A NUCLEAR WASTE STEAM PLANT CONCEPT

By
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1. INTRODUCTION AND BACKGROUND

In 1973, Dr. Harold Hollis of the Corps of Army Engineers at Fort Belvoir proposed to the DOD's Advanced Research Projects Agency (ARPA) that a study be undertaken to examine a possible military utilization of nuclear wastes.* Specifically, the Army Engineers wanted to explore the feasibility of plants which would be fueled by canisters of solidified high-level wastes from the U.S. civilian nuclear power industry and would produce 350°F saturated steam in power-quanta of 5-MW; that is, ~17,000 pounds of steam per hour. As evident from a recent paper by Hollis [1], a 5-MW system could provide peak-load heat to a military hospital and a 10-MW plant could provide base-load heat for an average, large troop installation (40,000 people).

The Army Engineer proposal reached ARPA about the same time as did a R & D Associates proposal on another nuclear-waste utilization concept. ARPA got the two parties together and a modest, one-year contract for a military base, steam-plant study was awarded to RDA just about a year ago. The Army Engineers at Fort Belvoir have administered the contract on behalf of our ARPA sponsor.

My purpose here today is to present a brief description of the few-man-year, RDA study and its major findings. Our work has been detailed in three quarterly reports [2, 3, 4] and a final report will be issued in the month ahead.

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*Dr. Hollis is attached to the Corps' Facilities Engineering Support Agency (FESA).

At the outset, I want to acknowledge the major engineering contribution of RDA's L. A. Gore who has, during the course of this program, developed a series of conceptual plant designs, including the one I will describe today. Also, our study has benefited from direct communications with Al Platt's people at the Battelle Northwest Laboratories and, of course, from the waste-solidification technology documented in Battelle reports. In 1969 Battelle's D. W. Bolme determined the power and radiation properties of solidified wastes by detailed machine computations and briefly discussed the potential of using mixed fission products as a source of energy; Bolme's work has been particularly useful to our program [5].

Finally, I want to point out that ours is not the first study on the military steam plant application of nuclear wastes. To my knowledge, Commander Joseph Renzetti, USN, was the first to examine the idea; his work is reported in a 1973 Pennsylvania State University master's thesis [6]. However, a particular and an important difference between Renzetti's work and ours exists. Renzetti's plant permits the water, which is ultimately delivered as steam for human use, to contact the nuclear-waste canisters, whereas our work is contractually constrained to a study of plants where no such contact could occur. This constraint is, we believe, a logical one and, in fact, it may be a necessary one for ultimate acceptance of the concept, per se.

The basic objectives of our study have been twofold: (1) to determine concept feasibility; and, (2) to develop a conceptual plant design which conforms with a few broad specifications provided by the Army Engineers. These specifications direct us to the design of a 5-MW plant which would output ~17,000 pounds/hour of 350°F saturated steam and which would have a 25-year life. And, of course, the design must conform with the constraint which I just mentioned; namely, the output steam molecules are not to touch the plant's nuclear-waste bearing canisters.

2. ON SOURCE SUFFICIENCY

To establish concept feasibility, the first obvious step is, of course, to determine whether or not the U.S. civilian nuclear power industry will, in fact, generate sufficient solidifiable wastes to fuel one or more 5-MW steam plants. Because of expected heat losses in a real system, we would actually need about 6-MW of nuclear-waste decay power to realize a plant with a thermal output of 5 MW.

Fig. 1 shows a forecast of the total decay-power of the solidifiable wastes that would be generated by the nation's power-reactors if they continue to be installed in parabolically increasing numbers as has been predicted by some recent AEC projections [7]. The forecast curves are labeled according to the age of wastes at the time of solidification. As noted on the Fig., the forecast assumes that all source reactors are light water types, whereas some forecasters expect minor, but significant, penetrations by breeders and gas cooled systems by about 1990. A simple model was normalized to the rigorous work of Battelle's Bolme for the purpose of the forecast shown in the Fig.

It is seen that sufficient decay-power (i.e., ~6 MW) could exist as early as ~1977 if all industrial wastes with ages above one year are solidified by that time. Actually, as I will discuss a little later, it may be economically logical (from both the solidifier's and user's viewpoints) to solidify wastes when they are about 4-years old. In this case, a first 5-MW plant might be fully fueled by ~1982. By the end of this century, it is indicated that some 40 5-MW plants might be fueled from wastes generated by U.S. civilian power reactors (solidification of 2- to 4-year-old wastes implied).

