ABSTRACT

The closed thorium fuel cycle is based on the use of fissile U-233 produced by the thorium fertilization in the original fuel element without any refabrication action, which is very difficult, due to the high activity of Thorium activated products.

The need of a consistent amount of fissile material for beginning the U-Th cycle activity, in order to sustain the Thorium conversion reactions, requires an high initial U-235 enrichment. This condition, due to high investment costs, stopped, in the last years, any initiative in this field.

The end of the cold war and the disarmament agreements pose the problem of the use of military grade fissile materials resulting from the dismantling of nuclear weapons both Russian and American.

In this paper the problem is analyzed and a High Temperature Gas-cooled Gas Turbine (HTG-GT) reactor, using a nuclear U-Th fuel cycle utilizing military grade highly enriched uranium, is proposed.

INTRODUCTION

The end of the cold war and the significant nuclear disarmament agreements are giving a new dimension to the world nuclear fuel market and pose the problem of the fissile materials resulting from the disassembling of nuclear weapons both Russian and American. Dismantling could take place at facilities previously used for warhead assembling.

On the one hand, fissile materials recovered from dismantled warheads represent a potential source of fuel for civilian power reactors, while, on the other hand, the recycling of military origin material represents a safe and productive way of reducing the world's inventory of weapon-grade materials.

Under the terms of the Intermediate-range Nuclear Forces Treaty (INF, signed on December 8, 1987) and the Strategic Arms Reduction Treaties (START I, signed on July 31, 1991, and START II, signed on June 16, 1992) the US and CIS are now about to reduce their nuclear arsenal by approximately 90%. This reduction in warhead numbers results in the availability of a large amount of highly enriched uranium (HEU) and plutonium (Pu). We can note that neither INF nor STARTs provide any arrangement concerning what to do with the nuclear warheads and their fissile materials.

The availability, as starting material, of highly enriched uranium could be the motivation to reconsider some designs, already proposed in the past, that use a highly heterogeneous enrichment, or alternative fuel cycles, like the uranium-thorium cycle which requires a mixture of highly enriched uranium and thorium for the initial start up. It might be worthwhile in this perspective to examine again some reactor and fuel cycle designs based on these concepts, in particular in order to explore if they present inherent safety features and economics advantages. A further and very important result is the contribution to the denaturation of weapons materials.

THE USE OF THE MILITARY-GRADE FISSILE MATERIALS IN POWER REACTORS

Recent estimations (U.I.B., 1993), (Amaldi, 1989) reported an amount of about 200 metric tons (MT) of military grade plutonium and of 1000 MT of highly enriched (93% U-235) uranium.
In order to make the nuclear disarmament process irreversible, the main safeguard is to denature the fissile material by lowering its reacting level.

The answer to the question of what to do with the strategic materials recovered from dismantled warheads is quite different for the plutonium and for the HEU.

The plutonium could be used, mainly, in the LMFBRs (Liquid Metal Fast Breeder Reactors) where it has the highest efficiency and also, in form of U-Pu mixed oxides (MOX), in LWRs (Light Water Reactors). A proposal was also done for using plutonium, as fissile material, in HTGR. Moreover, the first two proposed solutions have, as result, the production of new plutonium, although at "reactor grade".

For the enriched uranium the use in LMFBRs presents a lower efficiency in comparison with plutonium, due to the small value assumed in presence of an high energy neutron spectrum, by the "reactivity parameter".

The use of HEU in the LWRs, requires the dilution of enriched uranium with natural uranium either with depleted uranium or with the uranium recovered from the reprocessing of the spent fuel. This solution, even if proposed by some international groups, seems to be motivated by the prominent Companies interest towards LWRs; however, it is not economically convenient, due to the waste of potential energy, stored in form of Separation Work, previously used to reach its very high enrichment.

The possibility of HTGR fuel to reach a very high metallurgical burn-up (more than 100 Gwd/MTU) suggests, as the best solution, the use of HEU in the U-Th cycle.

Such a cycle allows to employ in the reactor core the produced U-233 without any refabrication need and give back, at the end of the cycle, non-military grade fissile materials.

