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SUBJECT: Proposal for Fused Salt Power Reactor Study Group

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PROPOSAL FOR FUSED SALT POWER REACTOR STUDY GROUP

I. Purpose

The purpose of the study is to investigate the technical and economic feasibility of producing power from a nuclear reactor using a fuel composed of circulating fused salts and to carry out the design of such a reactor.

II. Advantages of the Fused Salt System

The most important advantages offered by a fused salt system for power reactors are those arising from the use of a high temperature liquid fuel at low pressure. The high temperature yields a high over-all thermal efficiency and makes it possible to insert intermediate heat exchangers and still use the most modern steam generators. The thermal expansion characteristic of the liquid fuel provides a negative temperature coefficient of reactivity and thus makes the reactor self regulating. The circulation of the liquid fuel allows the continuous removal of fission product poisons and the convenient addition of fuel makeup. The fact that the fuel is liquid eliminates the fabrication of solid fuel elements and paves the way for cheaper chemical processing. The low pressure improves the safety of the reactor with respect to the possibility of the explosive dispersion of radioactivity. It also eliminates the difficulties in providing high pressure components for the reactor system.

The use of a fluoride salt with its moderating properties allows consideration of a truly liquid and homogeneous reactor operated at high temperatures. Thorium fluoride can be dissolved in the salt allowing a homogeneous converter or breeder reactor without recourse to slurries. No other reactor system offers all of these advantages.

It is believed that the advantages cited will make the cost of power from this reactor system less than for most other known reactor systems. Although it is recognized that it is impossible to estimate closely the cost of power from the reactor until a large part of the design has been completed, a general analysis of reactor costs is presented in Appendix A. From broad considerations, it is shown that it should be possible to produce electricity using present technology in a plant of approximately 200,000 kilowatts electrical capacity for a total cost of less than 10 mills/kw hr.

III. Present Status of the Problem

As a result of the intense effort expended on the fused salt aircraft reactor over the past several years, the necessary technology for a simple power reactor is much farther advanced than is commonly realized. Enough has been learned about fused salts and how to handle them that it should very soon be possible to proceed with the detailed design and construction of a simple reactor to burn U-235 and produce power at high thermal efficiency.

This simplest form of reactor would consist of a large vessel containing a fused NaF-ZrF_4-UF_4 salt to act as both fuel and moderator, the salt to be circulated through a primary heat exchanger to extract power. Since delayed neutrons from the fuel will make the first heat exchanger fluid radioactive, an intermediate heat exchanger can be used so that the fluid in the steam boiler will not be radioactive. The intermediate heat exchanger fluid may be either a salt or sodium, and sodium or sodium-potassium alloy will probably be used as the final heat exchanger fluid to operate the steam boiler.

The maximum temperature of the salt, the temperature drop through the heat exchanger, the uranium content and the power density are all so much less than for the aircraft reactor that the problems of corrosion, mass transfer and

reactor control are greatly simplified. At this stage, the principle concern over the reliability of a power reactor is with the steam boiler heated with non-radioactive sodium, a problem common to other high temperature systems. Appendix B lists some of the items that have been developed for the ANP program that can be adapted quite directly to this simple power reactor. The first part of Appendix C lists the new experimental work that should be undertaken and completed before design of this reactor has reached an advanced stage.

The fused salt system has many possibilities for improvement over the simple burner reactor and these should be examined carefully before freezing on any one design for initial construction. It is probable that these improvements in design over the simple burner will require additional experimental and development work before they can provide the same degree of confidence in their reliable operation.

The simplest modification is that of providing some degree of conversion or breeding to reduce the fuel costs. Preliminary calculations indicate that this can be done by the addition of thorium fluoride to the salt and by increasing the uranium concentration. The resulting reactor would operate on intermediate energy neutrons and thus reduce the parasitic capture by the components of the fused salt. If such a reactor could be fueled initially with U-233, a breeding ratio of not too far below one should be possible, provided that the recently discovered low value of η for U-233 at 2 volts does not extend to much higher energies.

A second modification consists of altering the salt to remove the neutron absorbing elements and also to improve the moderation. This would then provide a slow neutron breeder or converter reactor. The salt in this case might be a mixture of Li^7F, BeF_2, UF_4 and ThF_4, and a graphite or other solid moderator or reflector could turn out to be a desirable addition. This modification has an

obvious long-term desirability since it would eventually operate entirely on bred fuel; however, the procurement of Li^7, the greater care needed in handling the beryllium salt, and the introduction of graphite or other solid moderator either require additional research and development or otherwise complicate the early construction of such a reactor.