In passing it may be noted that an 80 percent efficient oil-fired boiler would consume some 1.5 million gallons of oil annually to produce 5 MW of steam. Hence, near 1980 this amount of oil might be saved for other, more

FIG I

FORECAST OF DECAY POWER
IN
SOLIDIFIABLE FISSION-WASTES

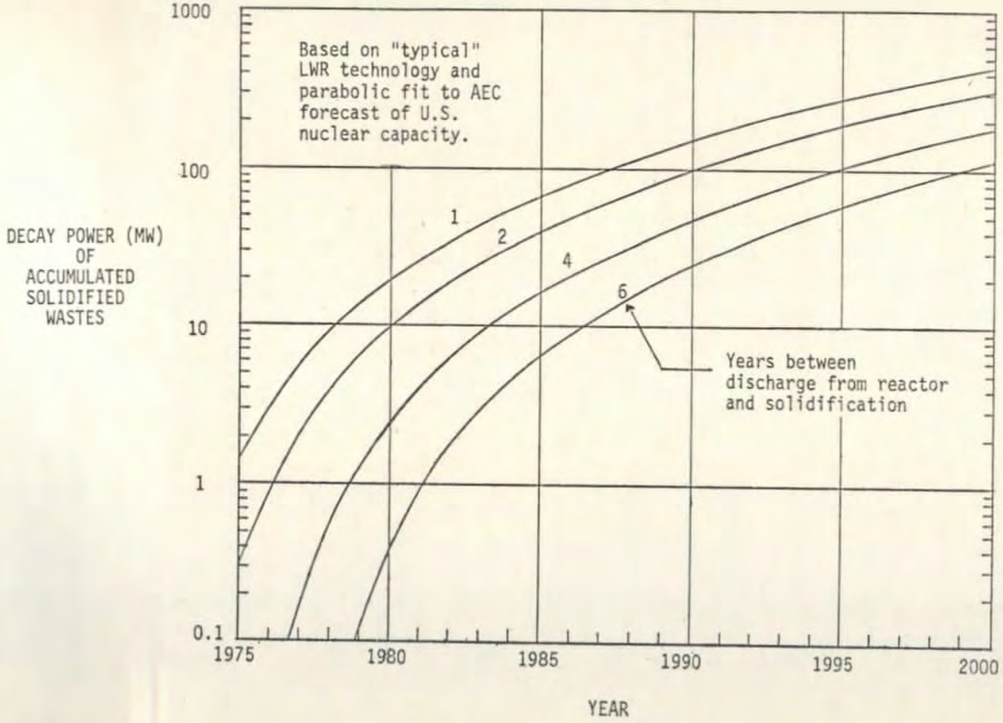


FIGURE 2

"Typical" AEC CANISTER

SIZE

6 TO 24 INCH DIAMETER

2 TO 10 FEET LENGTH

12 INCH DIAMETER × 10 FEET LENGTH TYPICAL

MATERIAL

300 SERIES STAINLESS STEEL

HEAT

<1 TO 20 KW

5 KW TYPICAL

NOTE: Figure taken from Nuclear Technology 24, December 1974, with permission.

vital, uses such as transportation. At the year 2000, the annual fuel-oil savings might reach the 60-million gallon level.

As most of you know, the decay-power of few-year-old wastes is truely miniscule relative to the fission-power of the reactor which produces the wastes (i.e., decay power is $\sim 10^{-4}$ of the fission power). However, as previously noted, 5-MW blocks of thermal power are not insignificant for certain military applications (i.e., hospitals and base-load heat) according to the Army Engineers [1]. In any event, in the final analysis, the existence of such plants may be motivated by reasons other than the obvious fuel-saving rationale. For example, a military base steam plant, while saving some energy, certainly provides secure interim storage for its radioactive canisters (i.e., secure from possible terrorists' attacks).

3. OUR ASSUMED "FUEL ELEMENT"

Fig. 2 shows what the AEC/ERDA organization has visualized as a likely "typical" canister for the containment of future solidified wastes. We have assumed a similar-sized, stainless steel canister for our steam plant's fuel elements. Our elements would consist of nominal 1-ft diameter by 10-ft long cylindrical blocks of borosilicate glassified wastes encapsulated in 3/8-in. thick canisters of similar diameter and length. The element would weigh about a ton and be similar in size and shape to a 10-ft length of telephone pole.

