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REQUEST FOR QUOTATION

Project Initiation Document for a Molten Salt Reactor Engineering Estimate

Purpose.

To assist potential vendors to develop a proposal and quotation for the creation of an up-to-date Engineering Estimate predicated on the Oak Ridge National Laboratory original 1970-75 Engineering Estimates for a molten salt reactor. We request that a quotation be generated to cover the costs of a full Project Initiation Document leading to an Engineering Estimate (including a quotation covering its costs).

Scope.

We are seeking an estimate of how much it will cost to specify the design effort for one of the three Molten Salt Liquid Fluoride Thorium Reactor Prototype Designs we intend to commission. Each of three design engineering efforts will be funded. The topics of scope are discussed below. In estimating the cost of a full Project Initiation Document leading to an Engineering Estimate, each vendor can expect to utilize the extensive previous work, now in the public domain, as a foundation (see **Appendix A**.). The application of this previous ORNL engineering effort will describe and design a modern approach to produce a commercialized version of the molten salt reactor – taking advantage of the scientific advances in process, systems, and materials since the Molten Salt Reactor Experiment (MSRE) was shut down in 1969.

Section 1. Reactor Design and Development

It is anticipated that approximately 80% of each of these three prototype designs required would involved identically engineered components. All of these prototype designs will involve the same molten salt types, melting at approximately 450˚ C. and operating at approximately 700˚ C.

with 3%-5% ^{235}U (low enriched uranium) as a starter / fuel and ^{232}Th (thorium) as a fertile addition for conversion to fuel.

The first two reactors are assumed at 200 MW(e) and the third is assumed at 100 MW(e) output. The final balance of power would come from whatever reactor design and power train system is paired with the heats to get the true plate rating for the entire system.

"The Molten-Salt Reactor Experiment (MSRE) was undertaken by the Oak Ridge National Laboratory to demonstrate that the desirable features of the molten-salt concept could be embodied in a practical reactor that could be constructed and maintained without undue difficulty and one that could be operated safely and reliably. Additional objectives were to provide large-scale, long-term, high-temperature tests in a reactor environment of the fuel salt, graphite, moderator, and high nickel-base alloy.

- *The fuel is fluid at reactor temperatures, thus eliminating the extra costs associated with the fabrication, handling, and reprocessing of solid fuel elements.*
- *Burnup in the fuel is not limited by radiation damage or reactivity loss.*
- *The fuel can be reprocessed continuously in a side stream for removal of fission products, and new fissionable material can be added to fuel the reactor while it is in operation.*
- *Molten-salt reactor can operate at high temperatures and achieve thermal efficiencies in the heat-power cycle equal to the best fossil-fuel-fired plants.*
- *The relatively low vapor pressure of the salt permits use of low-pressure containers and piping.*
- *The negative temperature coefficient of the reactor and the low excess reactivity are such that the nuclear safety is not dependent on control rods.*
- *The fluoride salts used as the fluid fuel mixture have good thermal and radiation stability and do not undergo violent chemical reactions with water or air.*
- *The fluoride salts are compatible with the graphite moderator and can be contained satisfactorily in a specially developed high nickel alloy.*
- *Use of relatively high circulation rates and temperature differences results in high mean power density high specific power, and low fuel inventory.*

--MSRE DESIGN AND OPERATIONS REPORT – PART I – DESCRIPTION OF REACTOR DESIGN – ORNL-TM-0728

1.1 MSR Reactor Design Types (3)

1.1.1 Single Fluid molten salt reactor with no in-line processing (200 MW(e) / 500 MW(t), approx.); denatured U^{238} / U^{235} with some thorium

Although a single fluid system is simple from a fluid management perspective, and has been most thoroughly explored by the MSRE, it will still require a complex graphite moderator core that represents a formidable engineering challenge itself.

The '*Prudent*' prototype design will be guided by the Denatured Molten-Salt Reactor with Once-Through Fueling first described in ORNL-TM-7207. This reference can sourced in **Appendix A**.

"The plant concept for a Denatured Molten Salt Reactor is a direct outgrowth of the ORNL reference-design MSBR (ORN-TM-4541). However, to comply with the anti-proliferation goals of the DMSR, it also contains a number of differences, principally in the reactor core design and the fuel cycle. The fuel circuit for a DMSR redesigns the core design so that there is a reduction in the core neutron flux and power density to:

- *Extend the life expectancy of the graphite moderator to the full thirty-year plant lifetime,*

- *Limit neutron captures in ^{233}Pa (Protactinium), which would be retained in the fuel salt to enhance proliferation resistance.*

- *Lower power density would reduce the poisoning effects of short-lived fission products and simplify the thermal-hydraulic constraints on the moderator design*

- *At design power the fuel salt, with a liquidus temperature of 500° C., would enter the core at 566 ° C. and leave at 704° C. to transport about 2.25 of its design power in MW(t) (in four parallel loops) to the secondary salt. The flow rate of sale in each primary loop would be about one M^3/s (16,000 gallons-per-minute).*

