APPENDIX I

PROPERTIES OF THORIUM

Thorium (Table I.I) [I.I] was discovered in Sweden by Jöns Berzelius in 1828 and named after Thor, the mythological Scandinavian god of war. Thorium does not occur to any significant extent in the biosphere and does not normally present a risk to human health. Thorium is a fertile material; there is probably more untapped energy available from thorium in the minerals of the earth's crust than from combined uranium and fossil fuel sources. Thorium abundance in the earth's crust (Figure I.I) is about 6 ppm (uranium, about 2 ppm) [I.I].

Since discovery, the production of thorium has been limited to specific uses (special glass fabrication, gas lightning candles, and special alloys). Production today is several hundred tons per year. There are basically 6 minerals in which thorium occurs at a significant concentration level (See Table I.II).

TABLE I.I. KEY DATA

Symbol	Atomic number	Atomic weight	Group number
Th	90	232.0381	actinide)

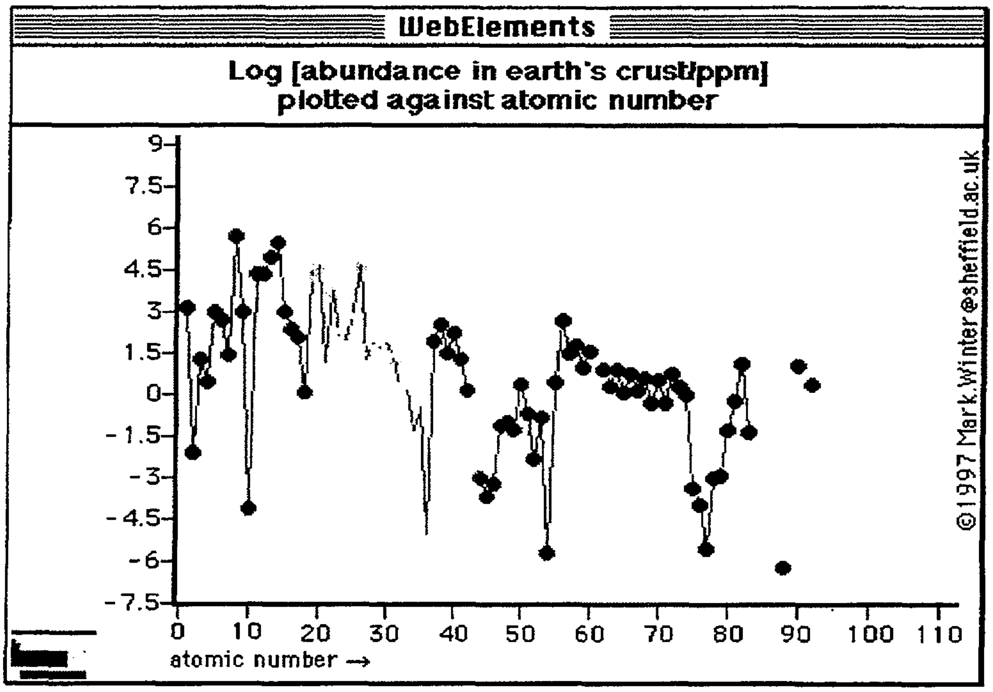

FIG. I. Abundance of elements in earth's crust [I.I].

TABLE I.II. MINERALS CONTAINING THORIUM AS MAJOR CONSTITUENT [Reference I.II].

Mineral	Composition	Th concentration (% In mass)
Cheralite	(Th, Ca, Ce)(PO_4, SiO_4)	29.5 - 31.5
Huttonite	$ThSIO_4$	81.5
Pilbarite	$ThO_2UO_3PbO\ 2SiO_2, 4H_2O$	31, variable
Thorianite	ThO_2	38.5 - 93
Thorite	Th $(SiO_4)_X$	7.83 - 58.9
Thorogummite	Th $(SiO_4)_{1-X}(OH)_{4X}$	24 - 58 and more

Thorium is a radioactive rare earth metal with a half-life of 1.4×10^{10} years (^{232}Th alpha decay compared to 4.5×10^9 years for ^{238}U) and it is a fertile material for nuclear reactors. Thorium fuel cycles require fissile material, which may be ^{235}U extracted from natural uranium, ^{233}U from reprocessing irradiated thorium, or plutonium similarly obtained from irradiated uranium. Up to the present, reactor development has been based mainly on the U/Pu cycle; the Th/U cycle is less developed. During 1950–1970, a number of options for energy production with thorium were investigated in the USA, the USSR, Europe and Asia. Work in thorium cycles focused mainly on the potential for enhancing uranium use in thermal systems.