Fig. 3 shows the decay-power history of such an element which contains (maximum concentration) wastes from about 9 metric tons of spent uranium fuel from a typical light water reactor (i.e., ~33,000 MWd/ton irradiation at ~30 MW/ton). About 3 to 4 such canisters would accommodate the wastes generated annually by a large (1 GWe) LWR.

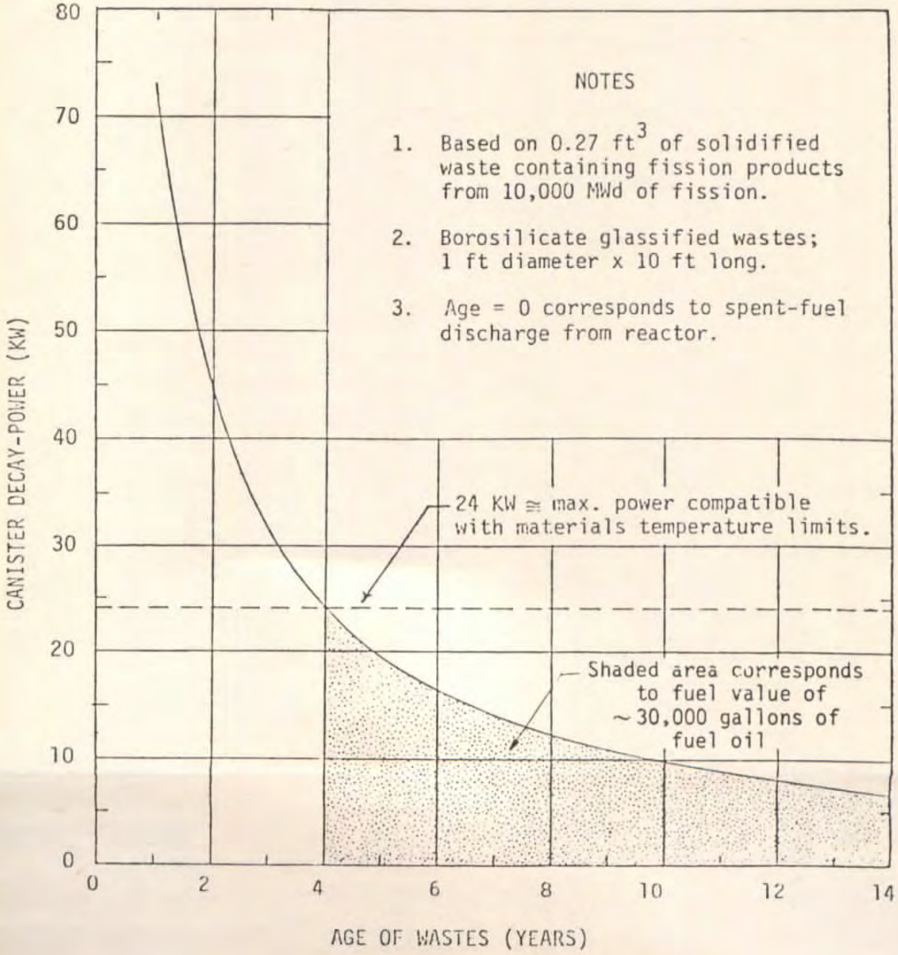
As indicated on the Fig., 24 KW is regarded as the maximum, "temperature-safe" power of such an element. At this power a canister could radiatively

Fig. 3

CANISTER DECAY POWER

VERSUS

AGE OF WASTES



dump its heat to normal environment-temperature sinks (e.g., ambient air) without exceeding certain "safe" temperature limits; namely ~900°C at canister centerline and ~427°C at the stainless steel wall.

With maximum-concentration wastes, then, a temperature-safe element is formed by solidification of 4-year-old wastes. Younger than 4-year-old wastes may, of course, be solidified at less than maximum concentration to form a 24-KW element, but more canisters would be required for a given number of source reactors. Older than 4-year-old wastes may be solidified at maximum concentration, but the initial canister power will, of course, be less than 24 KW. Finally, as it turns out, with either younger or older than 4-year-old wastes, the average power over a given canister use period is always significantly less than with 4-year-old wastes. Hence, the number of canisters (for a given steam-plant output) as well as the plant's cost will be minimized if nominally 4-year-old wastes are solidified to form our fresh fuel-elements. This explains my earlier remark on the economic logic of solidification when wastes are about 4-years old.