Therefore this is the solution that we have chosen for our research work.

THE THORIUM CYCLE

Both U-238 and Th-232 can be used as fertile materials in High Temperature Reactors, but the use of a thorium cycle seems to be, in the case under consideration, more suitable especially because it does not produce significant quantities of plutonium.

Current knowledge of the world’s thorium resources estimates a possible production of about two million tons of thorium at reasonable prices. Even if reactors or fuel cycles using thorium were adopted extensively during the post 2000 period and demand for thorium would expand greatly, the cumulative requirements for thorium seem to be less than the production possibilities (IAEA, 1982).

Th-232, after a neutron absorption and two β-decays, becomes U-233, a very efficient fissile material.

U-233 possesses an higher "thermal utilization factor" ($\eta=2.29$) than U-235 or Pu-239.

For a practical utilization the thorium cycle has the disadvantage of producing, from U-233, through one ($\alpha,2n$) reaction and an $\alpha$ decay, Th-228 that is a very radioactive isotope.

Therefore, for the fuel refabrication, the use of remote handling and of $\alpha$ and $\gamma$ tight hot cells is required. In Italy, in the past years, a reprocessing and refabrication experiment of fuel elements containing U-233 was performed by ENEA in the nuclear Research Center of Rotondella, in the ITREC plant. Fuel elements irradiated in the ELK RIVER (USA) Reactor were used and interesting results were obtained. Therefore it is not convenient to refabricate the fuel elements, and it is preferable to use U-233 directly in the reactor, possibly, in a once-through cycle.

The thorium cycle was used in almost all the HTGR nuclear plants, such as (e.g.), DRAGON in UK, AVR in Julich and the prototype plant THTR at Schemehausen both in Germany.

In the graphite moderated neutron spectrum, the nuclear properties of the U-233 bred from Th-232 are far superior to those of the fissile Pu bred in the low enrichment cycle due to the before mentioned higher value of $\eta$.

THE HELIUM DIRECT CYCLE

The high temperature capability of the HTGR, the small size and high reliability of modern high pressure gas turbines form an obviously appealing combination. Although gas turbine (GT) systems are "advanced" with respect to steam generating (SG) systems, it is now possible to build a Direct-Brayton-Cycle power plant with sufficient advantages. By using a modular HTGR heat source, any existing materials, within existing design codes, it is possible to obtain a 45-50% net efficiency at a cost below the one of steam generating plants.

A prototype design of a Modular Gas-Cooled Reactor has been developed by MIT and Toshiba starting from two recent developments: the improvement in coatings for fuel particles, which promises substantially lower circulating activity in the gas stream and a lower contamination of rotating machinery, and the use of magnetic bearings that are ideal for high speed turbomachinery. Combining the MGR with a closed-cycle gas turbine leads to a high performance, low cost electric power plant (fig.).

The MGR-GT utilizes a very simple Brayton cycle. The turbine is fed by helium at 850 C and 7.8 MPa and the gas leaves the turbine with a temperature of 606.5 C and a pressure of 4.05 MPa. A polytropic efficiency of 91% has been considered. The reference design core is a 200MWe pebble bed reactor, for which a greater level of detail is available at MIT. The reactor inlet temperature in a heavily recuperated Brayton cycle is substantially higher than it is in an equivalent steam generating system (600 C versus 200 C). The outlet temperature is somewhat higher: 850 C versus 700 C. The expected thermal cycle efficiency is about 50% with a total system efficiency of 46.7% (electric power output 93.5MW).

A preconceptual project of an other type of gas turbine direct cycle high temperature gas cooled reactor plant,
named MHTR-GT, is being studied by General Atomics (San Diego, CA). This project presents an unquestionable safety, a system simplicity, complete factory fabrication and assembly, a high thermal efficiency and is also proposed to be used in newly industrializing nations. The plant is arranged in a very compact structure (fig. 2), and is located in a below-grade concrete confinement silo.

The basic module rating is around 200 MW(e) and the modular approach allows incremental expansion as the electrical grid infrastructure expands. For the initial plant, a reactor outlet helium temperature of 850°C is selected and an overall efficiency of 46% is estimated. Due to its high temperature a consistent fraction of the heat rejected from the power plant, evaluated in about 250 MW(t), can be utilized for steam production, for desalination, and for hot water supply.