A third modification that should be kept in mind is the plutonium breeder. Previous studies have been made of this reactor and it is indicated that a fused chloride salt mixture should be used in place of the fluorides. Such a reactor would require a blanket containing a high U-238 concentration. It is also probable that the chloride salt should be made with a separated chlorine isotope to avoid the loss of neutrons through the (n,p) reaction of chlorine-35. Although the problems to be solved before the first fused salt plutonium breeder reactor could be built would, at first glance, seem considerably more difficult than for the other fused salt reactors, nevertheless, comparison with other proposed fast plutonium breeder systems indicates that the fused salt version may be preferable.

The simple burning of plutonium should be readily feasible in a fused salt reactor. "Fuel grade" plutonium containing appreciable Pu-240 is desirable, since the Pu-240 would be regarded as a fertile material. The major problems of the plutonium burner would be with the chemical stability of its salts and the fact that a fuel reprocessing method is yet to be developed.

Although a part of the work of this study group will be to determine areas for which additional experimental work is required, a number of items that should receive experimental attention are listed in Appendix C.

IV. Scope of the Proposed Study

It is proposed that this reactor study should proceed with the following general approach:

1. To examine various fused salt reactor designs in sufficient detail so that their relative desirability can be determined.
2. To determine the nature of and to initiate the additional experimental work and development engineering studies needed for further advancement of the desirable types.
3. To carry through with the design of a complete reactor system selected as the best compromise between practicality of early construction and the ultimate desirability of its features. The final report covering the design of this reactor will include as much detail as the manpower available will permit, and should be complete enough to permit a competent group to proceed with the detailed engineering and construction of the reactor.

V. Estimated Time Schedule

The following goals are set up as a general guide. It must be realized that unforeseen developments may cause changes in the planned schedule of events.

1. It is expected that by December 1, 1956, a tentative reactor configuration most suitable for detailed study will be decided upon by the study group.
2. After December 1, 1956, approximately 80 percent of the effort of the study group will be expended on working out the details of the selected reactor system. The remainder of the study group effort will continue to be expended on other modifications, on the basis that improvements in fused salt power reactors will depend on continuity of effort in exploring their possibilities.

3. By July 1, 1957, the reactor study should have progressed far enough so that an engineering group can start preparing detailed working drawings of parts of the reactor system. It should be possible to start construction of a reactor by July 1, 1958. The dates given presuppose that the reactor system selected for detailed study be a simple modification of the burner.

4. Experimental work in testing the long-time corrosion resistance of the most promising alloys will be started as soon as possible. Other experimental work in the Chemistry, Metallurgy, Chemical Technology and Solid State divisions of the Laboratory will be initiated and supported as indicated by the results of the study and as funds become available. As the design of the selected reactor system progresses, it is expected that some members of the study group may become involved in experimental research and development of components in cooperation with the regular departments of the Laboratory.

VI. Proposed Manpower and Budget

The persons at present available to work on this reactor study are:

H. G. MacPherson, leader
L. G. Alexander
D. A. Carrison
B. W. Kinyon
L. A. Mann
J. T. Roberts
F. C. VonderLage
Dorothy Smith, secretary

The estimated cost of supporting this group for fiscal 1957 and of starting the most necessary of the supporting experimental work is $200,000. It is anticipated that the strong desirability of supporting additional experimental work will be apparent before the end of fiscal year 1957 and that additional funds may be requested.

APPENDIX A

ECONOMIC CONSIDERATIONS IN THE PRELIMINARY DESIGN OF A FUSED SALT POWER REACTOR

It is recognized that without a specific reactor design for which the engineering has been completed, costs can only be arrived at by a very general approach. In the following write-up (prepared by D. A. Carrison), this general approach has been maintained, and it is believed that the figures are conservative and tend to overestimate the costs of the second reactor power station of this type. The calculations are made for a reactor that delivers 600 megawatts of heat and approximately 210 megawatts of net electrical power.

In the consideration of power costs from a nuclear fueled electrical generating plant, a convenient breakdown of cost factors is as follows:

1. Conventional turbogenerator plant
2. Operation and maintenance
3. Reactor complex
4. Fuel inventory
5. Fuel burn-up
6. Chemical processing

For a fused salt reactor heat source, steam temperatures of the order of 1000°F and pressures of about 1800 psig can be assumed. These conditions will not vary widely with different reactor designs. The installed cost of Item (1), the conventional plant, will be near to $110/kilowatt of capacity. For an 80% load factor and 14% per year charge, this amounts to 2.2 mills/kwh.

For Item (2), operation and maintenance, a figure of 1 mill/kwh can be assumed, which again will not be a variable depending on the reactor type to any great extent.

Cost of Item (3), the reactor complex, will vary with the reactor type, but probably not so widely as to be a compelling factor in determining the type chosen. If we are fairly conservative, a capital cost of perhaps $140 per kilowatt of installed electrical capacity can be assigned for a straight burner type. Going to a breeder might run to $170 per kilowatt. These costs would add 2.8 mills/kwh and 3.4 mills/kwh, respectively, for a variation with reactor type of only 0.6 mills per kilowatt hour.