As indicated on the slide, a maximum-concentration canister, with wastes solidified at 4 years, will yield in the following 10-year period the energy released by the combustion of some 30,000 gallons of fuel oil. This quantity of fuel oil weighs ~100 tonnes; that is, about 100 times the weight of our fuel element. And, since a canister surface temperature of 427°C, or 800°F, can be safely maintained for indefinitely long periods, it is readily shown that we have sufficient temperature differential to produce the desired 350°F steam.

Now each 24-KW canister contains some 6 MCi of radioactivity, about 2 MCi of which is in the form of rather penetrating gamma rays. Accordingly, to bring biological dose rates down to typical licensed-facility levels of a few mR/hour, the equivalent of ~5 feet of concrete shielding is required. Also, the transport of single canisters requires a nominal 40-ton cask, with appropriate cooling provisions, to keep radiation down to biological levels during transport. In addition, it may be noted that the operators of a 5-MW plant will be entrusted with a nominal 1.5-GCi inventory of radionuclides.

4. ECONOMICALLY LOGICAL DESIGN AND OPERATING PARAMETERS

A consideration of the purely physical properties of canistered-wastes has brought to light a first few necessary characteristics of a nuclear-waste steam plant. Massive in-plant and transport cask shielding will be required; a 5-MW operation will involve the care and custody of 1.5 billion curies of radioactivity; and, the plant will be fed by fresh fuel elements which contain maximum-concentration, nominally 4-year-old wastes.

To define further the logical specifications of such a plant and its operation, we first conducted cursory examinations of some candidate design philosophies to establish the general range of certain cost parameters. With the expected range of these parameters in hand, it was then possible to conduct a broad economic survey of the annual costs of 5-MW systems. That survey, in turn, brought out some economically logical plant design and operating parameters to narrow further our specification of a particular system for the conceptual design task.

It will not be practical in this brief presentation to go into a detailed explanation of the parametric survey of annual costs. Let me just report that an annual cost expression, which involves a fixed-cost term and a term which is proportional to the number of canisters in a plant, was used for the survey. The expression permits the computation of annual costs as a function of the number of canisters and a triplet of basic parameters: the age of fresh wastes; the canister replacement (i.e., transportation) cost; and, an effective plant-cost per canister.

As expected, other parameters being equal, a minimum annual cost is always obtained with fresh canisters which hold maximum-concentration, 4-year-old wastes. In addition, it was shown that a minimum annual cost results if canisters are used for about 10 years.

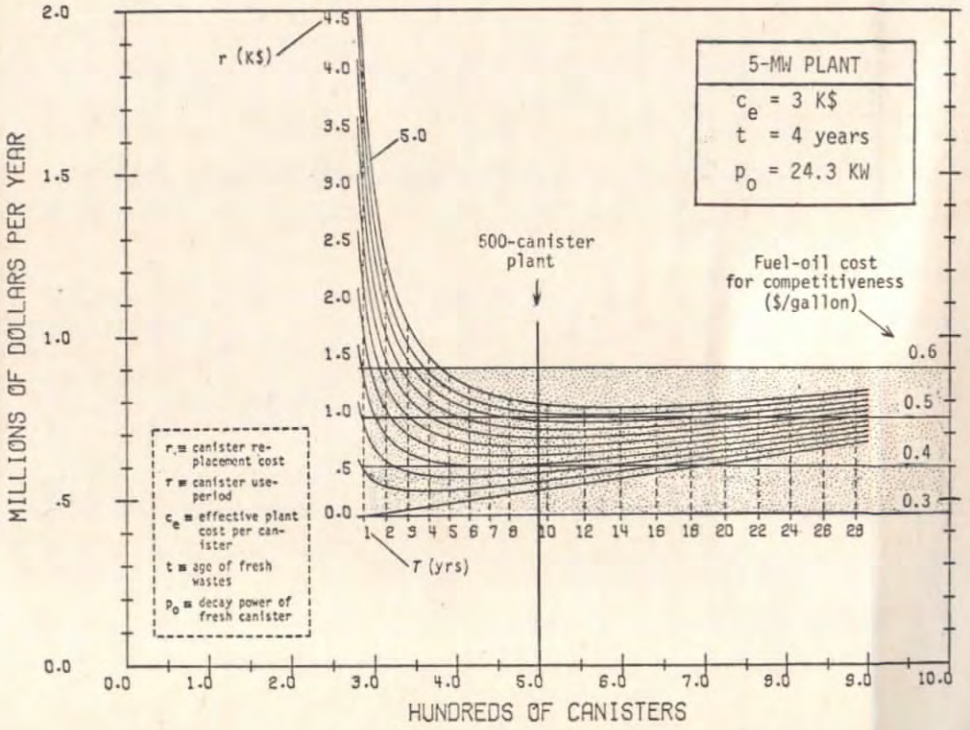
Fig. 4 illustrates this latter point. Here we show the annual cost of a 5-MW system whose per-canister scalable capital cost is 3K$/canister, a value close to what we believe is attainable by designs of the type I will show in a moment. Each of the solid-line curves is labeled according to an assumed per-canister replacement cost, which might typically be ~3K$/canister. The family of dashed, vertical lines indicates an assumed canister-use period in years. Finally, we have included a shaded horizontal band with lines that are labeled by the cost of oil at which our nuclear-plant and an oil-fired burner would have equal annual costs (i.e., be competitive).

