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THE ULTIMATE SAFE (U.S.) REACTOR*

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THE ULTIMATE SAFE (U.S.) REACTOR — A CONCEPT FOR THE THIRD MILLENIUM

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ABSTRACT

The Ultimate Safe (U.S.) Reactor is based on a novel safety concept. Fission products in the reactor are allowed to accumulate only to a level at which they would constitute a harmless source term. Removal of fission products also removes the decay heat — the driving force for the source term. The reactor has no excess criticality and is controlled by the reactivity temperature coefficient. Safety is inherent and passive. Waste is removed from the site promptly.

1. ULTIMATE SAFETY

Ultimate safety for a nuclear reactor is considered here to mean that a reactor event (accident), however remote, leading to a significant health hazard to the public cannot occur. Ultimate safety also requires passive and inherent safety. That means active intervention by an operator or one that requires a power source or mechanical activation is not required, nor can the safety features be overridden by external means since they are inherent to the system and rely on the physical properties of the system. Such an extreme safety usually implies that no significant damage to the plant will occur and no extraordinary economic penalty will result even if there is an unusual occurrence. The Nuclear Power Options Viability Study determined that a degree of passive safety and low economic risk are prerequisites for the success of an advanced concept.[1]

There are two major possible events that can lead to a dispersal of radioactivity from a nuclear reactor and become a health hazard. The first is an uncontrolled reactivity increase that will yield a power burst which would damage the reactor and disburse the radioactive fission products inventory. The other event could be failure to remove the decay heat of the fission products resulting in overheating and dispersal of inventory. The so-called source term — the likelihood for a quantified release of radioactivity — is the product of the inventory of fission products and the driving force or the energy to disperse this inventory.

The U.S. Reactor described here retains the inventory of fission products at such a low level that even if dispersed the safety hazard is within acceptable limits. But, furthermore, the driving forces — the decay heat and any excess criticality — are kept so low that there is insufficient energy to bring about such a dispersal.

2. SOURCE TERM CONTROL

The source term in the U.S. Reactor is controlled by continuous removal of fission products at the rate they are produced. Fission products are allowed to accumulate only to a level of 1 to 6 hours of full power operation equivalent. That is an

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equilibrium level as if the reactor had operated for the equivalent time without any removal of fission products; then any additional fission products are removed as they are produced. This retains the accumulated activity at a low level that reduces a hypothetical maximum accident to a manageable level. The exact equivalent build-up time is determined by the degree of desired hypothetical safety and the economics of the chemical processing plant removing these fission products. The need ease, and efficiency of removal of the various chemical elements may result in different equivalent build-up times for different elements.

It has been determined[2] that at the 1 to 6 hours equivalent build-up time the fused fuel salt of The U.S. Reactor will not reach boiling due to after-heat even without any heat removal. Thus decay heat cannot provide sufficient energy to disperse the fission products, and there is no source term associated with the decay heat.

The reactor is designed such that any excess buildup of fission products will not allow it to become critical due to neutron poisoning. There is no excess criticality to override this limitation. This safety feature is thus inherent, passive, and cannot be overridden.

3. CRITICALITY CONTROL

The U.S. Reactor is operated at no excess criticality as none is necessary for burnup or poisoning compensation. The fuel, based on the thorium-uranium cycle, is internally replaced by an exact breeding ratio of 1.0. The fuel composition, the fertile material contents, and the processing are coordinated such that the breeding ratio cannot exceed 1.0 and no excess fuel can be produced. The core also has a negative temperature coefficient.

An additional benefit of this arrangement is that if an attempt is made to divert fuel from the reactor, the reactor becomes subcritical and shuts itself down.

The criticality control is inherent, passive and cannot be overridden.

4. REACTOR CONTROL

The U.S. Reactor is designed with no mechanical controls or externally operated controls. Load following is accomplished by a negative temperature coefficient. The reactor operates at a constant core exit temperature which is determined by the core dimensions and the invariable fuel composition. This arrangement enhances the thermodynamic efficiency at partial loads and improves the economy of the reactor. This reactor control is inherent, passive and cannot be overridden.