It is thus obvious that the only important cost variables that are dependent on which fused salt design is chosen are the last three items, i.e, fuel burn-up, fuel inventory and chemical processing.

For a straight burner type, estimating that 94% of the fission energy is converted to heat, 35% of this heat converted to electrical energy, and that fuel costs $17 per gram, a fuel burn-up cost of 2.7 mills/kwh is calculated. A successful breeder under the same conditions may receive a fuel credit of as much as 0.3 mills/kwh, for a fuel burn-up cost variation, between the extremes, of 2.7 plus 0.3 or 3.0 mills/kwh. This is indeed an important difference. Offsetting this possible gain, however, are indisputably higher costs for fuel inventory and chemical processing.

The fuel inventory figures of the two 1956 ORSORT summer groups dealing with a breeder and a burner are 360 kilograms for the burner and 1958 kilograms for the breeder. At $17 per gram cost and 4% yearly charges, these inventories are responsible for costs of 0.16 and 0.7 mills/kwh, respectively.

It is believed that the burner could be operated for years with no chemical processing by making modest additions of uranium inventory; however, the maximum chemical processing costs for the burner have been estimated on the basis of processing the fused salt fuel once every two years, recovering only the uranium

and throwing the rest of the salt away. The fluoride volatility process under current pilot plant development was postulated, and the present high salt cost was used. On this basis, chemical processing should add no more than 0.5 mills/kwh.

Chemical processing costs for the self-sustaining breeder are unquestionably higher than for the burner, and there may not be a great economic preference for either. However, it is very likely that a converter or breeder with a ratio of less than one will provide improved fuel economy without greatly increasing the chemical costs, and that this type of reactor will produce the cheapest power. In any case, a fused salt reactor should produce power for less than ten mills per kwh when built in this size.

Our cost breakdown now looks something like this:

		Cost (mills/kwh)	
Item		Burner	Breeder
1. Conventional turbogenerator plant		2.2	2.2
2. Operation and maintenance		1.0	1.0
3. Reactor complex		2.8	3.4
	sub total	6.0	6.6
4. Fuel burn-up		2.7	0
	sub total	8.7	6.6
5. Fuel inventory		0.2	0.7
	sub total	8.9	7.3
6. Chemical processing		0.5	2.0
	TOTAL	9.4	9.3

APPENDIX B

ADAPTABILITY OF PRESENT FUSED SALT TECHNOLOGY

As a general statement, present data and knowledge are sufficient to design, build and operate a 600 Mw power reactor, using Inconel as the container material for salt and liquid metal. The following items can be adapted or designed from appropriate ANP developments:

1. A suitable circulating fused salt (NaF-ZrF_4-UF_4) fuel
2. Salt to Na or NaK heat exchanger
3. Fused salt pumps
4. Na or NaK pumps
5. Na, NaK and salt flow control valves
6. Na, NaK and salt shutoff valves
7. Level, flow, pressure and temperature measuring and controlling devices
8. Nuclear instrumentation and controls
9. Fill-and-drain tanks and storage tanks for salts and metals
10. Helium or argon blanket gas system
11. Oil or grease-lubricated pump shaft bearings
12. Fission gas removal equipment
13. Molten salt and liquid metal sampling devices
14. Devices for safely enriching the fuel

None of the above items are in a really doubtful category, except the life expectancy of container materials which will certainly be years (instead of months). Some items, including the reactor vessel, the pumps, the heat exchangers, the valves and instrumentation, will be based on experience less massive and detailed than for coal-fired boilers, for example, but the experience is with

real hardware and in numbers of tests sufficient to support solid confidence of successful operation for years.

In addition to the above hardware items, there is an abundance of technical data collected on the ANP program that will be useful in designing and calculating the performance of a fused salt reactor. These include:

1. Phase diagrams of various fused salt mixtures
2. Viscosity, density and heat transfer data on fused salts
3. Corrosion characteristics of various alloys in fused salts and liquid metals. In particular, the nickel-molybdenum alloy developments give hope of really long-life reactor parts.
4. Knowledge of the radiation stability of the fused salts
5. Development of a volatility process for the recovery of uranium from the fused salt
6. Operating data and experience with the ARE to give an understanding of the hazards and yet give confidence in the reliability and stability of the fused salt system

APPENDIX C

EXPERIMENTAL AND TESTING PROGRAMS THAT WILL BE DESIRABLE FOR THE FUSED SALT POWER REACTOR

It is believed that the three items in Group I below are most urgent in the sense that they should be completed before the first power reactor is built. The experimental problems in Group II are now known to be desirable for further study for the fused salt power reactor to reach its maximum potential. It is expected that our reactor study will determine more certainly the relative importance and priority of these items.