It is seen that, if canisters can be replaced (i.e., transported) for 3K$, then a minimum annual cost (~0.7 M$/year) is obtained by a nominal 500-canister plant. The canisters would be used about 10 years; hence, the canister replacement rate would be about one per week. This plant and operation might compete with 45-cent per gallon fuel-oil burners according to our analysis. We believe that if the operation enjoyed receipts for the 10-year interim storage of canisters, the 5-MW plant might compete with 33-cent oil. Finally, if we went to a 10-MW plant, competition with 33-cent oil is indicated without interim-storage receipts and with perhaps 22-cent oil with the benefit of such receipts. These oil costs may be compared with current values which range from 25- to 50-cents per gallon according to Fort Belvoir [8].

5. A PARTICULAR 5-MW PLANT DESIGN

In the course of the program we made cursory examinations of perhaps a dozen variations of canister/boiler/shielding/heat-transfer arrangements--all this in search of a particular design philosophy for a conceptual plant-design. With regard to heat transfer from a canister to its surrounding

ANNUAL COST OF 5-MW SYSTEM



boiler tube, schemes like metal conduction strips and conduction through a liquid metal or a molten salt were examined and then discarded in favor of simple radiative transfer. This latter scheme becomes feasible where 800°F canisters radiate to relatively cool (nominal 350°F) boiler tubes. Various excess and emergency heat dump and shielding possibilities were examined. The Army Engineers ultimately approved normal heat dump via forced air-cooled condensers; emergency dump via boiler-cell flooding; and, a combination of concrete and water shielding of basic cells which contained multi-canister boilers.

Fig. 5 shows an elevation view of a design, by RDA's Linn Gore, which conforms with the approved design philosophy. Here we see three 24-canister, insulated boilers, each in a concrete-walled cavity, two of which are covered above by a water-filled shield tank. The center cell has its lid tank removed and is flooded during a canister reloading operation. A single-canister, 40-ton cask has been lowered into the flooded cell by the plant's bridge crane to effect the reloading.

A boiler consists of a nominal 10-ft diameter by ~13-ft long closed cylindrical shell of 3/4-inch steel with 24 through-pipes which accommodate the canisters. Internal pipes are provided to enhance the natural circulation of the boiler water within the boiler. Small side pipes near the top of the boiler are provided for the outflow of steam and the return of condensate water.

The out-cropping on the right is a fan-driven air-duct system. A suction fan causes outside air to circulate through the space between boiler-insulation and its surrounding concrete which is held to temperatures below 150°F.