CORE DESIGN AND FUEL LIFE.

During the reactor operation, the fissile material is being burnt and the resulting change in reactor composition should be compensated, either by adding new fuel or by removing control elements. In the HTGRs, by using a U-Th cycle, an automatic reactivity compensation through the conversion of fertile into fissile material, namely of Th-232 into U-233 is possible.

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**Fig. 1** - M.I.T. Direct cycle HGR-GT power plant (Xing L. Yan, 1993)

**Fig. 2** - General Atomics MHRGR-GT power plant (McDonald, 1993)
In the last years, for economic reasons, due to the high enrichment cost of uranium, the U-Th cycle was not of interest, in the industrial environments, and was left, for a lot of years, at a research level, even if in a very advanced state. Therefore, at present, it requires a final phase of R&D activity oriented to the most recent types of High Temperature Gas Cooled Reactors, using direct cycle. (McDonald, 1992), (Mears, 1992), (Xing L. Yan, 1993), (McDonald, 1993)

The problems connected with the attainment of the reactivity level necessary at the beginning and during the core life are complex and require a serious and complete set of calculations. It is necessary to sustain the nuclear burn-up at the high levels planned (100 Gwd/MT), and to comply with the control requirements, assuring the presence of a negative temperature coefficient.

The HTGR has the advantage of an excellent neutron economy, since it uses helium as coolant and graphite as the construction material as well as moderator. If we introduce a U-Th cycle, the presence of U-233, with its excellent neutron production rate, allows to reach a very high conversion factor.

If properly designed, the HTGR presents a limited need of control rods (shim rods) to compensate the excess reactivity necessary to reach the foreseen high burn-up values.

A large number of survey analyses are required to explore and define the equilibrium conditions before performing the final calculations. At first the U/Th mixing values and the moderating ratio ($N_C/N_{U235}$) will be defined and the isotopic behaviour of fissile and fertile nuclei and of poisonous fission products will be evaluated. A monitoring action will be performed in order to check that the temperature coefficient constantly maintains negative values during the whole cycle.

The advantages will be increased if HEU of dismantled warhead is used, because it is possible to couple the destruction of military fissile materials with the supply of low cost highly enriched uranium necessary for the thorium equilibrium cycle.

Some results of preliminary calculations, showing the isotopic behaviour of the fuel versus the residence time, related to two U/Th values (1:10 and 1:20) with a tentative value for the moderating ratio of 4000, are presented in figs 3 and 4.

CONCLUSIONS

The dismantling of nuclear warheads and the conversion of the recovered HEU into commercial fuel are significant steps and HEU is, potentially, a large energy source as the nuclear fuel can be converted by using an already proven technology.

The total amount of the weapon-grade fissile materials contained, in various forms, in the nuclear weapons arsenals of the military nuclear powers gives a significant measure of the problem of the conversion of the nuclear weapons and of associated activities posed by the Disarmament Plans.

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The total amount of the weapon-grade fissile materials contained, in various forms, in the nuclear weapons arsenals of the military nuclear powers gives a significant measure of the problem of the conversion of the nuclear weapons and of associated activities posed by the Disarmament Plans.
Peaceful uses of nuclear weapons materials must proceed through the dismantling of these weapons and the utilization of strategic nuclear materials they contain, after appropriate changes in their physical, chemical and isotopic characteristics.

The pace of warhead dismantling is governed by the capacity of process facilities, by the presence of adequate storage places and by the ability to denature the military grade fissile materials.

The use of HEU as fissile and of thorium as fertile materials in HTG reactors represents one of the best ways to obtain a good HEU denaturation and an high efficiency energy saving, by using an inherently safe nuclear reactor and, as a supplementary advantage, final product containing only a very little amount of non military grade plutonium.

The combination of a HTG reactor with a gas turbine, in a closed helium cycle, allows to have a high performance, low cost, electric power plant that represents an optimum facility in order to denature the HEU recovered from the dismantling of nuclear weapons.

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REFERENCES