- *The secondary 'coolant-salt' circuits for the DMSR would be identical to those developed for the reference-design MSBR (ORNL-TM 4541). The nominal flow rate of the secondary salt (a eutectic mixture of $NaBF_4$ and NaF) would be about 1.26 M^3/s (20,000 gpm) in each of the four loops, with a temperature rise from 454° C. to 621° C. in the primary heat exchangers.*

- *This secondary circuit's primary function is isolating the highly radioactive primary circuit from the power train system and providing an intermediate heat-transfer fluid.*

- *The secondary circuit would also limit the release of tritium from the DMSR system. Engineering-scale tests in 1976 demonstrate this salt capable of trapping large quantities of tritium and transforming it to a less mobile, but still volatile, chemical form that transfers to the cover-gas system rather than diffusing through the power train's generators*

-- CONCEPTUAL DESIGN CHARACTERISTICS OF A DENATURED MOLTEN-SALT REACTOR WITH ONCE-THROUGH FUELING", J.R. ENGEL, ET AL, ORNL –TM-7207

1.1.2 1.5 Fluid molten salt reactor with some in-line processing (200 MW(e) / 500 MW(t), approx.) U^{235} / with Th^{232} thorium conversion

The 'Brave' prototype design will be:

…based on a technology which does not require major inventions or technological breakthroughs:

- *The reactor system will generate fission heat in the fuel salt in its passage through the reactor vessel that is removed in primary heat exchangers*

- *An off-gas system for purging the fuel salt of fission product gases and gas-borne particulates*
- *A chemical processing facility for continuously removing fission products from the fuel salt, recovering newly bred fuel, and replenishing the fertile material*

- *A coolant-salt circulating system, and a turbine-generator plan for converting the thermal energy into electric power*

- *General facilities and equipment, including controls and instrumentation, maintenance tools, auxiliary power equipment, waste disposal systems, electrical switchyard, stacks, and conventional buildings and services.*

…operating on the ^{232}Th – ^{233}U cycle, with both fissile and fertile materials incorporated in a single molten-salt mixture of the fluorides of lithium, beryllium, thorium, and uranium.

The salt has a liquidus temperature of 499° C. with a good flow and heat transfer properties, and has a very low vapor pressure in the operating temperature range.

It is also non-wetting and virtually noncorrosive to graphite and the high nickel alloy (Hastelloy N) container material.

The reactor vessel contains graphite for neutron moderation and reflection, with the moderating region divided into zones of different fuel-to-graphite ratios.

The MSBR's primary salt is circulated outside the reactor vessel through four loops – each circuit contains a 16,000-gpm single-stage centrifugal pump and a shell-and-tube heat exchanger.

Tritium, xenon, and krypton are sparged from the circulating primary salt by helium introduced in a side stream by a bubble generator and subsequently removed by a gas separator.

A 1-gpm (0.067 ltr/sec) side stream of the primary salt is continuously processed to remove ^{233}Pa (Protactinium), to recover the ^{233}U (uranium isotope) bred from ^{232}Th (thorium).”

-- CONCEPTUAL DESIGN STUDY OF A SINGLE-FLUID MOLTEN-SALT BREEDER REACTOR, COMPILED & EDITED BY R.C. ROBERTSON, ORNL-TM-4541

1.1.3 2 Fluid (Tube within a tube as per D. LeBlanc Design) with full in-line processing (100 MW(e) / 400 MW(t), approx.) to pure thorium fuel cycle

1.2 Systems and Components

1.2.1 Pumps

1.2.1.1 Circulation

The circulation impeller centrifugal type of pump will be required. We project that a custom version will be required of an off-the-shelf metal pump that is rated operationally up to 800˚ C. or higher. It should be designed so that should the pump stall then fluid would still be allowed to pass through.

1.2.1.2 Pump to Reactor from Tanks

The Storage / Drain Tanks will require a dedicated pumping circulation system to return the molten salt back up to the operating reactor fuel loop.

References:

“…The MSBR employs four primary-salt pumps and four secondary-salt pumps, with one of each located in the four system loops. In addition, there is a small ancillary salt transfer pump with the dual purpose of filling the primary-salt system and pumping the primary salt to the chemical processing plant.

The fuel-salt circulation pump in the MSRE accumulated over 29,000 hours of successful operation, the only problem encountered being partial restriction of the off-gas flow from the pump bowl. The pump had a capacity of 1,200 gpm and was driven by a 75-hp motor. The dependability of this pump, a similar pump in the coolant-salt system, and many others run for thousands of hours in test stands has given confidence that salt circulation pumps for the MSBR do not represent a major development problem.

