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THE ULTIMATE SAFE (U.S.) REACTOR*

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ABSTRACT

The Ultimate Safe (U.S.) Reactor is a reactor that eliminates the traditional safety concerns of nuclear fission reactors. The U.S. reactor has an insignificant source term and no reasonable criticality accident. Furthermore, the negligible residual after-heat in the reactor renders its shutdown capability comparable or superior to conventional power sources in that no actions or precautions are required following a shutdown of power.

The U.S. reactor utilizes two principles to achieve ultimate safety. Fission products are continuously removed at the rate they are produced, thus retaining the inherent source term at an insignificant level. The

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reactor is operated with no excess criticality, hence no criticality accident is reasonably possible. The reactor is controlled safely by its negative temperature coefficient. The reactor maintains criticality by an internal breeding ratio that is trimmed to be exactly one.

To facilitate the continuous fission product removal, The U.S. reactor requires a fluid fuel and on-line, continuous fuel processing. Molten salt fuel was selected for its well-known beneficial properties: low vapor pressure at high temperature; adequate solubility of uranium and thorium as fluorides; good compatibility with structural materials; absence of irradiation damage; high negative temperature coefficient and amply developed technology and experience.

The passive inherent safety features of The U.S. reactor make it a potentially very economical competitor with high reliability. Thus the reactor is a viable and attractive option for future energy generation.

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Introduction

The unique features of nuclear power generation stem from the utilization of nuclear fission as the energy source. With breeding, the nuclear option provides a long range cheap fuel. The fission process results, unavoidably, in radioactive fission products. These radioactive products constitute a health hazard if not contained. They also continue to generate energy after reactor shutdown regardless of any external circumstances. The possibility of this unabatable residual energy, or after-heat, dispersing the radioactivity, the so-called source term, is a major area of concern in nuclear reactors. Another area of concern is the possibility of unwanted and perhaps uncontrolled criticality or even supercriticality. There is also concern about proliferation of nuclear fuels that may lead to the production of weapons.

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Several studies [1-3] have determined that a prerequisite for the future viability of the nuclear option is a novel approach to safety. Safety must be provided by passive means, not subject to mechanical, electrical, or human failure or error. Furthermore, safety must not only assure the public health and safety but also the economic performance of nuclear plants. Thus a plant must be immune from even minor interruptions that may lead to decreased economic performance, let alone economic disaster, such as loss of investment.

Three basic approaches are possible to reduce or eliminate the source term [4]. The most common one is to provide assured ("diverse and redundant") energy removal systems that will disperse any after-heat, not allowing temperatures to reach a level that could lead to damaging the core and releasing any fission products. Most existing power reactors rely on various forms of active auxiliary and emergency core cooling mechanisms and systems to provide this core cooling, in the event that the regular heat removal system fails. These systems require reliance on their active operation, which is subject to failure, however remote and unlikely. A second method is to contain the residual energy in a way that will assure no damage for adequately long periods. The best known concept relying on this principle is the PIUS reactor [5,6] utilizing a huge reservoir of water to absorb the after-heat. The third principle, utilized by The U.S. Reactor, is to continuously remove fission products from the reactor so no accumulation of hazardous radioactivity is possible. There are various advantages to this method. Removal of the radioactive fission products also removes the decay heat source, thus not only is the hazardous material removed from the reactor but also the energy source that may lead to the dispersal of the radioactivity is no longer in the reactor. Further, this safety provision is inherently and totally passive and not subject to failure under any circumstances.

Control of criticality is usually accomplished by inherent physical properties design. Most commonly a negative temperature reactivity coefficient will render the core subcritical upon a power excursion. This is usually supplemented by active and passive control employing various forms of neutron poisons. One of the most effective passive and absolute means to avoid supercriticality is to eliminate any excess criticality, and any active control of criticality that could be misused. In power reactors this requires continuous replenishing of the consumed fuel.

To avoid proliferation and diversion of fuel, safeguards and controls are used. Reducing or eliminating the handling, manipulation, and above all the shipment of fuel are major contributing factors to avert proliferation and diversion. A condition for no fuel shipments is a self sustaining reactor. That is a reactor that exactly replaces its fuel through the breeding process with no excess fuel bred.