Group I.

1. To establish more firmly the lifetime of suitable alloys in contact with fused salt and with sodium under our temperature condition, new long-time test loops should be started as soon as possible. The two metals deemed most suitable are Inconel and a ductile nickel-molybdenum alloy. These loops should operate for a year, and if the expected low rate of attack is obtained, an estimate of the performance over several years can be obtained. Conditions desired are:

   a. maximum temperature - 1250°F

   b. maximum temperature differential, between hot and cold legs - 200°F

   c. turbulent flow

2. The sodium-to-water heat exchanger or boiler will also require additional development work. This problem is under investigation by other groups, and after we have become thoroughly familiar with their results, it is fully expected that additional engineering development will be desirable.

3. The processing of the reactor core and blanket fluids, preferably continuously, to remove fission and transmutation products, while not essential to the operation of a burner, is, nevertheless, of sufficient importance that a considerable research

and development effort should be mounted immediately. The development of suitable processes is essential to obtaining economic power from a breeder and would lower the cost of power produced in a burner.

Group II.

1. The introduction of substantial quantities of thorium will necessitate research on new salt compositions to keep the melting point of the salt to the desirable low limits. Studies of the corrosion behavior and physical properties of any new salts will require investigation.

2. The effects of fission product build-up on the corrosion by the salt and on its physical properties should be determined.

3. Work should be continued on obtaining better container materials, particularly those with a lower neutron cross section, so that a two region reactor would be more attractive.

4. Determine the chemical state of fission products in a fused salt fuel.

5. Determine the compatibility of graphite with our system. Particular problems include the soaking of salts into the graphite pores and the carburization of the container metal.

6. Study the problem of removal of protoactinium from fused salts.

7. Develop a suitable salt combination for a plutonium burner and for a plutonium breeder. Devise a process for recovering plutonium from the fused salt.

8. Design and proof test replaceable seals and bearings for pumps and heat exchanger sub-assemblies, and procedures for such replacements.

9. Optimize equipment and procedures for handling off-gases.

10. Develop and proof test shutoff valves for molten salts and liquid metals.

11. Devise and test means of maintaining liquid levels in fluid circuits with more than one free surface. (This is important in deciding whether more than one gas-sealed pump should be included in the same liquid circuit.)

12. The program on determination of better nuclear cross sections should be encouraged. In particular, the determination of η for U-233 for intermediate energy neutrons is of great importance.

A P P E N D I X   D

PROGRAM OF THE STUDY GROUP

1. Nuclear System - Nuclear calculations of critical mass and neutron balance will have to be made for a number of different reactor configurations and compositions so that the most promising ones can be selected. Configurations that must be evaluated nuclearly are:

   a. Homogeneous salts of several compositions, with and without the inclusion of fertile materials.

   b. Heterogeneous systems with various moderator configurations.

   c. Both single and two region configurations should be considered.

In addition, the effects of fission product build-up and heavy element build-up must be determined. This problem will be complicated by the high energy of the average neutron flux in some of the reactors considered, and by the long time of operation desired.

2. Thermo-Hydrodynamic System - Combinations of various modes of heat transfer with various thermodynamic cycles will be studied. The over-all thermodynamic efficiency, heat transfer areas, pressure drop and pumping power will be computed for these and compared. This study will include, for example, the possible use of salts as intermediate heat exchanger media in place of sodium.

3. Mechanical System - Structural design of components compatible with the requirements of combinations of the two preceding systems will be performed. Vessels, supports, connections, closures, etc., will be designed for thermal and mechanical stability. The gas removal system, including charcoal beds for gas holdup, will be studied. Specifications will be arrived at for the approximate size and design of components, including pipe sizes, valve locations, heat

exchanger sizes and locations, tentative component locations, and building design, including necessary shielding. Possible suppliers and fabricators of components will be determined.

4. Control System - Nuclear control by use of negative temperature coefficient, control rods and variation of fuel concentration will be investigated. The control problem will be broken down into the following: a) normal operation with load changes; b) long-term transients with fission poison, transmutation product build-up and burn-out effects considered; c) startup transient; d) normal shut-down transient; e) emergency shutdown; f) emergency operation, as during the replacement of an exchanger.

5. Chemical System - Problems considered will include conception and design of systems for continuous or periodic removal of fission products, removal of transmutation products, and reprocessing the fuel to recover U-235, Pa and U-233. The chemistry of plutonium and thorium salts will require study.

6. Biological System - The leakage of radioactive poison, chemical poisons, and radiations from the reactor and auxiliary systems will be considered. Methods of containment, shielding and monitoring will be developed.

7. Cost of Power - A detailed economic study will be made as soon as the reactor components have been ascertained.