The lower portion of the MSBR primary salt pump (comprised of the pump tank, impeller, casing, etc.) is located in the reactor cell, and the drive motor is located on the crane bay floor, that is, above the concrete shielding. The bearing housing is recessed into the concrete shielding to reduce the shaft overhang. The pump shaft is mounted on two pairs of preloaded oil lubricated ball bearings, and the impeller is overhung about 6.5 feet below the lower bearing. The first shaft critical speed will be greater than 1,500 rpm to enable the pump to run at 1,200 rpm when it is to be used for circulating gas… **P. 58-59, ORNL-TM-4541.**

“The fuel salt from the reactor flows directly to the centrifugal sump-type pump. The pump has a vertical shaft and overhung impeller and operates at a speed of 1160 rpm to deliver 1200 gpm at a discharge head of 49 ft. The pump bowl is about 36 in. in diameter and the pump and 75-hp motor assembly is about 8 ft. high.

Devices are provided in the pump bowl to measure the liquid level as a means of determining the inventory of salt in the system. Small capsules can be lowered into the bowl to take a 10-g sample of salt for analysis or to add 120 g of fuel to the system. About 65 gpm of the pump output is circulated internally to the pump bowl for release of entrained or dissolved gases from the salt.

The pump is equipped with ball bearings that are lubricated and cooled with oil circulated by an external pumping system. The oil is confined to the bearing housing by mechanical shaft seals. A helium purge enters below the lower seal. A small part of this helium flows upward along the shaft and leaves just below the lower seal, carrying with it any oil vapors that leak through the seal. The remainder flows downward along the shaft to the pump bowl and subsequently to the off-gas system. This prevents radioactive gases from reaching the oil.

Cooling oil is also circulated through a metal block above the pump bowl, which shields the lubricating oil and the pump motor.

The motor and the bearing shaft and impeller assembly are removable separately to facilitate maintenance." **P. 12-14, ORNL-TM-0728.**

1.2.2 Valves, Flanges, Freeze plugs

We anticipate that valves for the MSR will necessitate substantive research and development. The Freeze Plug System remains the principal model for the main drain valves at this time. A projection of the cost of valves would be acceptable. Flanges are desirable because of their potential utility in support of the maintenance removal of pipe / component sessions. Their design would involve unique configurations.

References:

"…The helium supply lines to the primary containment vessel and the associated valves used for control and blocking these supply lines against the escape of radioactivity from the primary system resulting from a reverse flow or back diffusion. There is also a fuel storage tank and line 530 that supplies pressurizing helium to this tank. …Two types of input signals are used to initiate helium supply block valve closure. The first, a reduction in the supply pressure from its normal value of 40 psig to 28 psig, actuates pressure switches and closes all the inlet helium block valves. The second, excess radiation measured by RM-596A, B, and C in any of the helium lines supplying the level probes (bubblers) and pressuring measuring instruments in the pump bowl and overflow tank, closes the block values in these lines…

"1.5.4. Containment System Instrumentation, pp. 70-75, ORNL-TM-ORNL-0729A."

"…5.1 – Layout - …The level of radioactivity in the reactor and drain tank cells prevents direct approach for maintenance of equipment. The items most likely to require servicing are therefore arranged to be accessible from above when using remotely operated tooling. In many cases the flanges, electrical disconnects, etc., are provided with special bolting, clamps, and lifting bails to facilitate remote manipulation. Five frozen-seal type flanges ("freeze flanges") are provided in the main fuel and coolant salt circuits to allow removal and replacement of major components. The drain line from the reactor vessel can be cut and rejoined by brazing, using specially developed, remotely operated tools and viewing equipment.

"…Salt is introduced into the primary circulating system or drained from it through line 103, which runs from the bottom of the reactor vessel in the reactor cell to the drain tanks in the drain tank cell. The line has a freeze valve, FV-103, to provide "on-off" control of the salt flow. The valve is located within the reactor furnace so that in the emergency situation of a loss of electrical power, the residual heat in the furnace will be sufficient to melt the salt in the valve and cause the system to drain. A cooling gas stream of 25 to 75 scfm is supplied through line 919 and directed against the valve to maintain a frozen plug of salt. A 1.5-kw electrical heater is installed on the valve to effect a quick thaw under normal circumstances.

"The freeze valve has three thermocouples, each with a spare, to monitor and control the operation of the cooling gas and the heater. Line 103 is insulated and heated by passing an electric current through the pipe wall. The heating capacity is 0.3 k/ft, resulting in a total load of 17 kw. The line temperatures are monitored by twelve thermocouples…." ***P. 74, ORNL-TM-728****.*