A reactor that is inherently safe, relying on passive means, has the potential for being economically very competitive. Many of the perils of reactors are related to safety and its assurance. The design must include diverse and redundant means, the purpose of which is to assure the safety. The licensing process is cumbersome and costly to assure beyond reasonable doubt that safety is adequate. Construction must be quality assured, inspected, and is constantly subject to modification to ascertain safety, often causing costly delays and changes. Finally, operation is controlled first and foremost by safety, often interfering with smooth continuous operation. Inability to completely shut down the reactor in a short time often requires precautionary power reduction or shutdown. A reactor that is subject to common industrial hazards but not to specific nuclear hazards can significantly reduce or even eliminate most of these economical adverse factors and thus become economically very competitive and reliable.

The U.S. Reactor Principle

The Ultimate Safe Reactor is a reactor that responds to contemporary requirements of inherent passive safety and is economically competitive by implementing this novel safety approach to the extent that the resulting simplified and/or reduced design, capital investment, construction, licensing, reliability, and operation make it extremely economically competitive.

To arrive at this ultimate safety, The U.S. Reactor is utilizing two techniques. The first is continuous removal of fission products and the second is exact fuel refurbishing ~~replacement~~, by breeding, of the consumed fuel. The continuous removal of fission products is done at the rate they are produced. The level of fission products is held such that the source term is rendered insignificant. A low level fission product reactor has been proposed before [7], however, reducing the level to an insignificant source term is unique to The U.S. Reactor. The reduction of the fission products to an insignificant source term also reduces the after-heat, in the case of The U.S. Reactor, to such a low residual level that the core will not exceed the design temperature level. No special means are necessary to accomplish this feature. Thus the source term loses its sting and the driving force simultaneously.

The constant continuous breeding and replenishing of fuel at the exact consumption rate accomplishes several advantages. No fuel shipments to or from the reactor are necessary, only fertile material is shipped to the reactor. In combination with the low and constant fission product level, no excess criticality is needed or used. Thus a criticality accident cannot occur during operation. No mechanical or burnable poison controls are used and no operation error is possible. Power following is achieved solely by an inherent temperature coefficient. A special shutdown feature is described later.

The U.S. Reactor can utilize the thorium-uranium-233 fuel cycle. In this fuel cycle the hard activity and the "denaturing" features of uranium-232 and its daughter products provide a further deterrent to proliferation and diversion.

Design Options

To facilitate the continuous removal of fission products, a fluid fuel [8] that can be readily circulated through a processing facility was chosen. Of the three common options — liquid-metal; aqueous; and molten salt — molten salt is elected. Molten salt is a well developed technology with many advantageous properties [9-12]. The molten salt enables the breeding ratio of one, needed for The U.S. Reactor, and has a developed and tried processing scheme [13,14]. Many versions of molten salt reactors are proposed [7-9, 15-18]. Molten salt reactors per se are already recognized as having the least environmental effect of several included in a Battelle Columbus Laboratory study [19].

Molten salt reactors have the advantage of [8,12,20]

- High negative temperature coefficient,
- Lack of irradiation damage,
- Avoidance of fuel element fabrication,
- Continuous on-line fuel processing and refueling,
- Low vapor pressure to high temperatures,
- Adequate solubility of uranium and thorium (as fluorides), and
- Good compatibility with structural materials.

Design parameters for this initial concept were chosen based on information availability and design simplicity. No optimization was attempted nor are the selections complete or necessarily mutually compatible. Specifically, no criticality or breeding calculations were done, and fuel composition adjustments are necessary. There is no dedicated moderator. Thus the neutron spectrum is harder than for a comparative thermal reactor. This enhances the breeding but will require a higher fuel concentration than shown for criticality.

The primary salt and secondary salt, a heat transfer salt, and their properties are detailed in Table 1. The external cooling option was chosen for the design simplicity requirement. The reactor core, primary heat exchanger, and pipes are made of Hastelloy N. Thermal and physical properties of Hastelloy N are given in Table 2.

A schematic diagram of The U.S. Reactor is shown in Fig. 1. The reactor is cooled externally by circulating the reactor fluid through the primary heat exchanger. External cooling was chosen to avoid structure in the core and to keep the system simple. With external cooling and no moderator, the core contains only the fuel salt.

The secondary salt circulates through the shell side of the primary heat exchanger and the steam generator. The turbo-generator plant is conventional and produces a gross of 625 MW(e). 50 MW is the assumed required plant load, therefore the net electric production is 575 MW; for a net efficiency of 40%.