Additional interest in thorium fuel recently arose because it generates less long lived minor actinides than the traditional uranium fuel cycle. Since the beginning of the 90s, there has been renewed interest in thorium related to accelerator driven systems (ADS). Future hybrid systems such as ADS, fusion driven, etc., using the thorium fuel cycle, have a potential for safe operation, plus the ability to incinerate the most dangerous long lived fission products.

Sufficient information on the physical and chemical properties of the fuel materials is prerequisite to design any type of thorium–fuelled nuclear reactor. Metallic thorium and its alloys, thorium oxide and other ceramics such as thorium carbide and nitride, molten salt with thorium fluoride and others can be considered fuel for thermal and fast reactors. Assessment of these fuel materials depends upon the type of reactors and system of fuel cycles, various physical and chemical properties, mechanical properties, chemical reactions with cladding materials, coolant and fission products, as well as irradiation behaviour.

Properties of thorium metal [I.I]

When pure, thorium is a silvery white air–stable metal and retains its lustre for several months. When contaminated with the oxide, thorium slowly tarnishes in air, becoming gray and finally black. Thorium reacts slowly with water, but does not readily dissolve in most common acids, except hydrochloric. Powdered thorium metal is pyrophoric; heated in air, it ignites and burns with a white light. Thorium metal has a high melting point, a stable isotropic structure below 1360C and good workability. It is soft and ductile with 2 allotropic forms. Some physical properties of thorium metal are shown below:

Density:	11 724 kg m^3 (25C)
Melting point:	2115K
Boiling point:	5093K

Properties of thorium oxide (thoria) [I.III]

Thorium oxide has a melting point of 3300C, the highest of all oxides. Only a few elements, such as tungsten, and a few compounds, such as tantalum carbide, have higher melting points. Thorium oxide is chemically very stable and has low vapor pressures and relatively high thermal conductivities:

Density	10 000 kg m^3 (300K)
Melting point	3370 (C)
Vapor pressure (atm)	3x 10^{-6} (2600K)

Properties of thorium carbides [I.III]

Next to thoria, the most prominent thorium ceramic compounds for nuclear application are the carbides. In particular, the monocarbide ThC has a relatively high melting point, a high density, a stable isotropic structure up to high temperatures and a high thermal conductivity even though it is highly reactive chemically.

Properties of thorium nitrides [I.III]

Thorium mononitride has a high thermal conductivity and is chemically less reactive to air and water than thorium carbides. However, the adsorption cross section for the thermal neutron of ^{14}N is relatively large and the nitride is usually unsuitable for thermal reactor fuel.

Molten salt fuel [I.III]

Molten salts such as uranium and thorium fluorides (or chlorides) have useful attributes of chemical stability and good physical properties. The molten salt reactor avoids fuel element fabrication and offers rapid, inexpensive reprocessing, on-line refueling, good neutron economy and high-temperature operation at low pressure.

Nuclear properties of thorium and uranium-233 [I.IV]

Transmutation of ^{232}Th into ^{233}U is analogous to that of ^{238}U into plutonium.

$$\text{U-238} \xrightarrow{n} \text{U-239} \xrightarrow[\text{23.5 min}]{\beta} \text{Np-239} \xrightarrow[\text{2.355 days}]{\beta} \text{Pu-239}$$

$$\text{Th-232} \xrightarrow{n} \text{Th-233} \xrightarrow[\text{22.3 min}]{\beta} \text{Pa-233} \xrightarrow[\text{27.0 days}]{\beta} \text{U-233}$$

An important feature of the thorium cycle is that a small but significant proportion of the ^{233}U undergoes an (n,2n) reaction to form ^{232}U, also formed by the sequence:

$$\text{Th-232} \xrightarrow{n,2n} \text{Th-231} \xrightarrow[\text{25.5 h}]{\beta} \text{Pa-231} \xrightarrow{n} \text{Pa-232} \xrightarrow[\text{13 days}]{\beta} \text{U-232}$$

This nuclide decays with a 70-year half-life to ^{228}Th (half-life 1.9 years), then by way of radium-224 and other short-lived intermediates (Figure I.II), with a minor branch to thallium-208 which has an unusually penetrating beta-gamma emission (γ 2.6 MeV). Thorium products require remote handling and a need for heavier shielding than uranium-plutonium fuel during re-fabrication, transport, and storage at the reactor site and thus, complicate reactor facilities.