"There are twelve freeze valves in the MSRE. All are fabricated of 1½ inch pipe. Six are installed in 1½ inch lines and six in ½ inch lines. One freeze valve is located in the reactor drain and fill pipe, line 103, and is inside the reactor furnace. Six of the freeze valves are in the fuel drain tank cell, three are in the fuel processing cell, and two are in the coolant cell. Figure 5.32 shows the general arrangement at a freeze valve. The valve illustrated is used at FV-104, 105 and 106, but with the exception of the flat-plate heaters, is also typical of valves 107 through 112. Electric heat is applied, either directly or indirectly, to thaw a valve and to keep it in the open condition. A stream of cooling gas or air is used to cool the pipe section to freeze a salt plug and positively stop the salt flow. Some system gases may diffuse through the froze plug but the seepage through the valve is inconsequential to operation of the MSRE….Preliminary investigations at ORNL of Kenametal seats and poppets, electrically-driven actuators, etc., indicated that a mechanical-type valve for molten-salt service may be practical provided that a satisfactory stem seal could be devised with reasonable effort…" ***P. 190, Freeze Valves, ORNL-TM-0728.***

1.2.3 Drain Tanks

Drain Tanks should be designed to accommodate the full load of fuel, blanket, and secondary loop molten salts. A draining system should be designed so that each fuel salt can be drained separately into individual tanks. Additionally, in the vent of a rupture or other failure, it should be possible to drain the entire contents simultaneously to either tank from any drain point, valves, freeze plug, floor drains.

Reference: *"The MSRE primary circulating system is provided with two fuel drain tanks and a flush salt tank. The drain tanks are used to store the fuel salt when it is drained from the reactor. Either of the two drain tanks can store th entire salt content of the primary circulating system. The flush salt tank is used to store the salt, which is circulated through the primary system to clear it of oxides and other contaminants before the enriched salt is added. (In addition, a fuel storage and reprocessing tank is located in the fuel processing cell.) The geometry of the fuel-salt drain tanks is such that the concentration of uranium in the MSRE fuel salt cannot produce a critical mass under any conditions. A fourfold increase in concentration would be necessary for criticality. Although studies have indicated that in equilibrium cooling of salt mixtures the last phase to freeze may contain about three times the uranium concentration in the original mixture, it is unlikely that the salt in the tanks will freeze, in that this would require an electric power outage of more than 20 hours, or that gross segregation of the concentrated phase could take place in a large-sized tank having so many thimbles in which initial solidification would take place. The risk of criticality can be eliminated altogether by dividing a fuel-salt charge between the two drain tanks. One tank will be kept empty for this contingency.*

"…The two drain tanks and the flush salt tank are located in the drain tank cell, which is just north of the reactor cell and connected to it by a short 36 inch diameter tunnel. The draink tank cell is constructed of heavily reinforced concrete, lined with stanless steel, and of the general dimensions given in Section 4.3.2. The layout of the equipment in the cell is indicated in Figures 4.4 and 4.5, and is shown in more detail in ORNL Drawing E-GG-D-41512. The arrangement was primarily influenced by the requirement that all maintenance operations be performed from overhead. Other considerations were the arrangement and flexibility of the piping, and the relative elevations so that the reactor could drain by gravity.

"…The drain line from the bottom of the reactor vessel, line 103, branches inside the drain tank cell into three lines which lead to the two drain tanks and to the flush salt storage tank. The fuel salt lines from these tanks, which permit interchange of salt with the fuel processing area, combine into a single pipe, line 110, before leaving the drain tank cell. Each of the six lines mentioned has a freeze valve, as described in Section 5.6.5…" ***pp. 220-221, ORNL-TM-0728.***

1.2.4 Plant Piping

This will require other plant piping installation, mounting, and supports with a plan for maintenance.

Reference: *"…5.6.2 – Piping Stresses and Flexibility Analysis – The reactor vessel is suspended from the stationary top cover of the thermal shield and is thus fixed in position and the anchor point for the piping in the primary circulating system. The circulating loop is rather compact, with short relatively stiff lengths of 5-inch pipe connecting the equipment. To avoid use of bellows-type expansion joints to relieve stresses due to thermal expansion, the heat exchanger and fuel pump supports were designed to allow relatively free movement. The fuel pump mount allows the pump to move on rollers in the horizontal plane and a parallel-link framework, supported on springs, permits vertical movement from the cold to the hot position (See Section 5.4.4). The pump bowl is thus restrained from rotation about any axis. The heat exchanger supports permit it to move horizontally in two directions on rollers and to move vertically and rotate about its longitudinal axis by acting against the spring supports…*

"The sustain stresses in the piping, i.e., those due to internal pressure and weight of the equipment and contents, were estimated using conventional relationships and found to be less than the allowable stress of 3,500 psi at 1300° F. (705° C.)