Reactor shutdown, or scram, is accomplished by dumping the fuel into dump tanks which guarantee subcriticality. The dump valve can be designed as a freeze valve which will open by removal of cooling or by overheating of the fuel — a safety feature which cannot be overridden.

Reactor startup is accomplished by pumping the fuel into the core. The pump is sized such that at maximum capacity the design startup parameters cannot be exceeded. As the fuel reaches cold criticality level, it becomes critical and heats to the temperature corresponding to that level. As the level rises it continues to heat until it reaches the design temperature at full core, which it then maintains by the temperature coefficient control.

5. WASTE CONTROL

The radioactive fission products are processed into the desired and acceptable chemical composition and concentration. This composition will be determined by regulations and governing authorities and will affect only the design details of the processing plant tail end. The fission products waste contains significant amounts of radioactivity and decay heat. The safety of this waste is provided by small container units and adequate geometry for cooling. The waste will be contained in very small containers, perhaps as small as 100 ml or less, in narrow cylinders of 10 mm diameter or less. The small quantity per unit reduces the hazard associated with each to tolerable levels even for a major hypothetical accident. The narrow cylinders make it easy to design the cylinders such that they will retain their integrity under all circumstances. The narrow cylinders also assure that they will not overheat without requiring any active cooling. The cylinders can be designed so that conduction to the shielding container, or natural convection, as augmented by radiative heat loss, will assure the temperature can not rise above the design level. This safety is inherent and passive.

The small waste containers are shipped frequently, daily or several times a day, to the waste repository site. There is no accumulation of radioactivity anywhere on the site to feed a source term.

6. FUEL CONTROL

The U.S. Reactor is designed to be exactly self-sufficient in fuel. No fuel shipments are necessary. Overproduction of fuel cannot be done since the neutron economy of the system will not allow it. An attempt to remove fuel will shut the reactor down as it will become subcritical.

7. FISSION PRODUCT REMOVAL

To facilitate the on-line continuous fission product removal, a liquid fuel is used. Fluoride molten salt was chosen to take advantage of the already developed technology.[3] Specifically the processing has been investigated in great detail.[4] In addition the thorium-uranium fuel cycle was chosen. This eliminates the plutonium as a fuel component and all but eliminates the actinides from the waste products.[5]

8. REACTOR DESIGN

Though many design options are open for The U.S. Reactor, a single fluid, epithermal, externally cooled concept is chosen as the first concept.[6] The single fluid simplifies the design. The epithermal neutron spectrum also simplifies the design, eliminates the need for a moderator, and provides for the breeding ratio of 1.0 with relative simplicity. The external cooling makes the design of the reactor into a core and a primary heat exchanger connected by pipes, with the fuel circulated by a pump. Connections are needed to and from the processing and into the dump tanks.

9. ECONOMIC OUTLOOK

It is anticipated that the ultimate safety features of The U.S. Reactor will allow the elimination of most safety systems required on reactors. There is no safety need for a containment. The extreme simplicity of the design should result in a very economic, low in capital cost, reactor. The inherent and passive safety features do not require mechanical precision or extreme reliability of any operating parts. The construction cost and cost associated with quality assurance can be relatively low. There is no expectation of regulatory delays or back fitting, as safety is not dependent on construction or design details. This reduces the risk of unplanned or unanticipated cost. The small dimensions of the components and the absence of sophisticated or complicated systems allow for off-site fabrication and quick and simple on-site assembly, yielding further potential for an economic system. The simplicity of the system also allows for size flexibility or modular units which are economic.

The relative simplicity of the design and absence of mechanically operating parts, except the pump, are expected to make maintenance simple and availability high; also there is no downtime for fuel exchange.

The onsite processing facility is an added capital cost which comes in lieu of most of the fuel cycle cost.