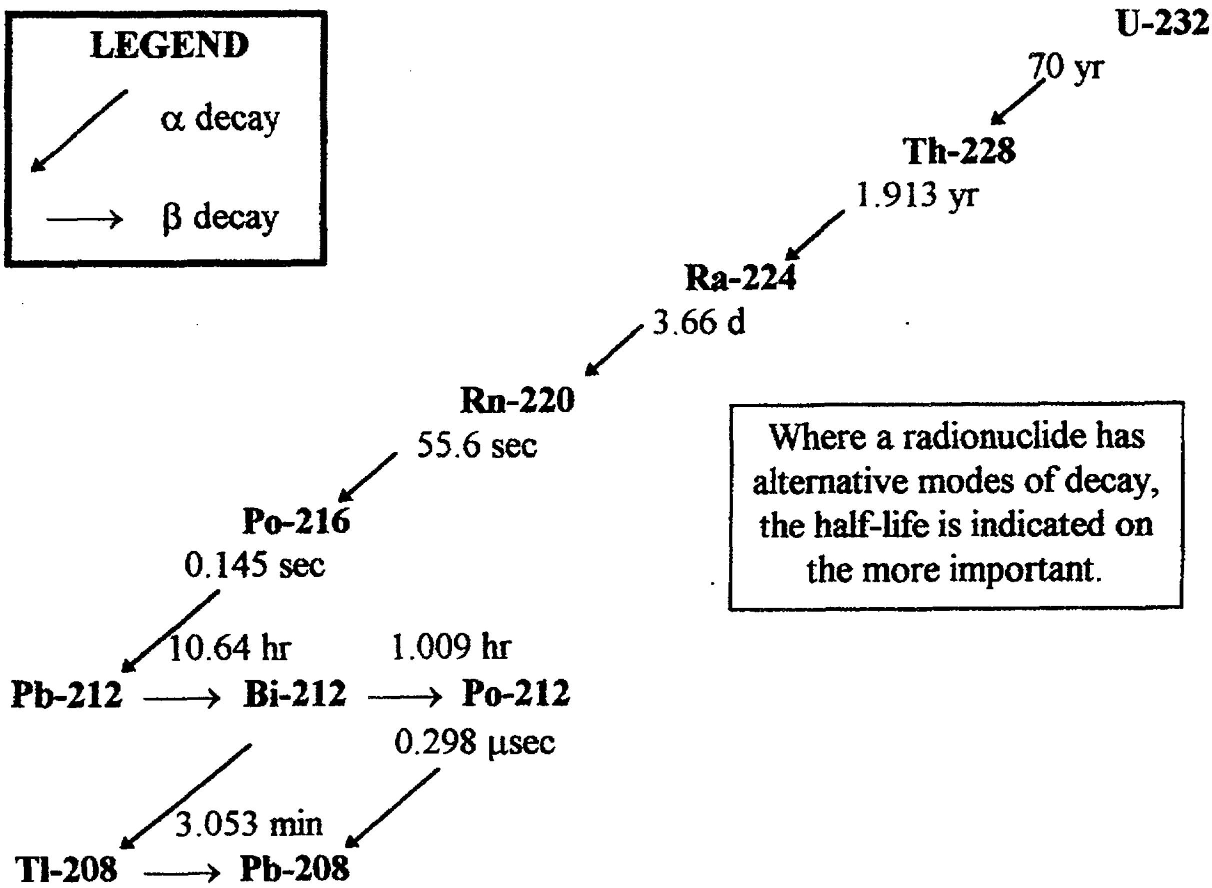

FIG. I.II. Uranium-232 decay series [I.IV].

REFERENCES

I.I. The Periodic Table on the WWW by Mark Winter, University of Sheffield, UK, (http://www.shef.ac.uk/chemistry/web-elements/), 1998.

I.II. SCHAPIRA, J. P., MENARD, S., "Long term potential risk due to thorium mining", Technical Committee Meeting on Advanced Fuels with Reduced Actinide Generation, Vienna, 1995, IAEA-TECDOC-916 (1996)

I.III. KANNO, M., "Physical and chemical properties of thorium fuel", Japan -U.S. Seminar on Thorium Fuel Reactors, Nara, Japan, 1982 (1985).

I.IV. WILSON, P. D., R&T Department, BNFL, Sellafield, UK; AINSWORTH, K. F.,BNFL, Risley, Warrington, UK. "Potential advantages and drawbacks of the thorium fuel cycle in relation to current practice: a BNFL view", IAEA Advisory Group Meeting on Thorium Fuel Cycle Perspectives, Vienna, 1997.