"…Flexibility analyses were made on the primary circulating system piping using the IBM Modification of Pipe Stress Program, SHARE, No. GS 3812. Estimates were based on a reactor power level of 10 MW when the primary

piping is between 1175° F. (635° C.) and 1225° F. (663° C.), the coolant-piping is between 1025° F. (552° C.), and 1100° F. (593° C.), and the reactor vessel and heat exchanger are at about 1200° F. (649° C.). For every anticipated reactor operating condition the maximum stresses were calculated to be well below the allowable stress range of 32,125 psi, as determined from the Code of Pressure Piping, ASA B31.1. The maximum stress in the piping system was estimated to be 7,700 psi, which occurs at the coolant-salt inlet nozzle to the heat exchanger. Calculated movements of the pump from the cold to the hot condition at 10 MW were: Δx (N-S) = .401 inch; Δy (E-W) = 0.335 inch; and Δz (vert) = 0.826 in…." ***pp. 174-175, 1-ORNL-TM-0728.***

1.2.5 Off-Gas Capture and Processing

The Gas Capture System should be vessel connected to the very highest point in the system that would bleed off gases such as Xenon^{135}. The vessel should be removable and replaceable when full. The System must accommodate the temporary storage of gas containment vessels while they cool and await post processing and disposal.

Reference: "*Off-Gas System - As previously mentioned, a portion (approximately 10%) of the fuel flow is bypassed through a gas stripping system. Directly above the fuel heat exchanger inlet header there are nozzles located in a plate to jet the fuel into the gas space. Helium is admitted into the expansion tank from a fuel pump purge at a rate of 1 scfh. This gas and the gaseous fission products stripped from the recirculating fuel are taken out of the fuel surge tank to primary holdup tanks, which are located in the main reactor cell. The effluent from these tanks is then circulated out of the system into two stages of cooled charcoal beds, which hold up the krypton and xenon. The purge gas, then essentially free from activity, is purged back into the reactor expansion tank. Parallel installations of charcoal beds and gas recirculating pump are installed in the system to ensure continuous operation…"* ***P. 16, ORNL-TM-2796***

1.2.6 U^{238} Denature System

An optional system is required that would hold a molten charge of U^{238} above the main reactor vessel. In an emergency, the molten slug would be injected into the fuel salt by a charge of nitrogen gas to destroy the fuel salt's viability.

1.2.7 – Heat Exchangers

Two (2) heat exchangers should be specified with multiple molten salt loops that cannot cross-contaminate in case of an internal rupture.

1.2.8 Hot Cell, Reactor Vessel

In general, the entire hot cell (which should contain the main pumps, the two salt loops, the two heat exchangers, the heat lines to the turbine hall, and the reactor vessel itself) should all be designed concurrently. The specifications for the reactor vessel will be delivered to the engineering company as per the final design. We are considering a tube within a tube system for the two-fluid Design that is approximately 3 meters in diameters and approximately 9 meters in length. It could be mounted on its side with a slight upward tilt towards the "hot" end. Each of the three design prototypes should take advantage of this overall elongated tube design approach, so that the ready evolution from first, to second, to third generation can be ultimately derived more effectively.

Reference:

"5.2 – Corrosion Behavior – Corrosion of Hastelloy N as a container for molten LiF-BeF$_2$ mixtures may originate from a very limited number of sources: from impurities in the melt, from oxide films on the metal and from mass transfer of metal constituents in the fluoride. Of these sources, only the latter, which is caused by the differential temperature coefficient for solubility of metals in salts, affords a mode of continuous attack in reactor systems that are protected from in-leakage of contaminants. In the early stages of MSRE operations, samples of flush salt were removed from the circuit at a rate of one per week. However, as our experience developed, and it was confirmed

that chronic sources of oxidizing impurities were absent, the frequency was decreased, finally to intervals of a month or longer….The results of the chemical analyses performed with coolant-salt samples showed that no measurable increase in the concentration of Cr, Fe, and Ni (with average values of 32, 64, and 20 ppm respectively) developed after the coolant salt was first charged into the MSRE. The fact that the chromium concentration remained unchanged is remarkable, since it indicates that within the limitation of the analytical precision (±7 ppm) no corrosion, excepting that possibly resulting from mass transfer, occurred in the coolant circuit during the entire period of MSRE operations. The demonstrated compatibility of the coolant salt with its containment alloy is believed to be unmatched in any prior experience with either molten salts or liquid metals as recirculating heat-exchange media…

6.0 – Corrosion in the Fuel Circuit - 6.1 – Modes of Corrosion -- It was noticed that the fluorides of commonplace alloy constituents such as iron, nickel, chromium, and molybdenum were less stable than the various compounds which might serve as components of molten-salt reactor fuels and coolants, and thus good alloys were potentially available. Subsequently, a materials development was initiated culminating in the development of the alloy now designated as Hastelloy N specifically for use in constructing the MSRE; its approximately composition was Ni-Mo-Cr-Fe (71-17-7-5 wt %). The basis for the selection of this exact composition is described by Taboada (1) in a detailed review of the allow development program.