Table 1. Physical Properties of Primary and Secondary Salt [17,21]

	Primary salt	Secondary salt
Components	$LiF-BeF_2-ThF_4-UF_4$	$NaBF_4-NaF$
Mole %	71.6-16-12-0.4	92-8
Molecular mass	64	104
Melting temperature, °C	499	385
Density, kg/m^3	3500 (at 510°C) 3300 (at 700°C)	1900 (at 530°C)
Viscosity, ~~M~~Pa•s	7 (at 700°C)	1 (at 482°C)
Thermal conductivity, W/(m•K)	1.3	0.47
Heat capacity, kJ/(kg•K)	1.34	1.51
Total volume, m^3	37	
Total mass, kg	1.3×10^5	
Total mass uranium, kg	1.9×10^3	

Table 2. Physical Properties of Hastelloy N [21]

Density, kg/m^3	8850
Thermal conductivity, W/(m•K)	22
Specific heat, kJ/(kg•K)	410
Melting temperature, °C	1371
Maximum allowable temperature in this design, °C	750

The 50 MW consumed in the plant were estimated as 25 MW to operate pumps and other auxiliaries and 25 MW used in the processing plant. A side stream of fuel circulates from the reactor to the processing plant where the fission products are removed. The U.S. Reactor is designed to be poisoned to a subcritical condition unless the fission products are removed. There is no excess criticality in the core to overcome poisoning due to fission product buildup. The conversion/breeding ratio of the U.S. reactor is exactly one.

The insignificant source term in the core renders a conventional containment unnecessary. Also, the heat exchanger need not comply with any stringent safety requirements, nor is there need for any means of afterheat removal, since the core contains only a negligible amount of afterheat. Furthermore, shutdown of the reactor is accomplished by dumping the fuel into storage vessels solely designed for that purpose and incorporating all the needed safety measures.

Reactor Core

The core of The U.S. Reactor is a simple cylindrical structure, made of Hastelloy N with a single fluid, externally cooled. The core diameter and height are 2.6 m and 2.7 m, respectively. The core dimensions presented here are based on thermodynamic calculations. Criticality is achieved by adjusting the fuel concentration as needed to achieve criticality at these dimensions, however, the necessary fuel concentration was not calculated for this design and was chosen for availability of physical properties. Power density was arbitrarily chosen to be 100 MW/m^3 in the core.

For the net electrical output of 575 MW, the reactor thermal power is 1420 MW. Fuel salt enters at the bottom of the core at 510°C and exits from the top at 700°C. Flowing at 5.6 Mg/s, the fuel passes through the core in 8.3 seconds. Figure 2 shows a schematic diagram of the reactor core, and Table 3 gives important characteristics related to the core.

Table 3. Important Characteristics of
The U.S. Reactor Core

Thermal duty, MW	1420
Mass flowrate, Mg/s	5.6
Volume flowrate, m^3/s	1.7
Inlet temperature, °C	510
Outlet temperature, °C	700
Power density, MW/m^3	100
Core volume, m^3	14.2
Core inner diameter, m	2.6
Core height, m	2.7
Time for salt to pass through core, s	8.3
Salt velocity in core, m/s	0.33
Conversion/Breeding ratio	1

Primary Heat Exchanger

After exiting the reactor core, the fuel salt passes through the primary heat exchanger. The heat exchanger consists of three shell and tube heat exchangers in series. Each is made of Hastelloy N and contains 1736 tubes. The fuel salt flows slightly downhill (3°) through the tubes so the system is drainable. The secondary salt flows counterflow through the shell side. The heat transfer salt enters at 400°C, leaves at 617°C, and has a mass flowrate of 4.3 Mg/s. The log mean temperature difference is 96 K, and the overall heat transfer coefficient is 5400 $W/(m^2 \cdot K)$. A primary salt flow velocity of 3 m/s was chosen, resulting in the 1736 tubes of inner radius 10 mm and a total length of 25 m per tube. To provide reasonable tube lengths, the heat exchanger was divided into three parts with a length of 8.4 m each. Although subdividing the unit increases entrance and exit losses, it provides flexibility in arranging the equipment and has the additional advantage of providing smaller modular units for easier and simpler manufacturing and maintenance. With a vertical spacing of 0.2 m between the units, the total height of the heat exchanger arrangement is about 4.7 m. The storage tanks are designed to guarantee subcriticality under all circumstances and adequate cooling by natural convection. A freeze valve is under consideration for the dumping valve for additional inherent passive safety.