Fig. 6 shows the 5-MW plant in plan view. Basically, the plant consists of four essentially independent quarter-sections. A section conists of 6 boiler-cells, 3 on each side of a pipe-tunnel/air-duct system. Most of

Fig. 5

ELEVATION: 5-MW FISSION-WASTE STEAM PLANT

(Design by L.A. Gore)

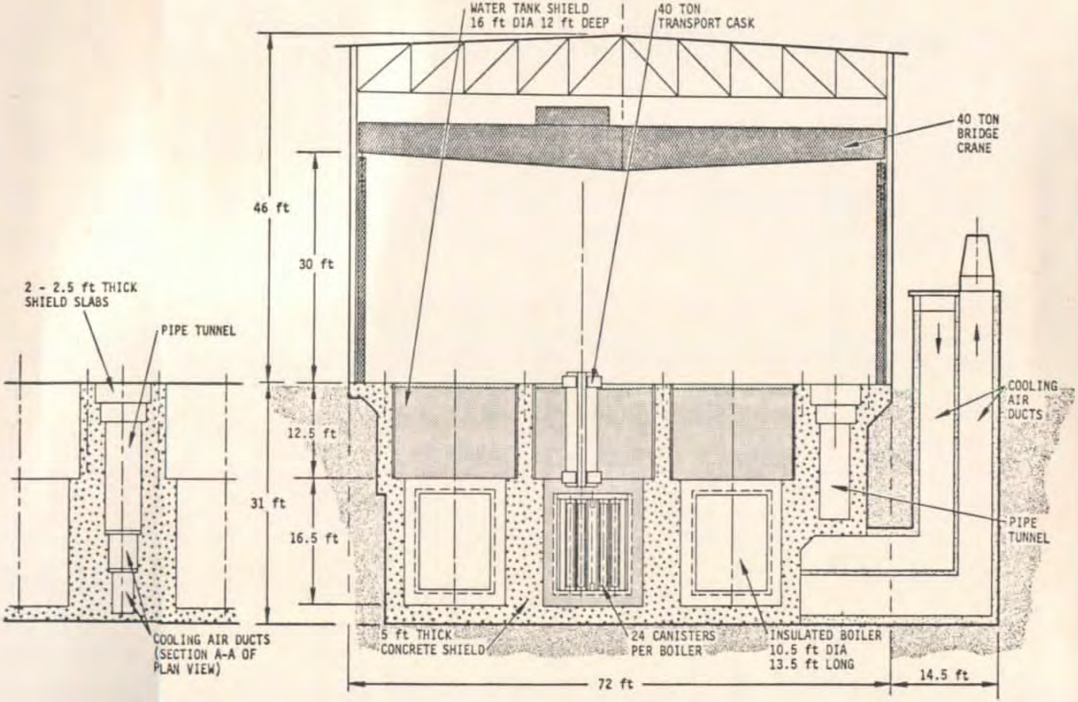
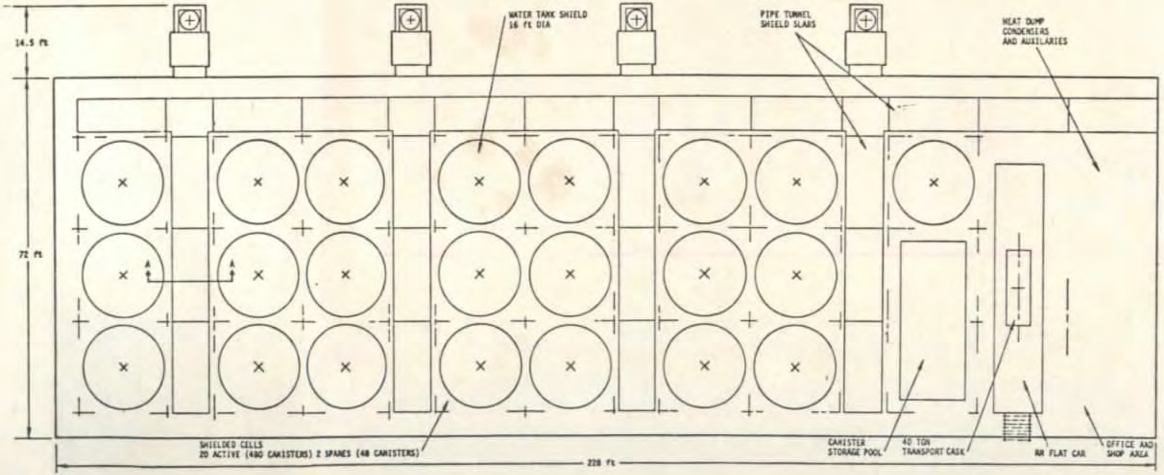


Fig. 6

PLAN VIEW: 5-MW FISSION-WASTE STEAM PLANT

(Design by L.A. Gore)



the 72-ft by 228-ft floor area is occupied by 20 working-boilers which hold 480 canisters. Two additional boiler-cells stand by as spares. A canister storage pool is seen near the railroad loading dock.