The major components of the MSRE salts, LiF, BeF_2*,* ZrF_4*, and* UF_4*, are much more stable than the fluorides which can result from the corrosion of Hastelloy N – i.e.,* MoF_3*,* NiF_2*, and* FeF_2*. Thus, compatibility of the molten-salt mixtures and Hastelloy N was essentially assured.*

…Preponderantly, oxidation-reduction reactions are responsible for all the corrosion in molten-salt reactor fuel systems. The principal reaction which controls the process is

$$UF_4(d) + \tfrac{1}{2}\, Cr(a) \neq UF_2(d) + 1.2\, CrF_2(d),$$

For which the standard free energy at 727˚ C. is +15.1 kcal…” ***- Pp. 71-72, ORNL-TM-4658”***

“…3.2.4 – Hastelloy N – In this reference design of the MSBR, the material that is specified for nearly all of the metal surfaces contacting the fuel and coolant salts is an alloy which is a slight modification of the present commercial Hastelloy N. (The only exceptions are parts of the chemical processing system, which are made of molybdenum, and the infrequently used fuel storage tank, which is of stainless steel). The modified Hastelloy N anticipated in the MSBR design is currently in an advanced stage of development. It is very similar in composition and most physical properties to standard Hastelloy N, which has been fully developed and approved for ASME Code construction and was used successfully in the MSRE. The modified alloy is superior to standard Hastelloy N, however, in that it suffers much less loss of ductility under neutron irradiation. The design of the MSBR reactor vessel counts on this improvement, and throughout the description of the design in this report “Hastelloy N” means the modified alloy unless otherwise stated.

“…The metal in the reactor vessel and in the primary piping will be exposed to molten fuel salt at temperatures up to 705˚ C. on one side and to the cell atmosphere (95% N_2 *-5%* 0_2*) at 538˚ C. on the other. The anticipated service life is 30 years, during which time the most highly irradiated portions than ions of the reactor vessel will be exposed to a fast-neutron (E > 0.1 MeV) fluence of less than* 1×10^{21} *neutrons/*cm^2 *and a thermal-neutron fluence of about* 5×10^{22} *neutrons /* cm^2*.*

“…Hastelloy N is an alloy developed specifically for use in molten fluoride systems. Among the major constituents, chromium is the least resistant to attach by the fluorides. The chromium content of Hastelloy N is low enough for the alloy to have excellent corrosion resistance toward the salts. (The leaching of chromium is limited by the rate at which it can diffuse to the surface.) The chromium is high enough, on the other hand, to impart good oxidation resistance toward the cell atmosphere. The molybdenum content was adjusted to give good strength without an embrittling second-phase formation. The resulting alloy has very good physical and mechanical properties. …Hastelloy N was explosed to salt at about 649˚ C. for 22,000 hours. Corrosion was very moderate, with chromium leaching equivalent to complete removal from a layer only 0.2 mil deep (Surveillance specimens showed a chromium gradient to a depth of 2 mils.) Oxidation on surfaces exposed to the cell atmosphere amounted to only 2 mils. However, surveillance specimens exposed just outside the reactor vessel and at the center of the core showed marked reduction in fracture strain and stress-rupture life due to neutron irradiation. In the MSBR reference design the metal in the vessel walls is protected by a thick graphite reflector and sees a fast-neutron fluence only on the order of 1×10^{21} *neutrons/*cm^2 *(actually* ***less*** *than was received by core specimens in the MSRE).*

This fast-neutron fluence is too low to produce the swelling or void formation that is associated with the metal used for cladding of the fuel in fast reactors. The major concern in developing an improved alloy was therefore not fast-neutron damage but the ***production of helium in the metal****, primarily due to the thermal-neutron transmutation of* ^{10}B *to* ^{4}He *and* ^{7}Li*.*

"Boron is an impurity of Hastelloy N that comes from the refractories used in melting the alloy. Careful commercial practice makes it possible to produce alloys containing 1 to 5 ppm boron (18.2% of natural boron is ^{10}B*). Irradiation tests, however,* ***show that the amount of helium (and thus boron) required to cause embrittlement is so low that even alloys containing 0.1 ppm of boron are badly damaged in this respect*** *(see: H.E. McCoy, Jr., and J.R. Weir, Jr., "Stress-Rupture Properties of Irradiated Hastelloy-N Tubes," Nuclear Appl. 4(2), 96-104 (February 1968). The strong influence of such a small quantity of boron is due to the segregation of boron at the grain boundaries, where helium production can have a profound effect on the fracture behavior. It was thus concluded that the problem of irradiation-induced embrittlement could not be solved by reducing the boron level.*

The embrittlement problem was addressed by adding alloying metals, such as titanium, niobium, zirconium, and hafnium, so as to form borides that would be dispersed as precipitates and not particularly segregated at the grain boundaries.

This approach proved successful, with a fine dispersion of MO-type carbides giving the most desirable properties (see: H.E. McCoy, Jr., "Influence of Titanium, Zirconium, and Hafnium Additions on the Resistance of Modified Hastelloy N to Irradiation Damage – Phase I, ORNL-TM-3064 (January 1971).