10. CONCLUSION

The U.S. Reactor is designed to achieve ultimate safety. The source term is reduced by reducing the radioactive inventory to such low levels that they cannot constitute a major hazard and so that they lack the power or energy to cause damage to the reactor or provide the driving force for the source term.

The reactor has constant reactivity at exact criticality. Excess criticality is neither needed to compensate for burnup or poison buildup nor available; thus a criticality accident during operation is not possible. Power control is provided by the negative temperature coefficient. All these safety features are inherent and passive and cannot be overridden resulting in the ultimate safe features. The extreme safety simplifies the reactor design and can be anticipated to yield good economy.

The waste is packaged in dedicated small containers of size and shape that provide assurance against exceeding a set temperature. The size is small enough so that the maximum credible accident does not exceed acceptable level. The waste is shipped frequently from the site so there is no site hazard associated with it.

The benefits and advantages of a liquid fuel-molten salt system are also utilized.

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The

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CONCEPT
FOR THE THIRD MILLENIUM

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4TH ICENES
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THE U.S. REACTOR
MAJOR ADVANTAGES

SAFETY IS ABSOLUTE, INHERENT, AND PASSIVE, CANNOT BE TAMPERED WITH

AFTER-HEAT IS REDUCED TO BENIGN LEVEL

CRITICALITY IS INHERENTLY CONTROLLED

TECHNOLOGY THE BASE TECHNOLOGY IS DEVELOPED

PROLIFERATION AND DIVERSION RESISTANT

SIZE EXPECTED TO HAVE GREAT SIZE FLEXIBILITY

ECONOMY POTENTIAL FOR BEING ECONOMIC DUE TO ADVANTAGES

FUTURE POSSIBLE VARIATIONS TO ADJUST TO NEEDS

OTHER ADVANTAGES

LIQUID FUEL — INHERENT SAFETY AND FLEXIBILITY

MOLTEN SALT — SIMPLE DESIGN;

NEGATIVE TEMPERATURE COEFFICIENT;

NO IRRADIATION DAMAGE;

NO FUEL ELEMENT FABRICATION;

CONTINUOUS ON-LINE PROCESSING

COMPATIBLE MATERIALS

LOW PRESSURES

HIGH TEMPERATURES

GOOD COMPATIBILITY WITH STRUCTURAL MATERIALS

THE U.S. REACTOR

PRINCIPLES

CONTINUOUS ON-LINE FISSION PRODUCT REMOVAL

- INNOCUOUS SOURCE TERM
- INSIGNIFICANT AFTER-HEAT
- NO EXCESS CRITICALITY
- STEADY STATE

INTERNAL EXACT FUEL REPLACEMENT (BR = 1.0)