Table 4. Primary Heat Exchanger Data

	Tube side	Shell side
Fluid	Primary (fuel) salt	Heat transfer salt
Inlet temperature, °C	700	400
Outlet temperature, °C	510	617
Mass flow rate, Mg/s	5.6	4.3
Average density, Mg/m^3	3.4	1.9
Volume flow rate, m^3/s	1.6	2.3
Velocity, m/s	3.0	
Reynolds number	2.9×10^4	1.4×10^5
Pressure drop, kPa	150	
Inner diameter, mm	20	1400
Wall thickness, mm	1	60
Cross sectional flow area, cm^2	3.1 (per tube)	3400
Number of tubes	1736	
Heat transfer area, m^2	2740	
Tube length, m	8.4	
Heat flux, MW/m^2	0.52	

Processing

The required rate of processing for The U.S. Reactor was estimated [22] assuming, very conservatively, that the entire inventory of the reactor will reach the site boundary six hours after reactor shutdown. The fission yields were based on an LWR ORIGEN code calculation. The resulting exposure was held to less than 0.15 Sv using published dose conversion factors [23]. The fission products were grouped in three groups. A total removal of the respective group elements in the processing was assumed. The three groups required a removal cycle time of one hour, three hours, and six hours. The one hour processing group includes Kr, Sr, Nb, I, and La. A one hour cycle time for processing the fuel volume is assumed. That means that the three and six hour group elements do not have to be removed completely in processing. The processing rate has to be doubled if the removal efficiency is reduced to 0.5.

To process the 37 m^3 of molten salt in one hour requires a flow rate of about 10 L/s. At a flow velocity of 1.3 m/s a pipe diameter of 100 mm (4 in.) is needed for the processing plant supply and return lines. Slower flows in reactors and extractors require correspondingly larger flow cross-sections.

Waste

The reactor produces about 1.7 kg of fission products per day, at 1.2 kg/GWd. The fission products contain most of the radioactivity and a considerable amount of after-heat. There are two major groups of fission products. The gaseous and highly volatiles are collected in bottles, and the other fission products are collected in suitable containers. Fission products may be mixed and diluted with matrix salt or other fixing and stabilizing components as desired.

The storage and shipping containers are totally independent of any reactor considerations. These containers are designed in size so that they contain the desirable quantity that is acceptable from a hazard point of view. The shape of these containers is designed so that they provide the desired level of passive safety to contain the materials and to assure they do not exceed temperature limitations even under the most adverse conditions. Containers are shipped to a waste repository site at frequency and quantity dictated by safety.

Summary

The U.S. Reactor utilizes a novel form of passive safety that eliminates the hazard rather than prevent or mitigate the consequences. This passive inherent type safety is complete and absolute and can not be tampered with. There are two major features that provide this safety. Fission products are removed continuously so that the level of radioactivity in the core is of no significant health hazard. This simultaneously reduces the after-heat and removes the driving force of the source term. The core sustains its fuel level for exact criticality and there is no excess criticality for a supercriticality hazard. The fuel self-sustaining core also eliminates fuel shipments, which is a deterrent to diversion and proliferation. The uranium-233 with some uranium-232 in it is a further deterrent to misuse of the fuel. This makes The U.S. Reactor very suitable for deployment with very few restrictions and a minimum of precautions.

The U.S. Reactor is utilizing the molten salt technology, which is already endowed with many important safety features. These safety features include negative reactivity temperature coefficient, lack of irradiation damage, avoidance of fuel element fabrication or handling, low pressures at high temperatures, good compatibility with structural materials, and the ability for a quick dump, or transfer, of the fuel to safe storage. The lack of fuel elements and elaborate control and safety devices result in very simple and transparent designs which enhance the economy. The simple designs make the size of the reactor very flexible and facilitate modular construction. The relatively small components can be shop-fabricated and easily shipped to any site.

