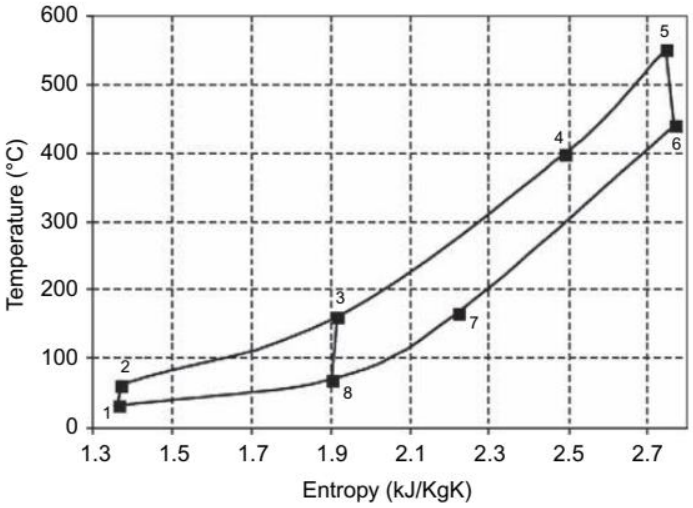


Figure 4.7. Entropy temperature diagram [41].

The CO_2 supercritical Bryton cycle can work with a low range of temperature between (550 – 850 °C) with an efficiency equal to 46% and can be increased to 50% if we change the pressure from 8 to 20 MPa. The turbomachinery is very compact and high speed so a 246 MW turbine can be 1.2 m in diameter and 0.5 m long which is considered very small compared with Helium or steam Bryton cycle had 5 m long so

we should be very careful when we choose manufacturing materials for turbine and heat exchangers and because of its high speed and small size we need powerful speed reduction or gearbox in large scale sophisticated frequency control to set operation because a big range of temperature and pressure as shown in Figure 4.8[41].

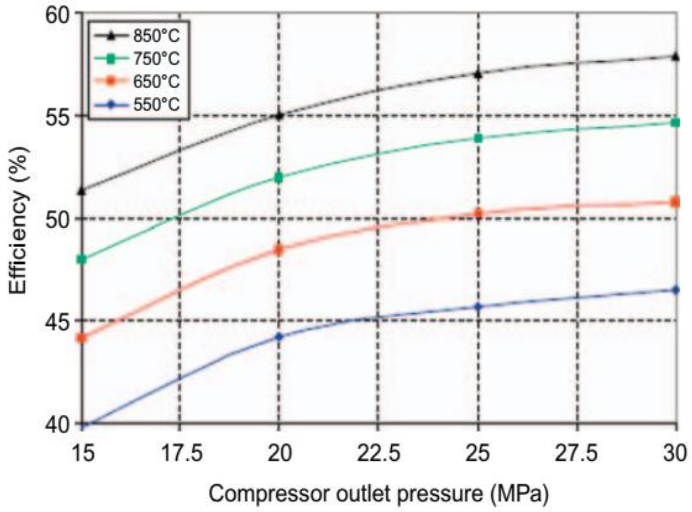


Figure 4.8. Effect of temperature and pressure on efficiency.

PART 5

CONCLUSION

From all the above Thorium reactor's main concept is nuclear-molten fuel salt gives us the ability to choose the suitable design can select between a multi-column core heart or vessel core heart according to the chemical process complexity and power generate needed.

The operation process starts from preparing the fissile and fertile fuel in high purity concentration and keeps it as possible in this case by chemical processes facility during the chain reaction and continues the separation of harmful and advantageous isotopes to keep the main fuel reaction in good conditions with the ability to recycle the fuel and secondary products.

When we considered the power generation in low cost and high level of safety with 1% of pollution products.

There is the ability to develop this kind of reactor to create many applications like medicine, seawater desalination, air space engines, submarines, and Thorium battery. Actinium isotope could be produced from Thorium reactor heart as a side effect product that can be a powerful element in many medical applications.

Helium Bryton cycle closed system has many properties some of them are useful like the high range of heat exchanging from 650°C to 100°C which means a great cooling rate from the heart of the reactor which we needed to keep the heart under control in the same time 60% of electrical power heat conversion efficiency.

The CO_2 supercritical Bryton cycle can work with a low range of temperature between (550 – 850°C)with an efficiency equal to 46% and can be increased to 50% if we

change the pressure from 8 to 20 MPa. the turbo machinery is very compact and high speed so a 246 MWe turbine can be 1.2 m in diameter and 0.5 m long which is considered very small compared with the Helium or steam Bryton cycle.

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RESUME

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