- NO EXCESS CRITICALITY
- NO FUEL SHIPMENT
- ENHANCED ECONOMY
- NO NEED FOR CONTROLS
- RESISTANT TO FUEL DIVERSION

NEGATIVE REACTIVITY TEMPERATURE COEFFICIENT

- ENHANCED SAFETY
- SELF REGULATING
- NO CONTROLS NEEDED
- NO OVERRIDE OF SAFETY

DEVELOPMENT

DETERMINE PROCESSING RATES

DEVELOP AND TEST PROCESSING

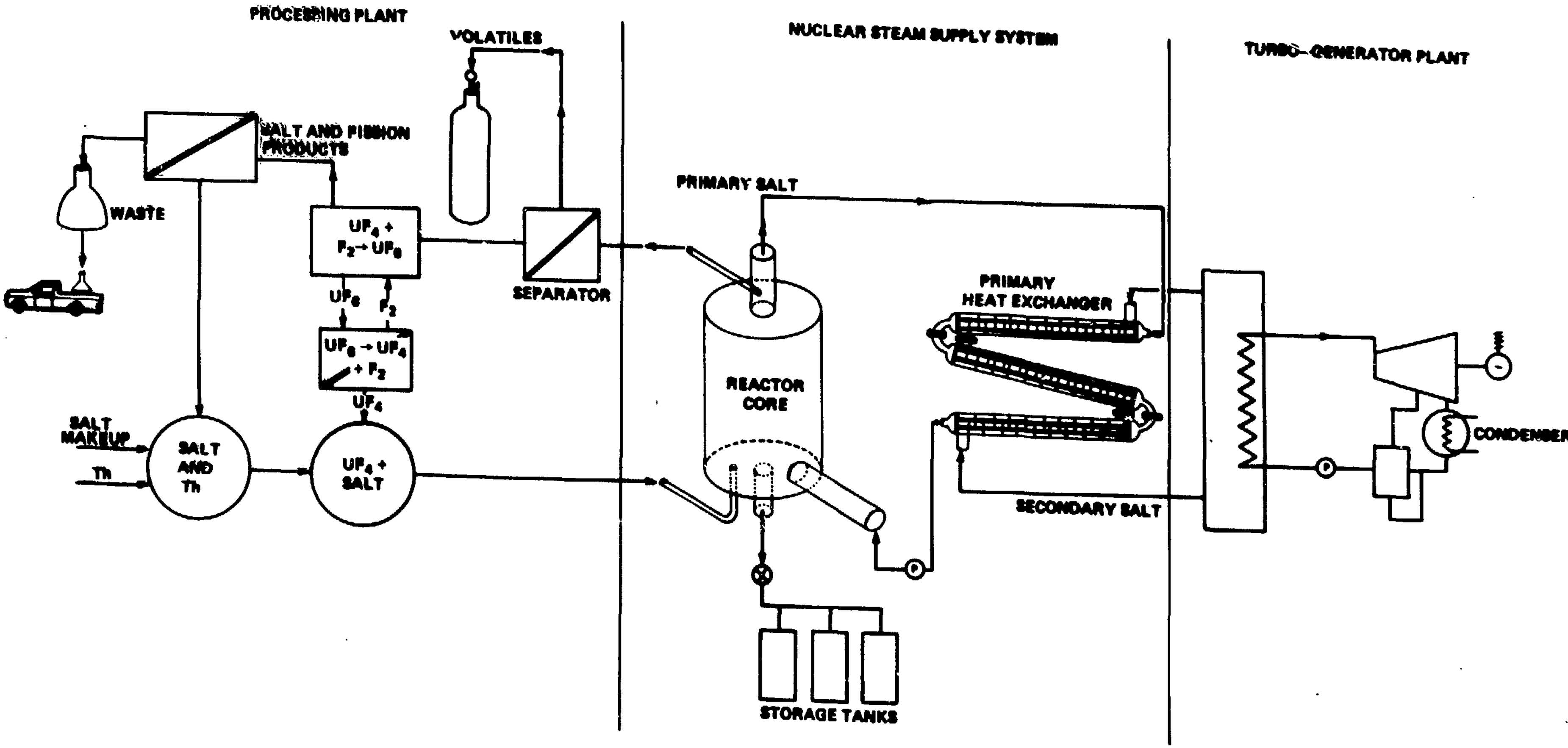
CALCULATE CORE PHYSICS AND FUEL CYCLE

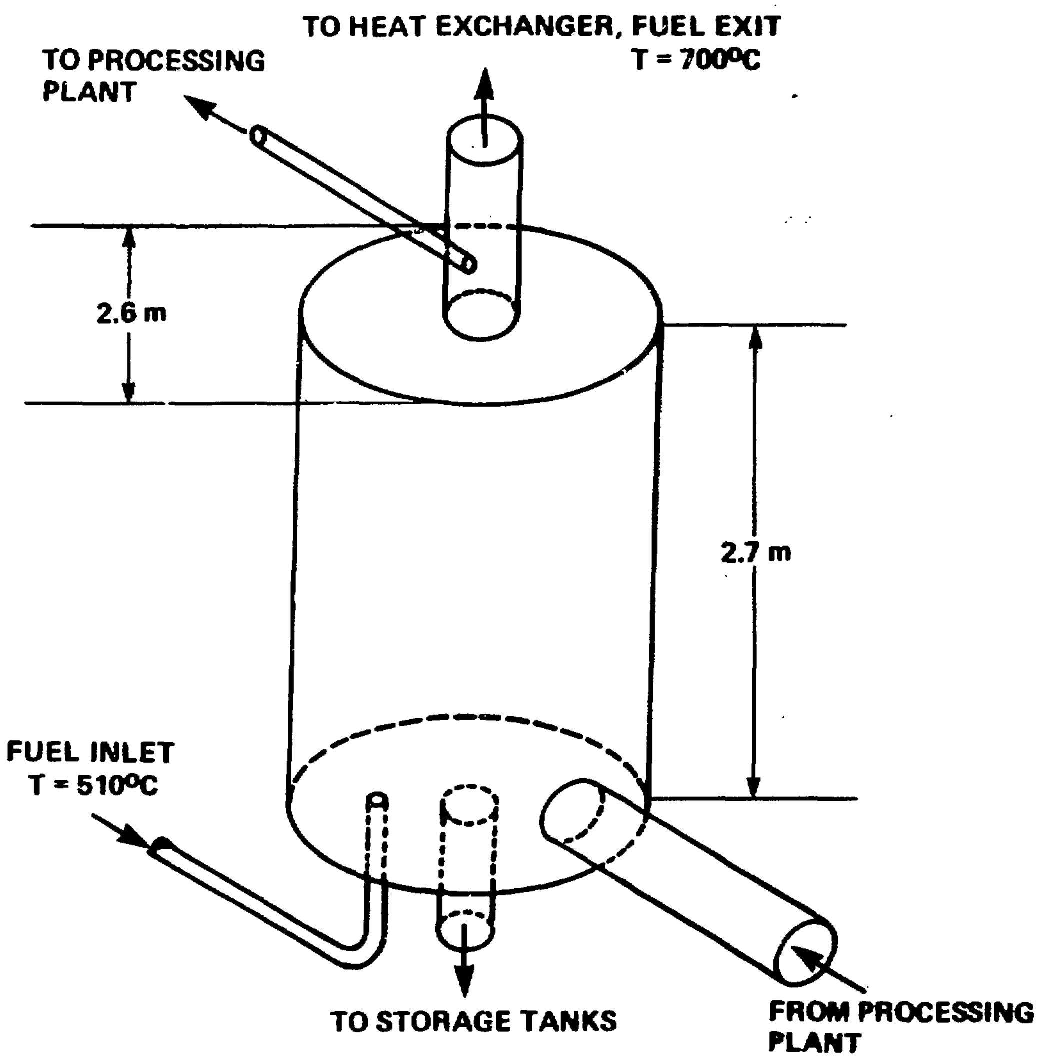
TEST MATERIAL COMPATIBILITY

CALCULATE AND TEST DYNAMICS

DESIGN

CONSTRUCT


PROCESSING PLANT
NUCLEAR STEAM SUPPLY SYSTEM
TURBO-GENERATOR PLANT
VOLATILES
SALT AND FISSION PRODUCTS
WASTE
UF4 + F2 → UF6
SEPARATOR
UF6
F2
UF6 → UF4 + F2
UF4
SALT MAKEUP
Th
SALT AND Th
UF4 + SALT
PRIMARY SALT
PRIMARY HEAT EXCHANGER
REACTOR CORE
SECONDARY SALT
CONDENSER
STORAGE TANKS


TO HEAT EXCHANGER, FUEL EXIT
T = 700°C
TO PROCESSING
PLANT
2.6 m
2.7 m
FUEL INLET
T = 510°C
TO STORAGE TANKS
FROM PROCESSING
PLANT

U. S. REACTOR REPROCESSING SCHEMATIC