The high degree of inherent passive and absolute safety eliminates the need for many safety components, features, and devices. For example, there is no safety requirement for a containment, or diverse and redundant heat removal systems and back-ups. The reduction in components means a reduction in cost and investment. The absence of safety requirements eliminates the need for elaborate assurance means during design and analysis, during construction and operation. The construction and operation can be similar to those of non-nuclear facilities, greatly reducing cost and averting any potential for costly delays. Once the principal of the inherent passive and absolute safety is proven and accepted, the licensing process should be greatly simplified and reduced. The easier to understand, simpler, and more transparent safety is expected to also greatly enhance public acceptance.

The U.S. Reactor combines a series of highly desirable characteristics and properties. The passive absolute safety can make it an economically very attractive and competitive power source. The U.S. Reactor is a viable option for future power generating stations.

Acknowledgement REM

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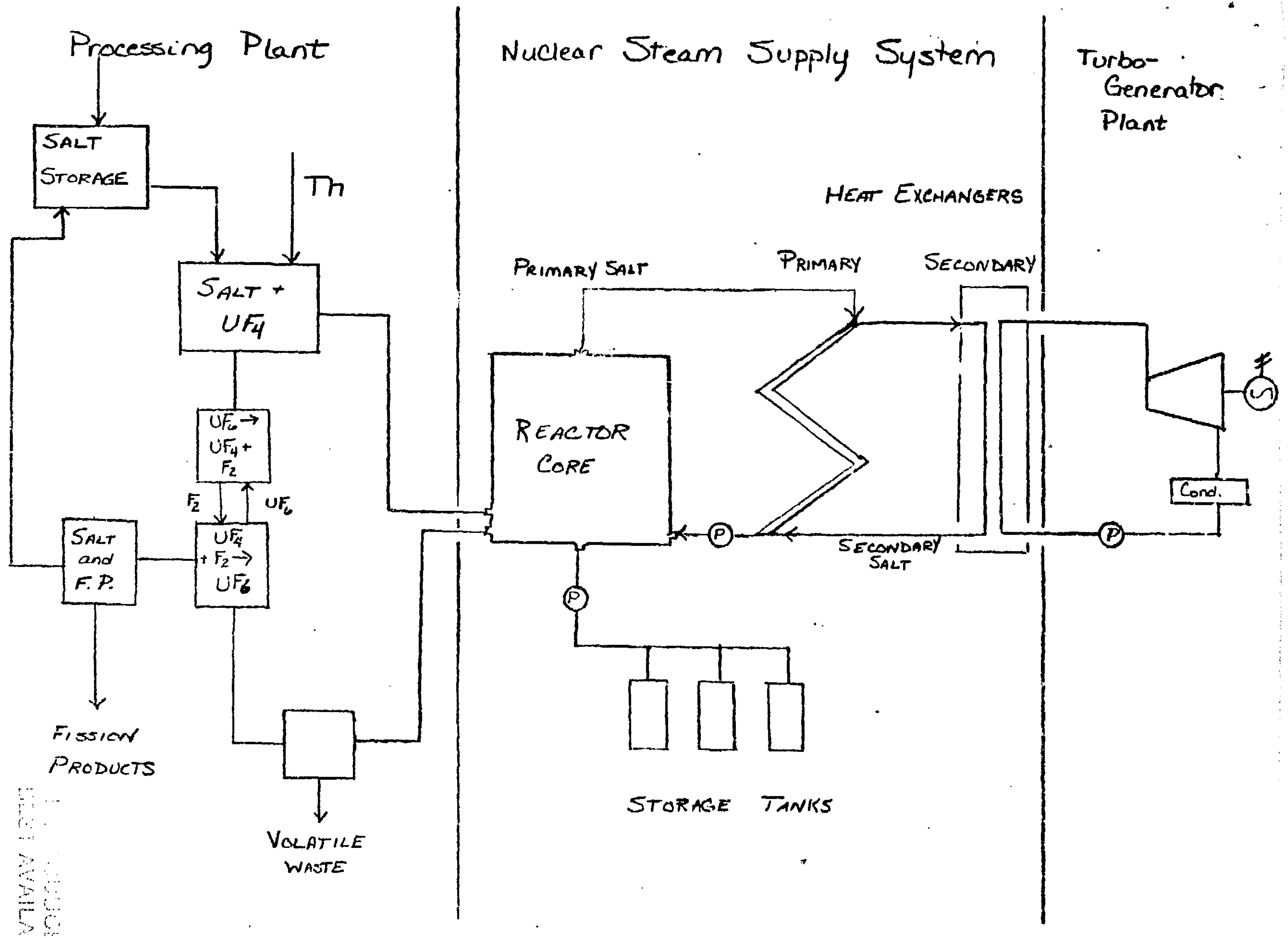