The post-irradiation fracture strains of several promising alloys are shown in Fig. 3.1.3. (Although the fluence received by these specimens is low compared with that expected in the MSBR, over ½ of the boron will have been transmuted at the 5×10^{20} *–neutron/cm*^{2} *fluence level, and there is relatively little change in ductility beyond this point.)*

To obtain the desired structure and welding properties of the modified alloy, close control is required of the concentrations of titanium, niobium, and hafnium.

Successful highly restrained test welds have been made in ½-inch-thick plat using alloys containing 1.2% titanium, 0.5% hafnium, combined 0.75% hafnium and 0.75% titanium, and combined 0.5% titanium and 2% niobium.

Zirconium induced severe weld metal cracking and is no longer considered as a constituent.

The composition of the Hastelloy N for the MSBR has not been optimized, but the anticipated values are given in Table 3.5.

The corrosion resistance of the modified material has been tested and specimens have been exposed in the MSRE core. The melts used to date have <0.1% iron and have even lower corrosion rates than observed for the standard alloy with 4% to 5% iron. Iron does not serve a critical role in the alloy and could be removed to give a lower corrosic rate in sodium fluoroborate should this prove to be necessary. The presence of titanium and the other reactive metals will not contribute appreciably to the corrosion rate at the anticipated concentrations. The molybdenum was dropped from 16% in the standard material to about 12% in the modified alloy to obtain the desired carbide." ***Pp. 26-28, ORNL-TM-4541.***

1.2.9 Drain Tank and Pipe Heating System

The tanks and pipes require an external heating system that will heat up the salts to melt them. The molten salt is then pumped to the top of the reactor loop in the hot cell.

1.2.10 Insulation

A suitable removable insulation should be specified that will be able to withstand 1,000° C. for an indefinite amount of time without degradation.

1.2.11 Instrumentation and Viewing Ports

Sensors and remote monitoring systems should be specified to enable remote operation of all reactor systems. Visual inspection systems, sight glasses, and fuel quality monitoring and characterization should be specified. Our colleague, Robert Steinhaus, will be put in touch to assist in these remote monitoring technologies.

1.2.12 Graphite and Control if needed

A source for and design of a graphite moderator with cost estimates for optional control rod insertion system is called for here.

1.3 Command and Control

The MSR is highly self-regulating and is classified as a 'load follower'. The system's basic operation lets it follow loads without any outside control. This does not negate the requirement, however, that there must be a sophisticated monitoring and control system in place, especially since several facilities should be able to be controlled by a central controller.

1.3.1 Software

1.3.2 Monitoring / Measurement / Reporting Instrumentation

1.3.3 Back-up Reserve Power Systems

1.3.4 Theory of Operation (proposed Standard Operating Procedures Manual)

1.3.5 Schedule for Maintenance Program

1.3.6 Remote Monitoring / Measurements / Diagnostics for Maintenance

1.4 Flow Diagram

A complete visual flow process for the system is required here. Fuel Salt Loop, Blanket Salt Loop, Secondary Salt Process Heat Loop, Drain System, Turbine System, with call-outs for presence of sensors, sight tubes, and other major components are required here.

1.5 Refueling and Salt Processing Conceptual Procedures

A separate system for spent fuel processing and on-line refueling should be proposed.

1.6 Components and Materials List (Bill of Materials) and Cost Estimate

A complete Bill of Materials with component-level costing for the equipment (keeping the structures costs separate if possible) should be linked to the CAD so that each component can be located in the design. Other data that should be available in columns: Suppliers, Number per Unit, Isometric View of each, the Designer, Manager, and Program Section, its Availability, and its ETA if not currently in stock.

Section 2: Site Planning and Development

The Facility Design should place as much of the operating system as possible well below grade. A great deal of earth works is required. The removed material is then used for a security berm with setbacks to IAEA international standards. A control building may be remotely located. Alternatively, a single central control building can be specified to operate several remote sites. Local controls should also be available for each facility -- separate and apart from the dedicated control function. In all cases, an access building is required to support on-site maintenance for each generator facility.

Basic plans and cost estimates for all specified buildings and structures are required in this Estimate – without regard to land cost. The type of land for the proposed first facility will be provided so that an accurate estimate of the difficulty of excavation can be made.

2.1 Standard Location Plan

2.2 Setbacks and Security

2.3 Earth Works

2.4 Architecture

2.4.1 Control Building

2.4.2 Maintenance Hall

2.4.3 Sub-Grade Fuel Drain Tanks and Reprocessing Systems

2.4.4 Turbine Hall

2.4.5 Sub-Grade Containment Structure for Hot Cell

2.4.6 Sub-Grade Pipe Hall / Galleries

2.4.7 Hot Cell Structure

2.4.8 Equipment Pedestals

2.5 Transformer Yard / Grid Interconnect Project Plan

The utility-interconnect for a 200 MW output should be specified for Prototype designs one and two. The utility-interconnect for a 100 MW output should be specified for Prototype design three. The specific utility will be given so that an accurate accounting of equipment and controls can be made.