Fig. 1 Schematic Diagram of U.S. Reactor

(Tentative - for review, being revised 1985-11-20)

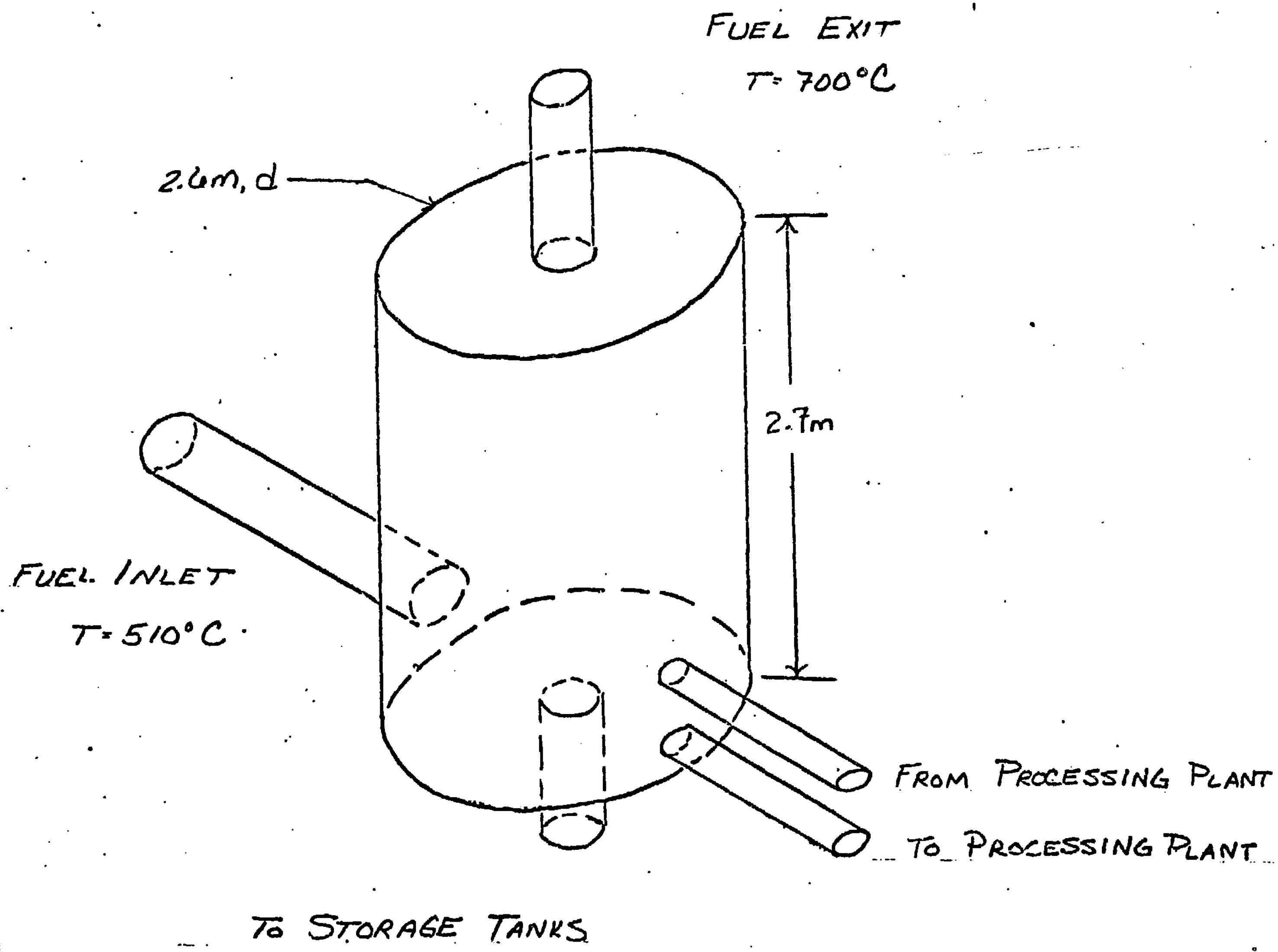

Fig. 2 REACTOR CORE
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