Section 3: Turbine Design and Specifications

3.1 Secondary Process Heat Loop

An estimate for using the heats for processes such as water desalination (multi-effect distillation) should be provided.

3.2 Rankine

Cost and integration of a standard, commercially available system should be provided.

3.3 Wet Steam

Cost and integration of a standard, commercial available system should be provided.

3.4 Open Cycle Gas Turbine modified for molten salt loop heating of flue gas

Gas Turbine Department of Czech Institute of Technology, Czech Republic shall be made available for consultation on this requirement.

3.5 Brayton Closed Cycle (Supercritical CO_2)

Estimated cost of commercialized Brayton cycle system should be derived from the Prague Brayton organization, and the Gas Turbine Department of Czech Institute of Technology, Czech Republic which shall be made available for consultation on this requirement.

Section 4: Balance of Power

Calculations and simulation of balance of power and load following capability of the MSR are required here.

Section 5: Areas Not Covered By This P.I.D.:

New Materials Development

Molten Salt Re-Processing
    Actinide Byproduct Removal, other than Xenon^{135}
    Rare Earth Removal

Molten Salt Production Facility

Appendix A.

We will build a new molten salt LFTR research reactor with three validation test intermediate loops. Dr. Ralph Moir and Dick Engel have urged us to access the myriad vellum engineering illustrations generated in support of the original MSRE as a primary resource to follow.

While a number of engineering drawings have been located both in the MSRE building and elsewhere within ORNL, the consensus has come back to access a different, and more thorough resource:

A series of documents that went into great detail in describing the decisions and their background on the design and operation of the Molten-Salt Reactor Experiment.

The following references are available in the preparation of the vendor's response:

Program Plan for Developing Molten Salt Breeder Reactors
http://twugbcn.files.wordpress.com/2011/07/ornl-5018.pdf

Conceptual Design Study of a Single-Fluid Molten Salt Breeder Reactor
http://twugbcn.files.wordpress.com/2011/07/1__ornl-4541.pdf

Conceptual Design Characteristics of a Denatured Molten-Salt Reactor with Once-Through Fueling
http://twugbcn.files.wordpress.com/2011/07/ornl-tm-7207.pdf

MSRE Design Study
http://twugbcn.files.wordpress.com/2011/07/1ornl-2796_1960-msr-design-study.pdf

Description of Reactor Design
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-0728.pdf

Nuclear and Process Instrumentation-1
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-0729a.pdf

Nuclear and Process Instrumentation-2
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-0729b.pdf

Nuclear Analysis
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-0730.pdf

Chemical Aspects of the MSRE
http://twugbcn.files.wordpress.com/2011/07/1msre-chemical-aspects_ornl-4658.pdf

Reactor Safety Analysis Report
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-0732.pdf

Safety Analysis of Operations with ^{233}U
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-732a.pdf

1st Rev: Operating Limits
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-0733.pdf

2nd Rev: Operating Limits
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-0733rev.pdf

3rd Rev: Operating Limits
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-0733rev2.pdf

4th Rev: Operating Limits
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-0733rev3.pdf

Fuel Handling and Processing Plant
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-0907.pdf

MSRE Operator Training and Operating Techniques
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-3041-msr-operating-procedures.pdf

Safety Procedures and Emergency Plans
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-0909.pdf

Maintenance Equipment and Procedures
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-0910.pdf

Test Program
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-0911.pdf

Test Program for ^{233}U Operation
http://twugbcn.files.wordpress.com/2011/07/1ornl-tm-2304.pdf

MSRE Fluid Dynamic Studies
http://twugbcn.files.wordpress.com/2011/07/1__fluid-dynamic-studies_msre.pdf

Critique of the Molten-Salt Reactor Experiment: A Collection of Comments Submitted by Persons Associated with the Reactor
http://twugbcn.files.wordpress.com/2011/07/1cf-70-9-3_afteraction-critique-of-msre.pdf

Thermal-Stress and Strain-Fatigue Analyses of the MSRE Fuel and Coolant Pump Tanks
http://twugbcn.files.wordpress.com/2011/03/ornl-tm-0078.pdf

Development of Fuel- and Coolant-Slt Centrifugal Pumps For The Molten-Salt Reactor Experiment

http://twugbcn.files.wordpress.com/2011/03/ornl-tm-2987.pdf

Spray, Mist, Bubbles, and Foam In The Molten-Salt Reactor Experiment

http://twugbcn.files.wordpress.com/2011/03/ornl-tm-3027.pdf

Magnetic Drive Pumps

http://twugbcn.files.wordpress.com/2011/03/1__magnetic-drive-pumps.pdf

http://www.klausunion.com/mag-drive-pumps/features/mag-drive-cutaway.php

Depictions of Molten Salt Reactor Configurations