A flat car would deliver a fresh canister to the storage pool and remove a spent canister from the pool on a weekly basis. Semi-annually, a boiler, which used its canisters for 10 years, would be reloaded. The boiler's spent elements would go into the pool and fresh elements would be taken from the pool for its reload. Plant power dip at reload-time would be ~6%.

Output steam would be fed into the users lines and any excess steam would be condensed in the plant's air-cooled heat-dump condensers. These would be located opposite the plant's office/shop area where indicated in the Fig. Emergency cooling is provided by flooding the boiler-cell or cells where corrective action is required.

Fig. 7 shows a breakdown of estimated capital cost items; these data are based on input developed by Gore. It is seen that the 5-MW plant might be built at a cost of a little less than 2 M$, which could be allocated over a 3- to 4-year period as the plant's basic quarter-sections are constructed and made operational.*

Annual costs are estimated at a little less than 0.7 M$/year if no interim canister-storage receipts are realized. In this case, the system could compete with ~45-cent per gallon oil. With the benefit of such receipts, the annual cost would drop somewhat below 0.5 M$/year and the system would be competitive with ~33-cent oil. As I mentioned earlier, in today's oil market, fuel-oil costs range from 25 to 50 cents per gallon.

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*Gore has recently indicated that it should be possible to increase the number of canisters per boiler from 24 to 30. In this case, the size and cost of the plant could be reduced by ~20%.

Fig. 7

CAPITAL COST ESTIMATE[*]

(5-MW FISSION-WASTE STEAM PLANT)

"FIXED" COSTS	40-Ton Bridge Crane System (crane 80 K$, structure 40 K$, electric 10 K$)	130 K$	
	Canister-Transfer Cask	50 K$	
	Shop/Office Equipment	30 K$	
	Instrumentation (radiation)	60 K$	
	Site Drainage, Parking, Road	20 K$	
	RR Dock	10 K$	
			300 K$
"CANISTER-SCALABLE" COSTS	Boilers (with insulation; 22 total)	559 K$	
	Concrete (shielding, building foundations, ducts)	574 K$	
	Building (incl. std. electric, plumbing)	220 K$	
	Lid Tanks (top shielding; 22 total)	107 K$	
	Pipes, Valves, Controls	65 K$	
	Condensers (heat dump; air cooled)	50 K$	
	Pumps and Fans	10 K$	
			1,585 K$
	Total Capital Cost		1,885 K$

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[*] Based on data developed by L.A. Gore

6. CONCLUDING REMARKS

6.1 In Summary Review

Our mission has been to determine whether or not it would be feasible to produce 5-MW quantities of 350°F saturated steam from the energy of solidified nuclear-wastes, specifically from the residue of the U. S. civilian power industry during the remainder of the century. And, if we found concept feasibility, then we were to develop a conceptual design of a particular 5-MW plant for the production of military base steam. We found the concept to be feasible and, after a series of iterative design exercises, we developed the conceptual design of a particular plant in accordance with a design philosophy approved by Fort Belvoir, our ARPA sponsor's representative.

Our first logical task was to forecast the schedule of available decay-power to determine source-sufficiency for one or more 5-MW systems within the time-frame of interest. We found that sufficient power in solidifiable wastes would be available near 1980 for a first plant, a facility which could save ~1.5 million gallons of fuel-oil per year. By the year 2000, perhaps 40 5-MW plants could be fueled by nuclear wastes. The fuel oil savings then would amount to about 60 million gallons annually.

With modern solidification technology, borosilicate glassified wastes could be encapsulated in nominal 1-ft diameter by 10-ft long cylindrical canisters of stainless steel to form 1-ton "fuel elements" for our nuclear-waste steam plants. Each one-ton canister would release the fuel-energy equivalent of ~100 tons (30,000 gallons) of fuel-oil over a 10-year period, an economically optimum use-period. In ambient air, the canisters would be "temperature-safe" for indefinite periods with canister wall-temperature near ~300°F. This temperature readily permits the production of the desired 350°F steam by any number of heat transfer schemes. The most simple scheme appears to be radiative transfer of a canister's thermal power (nominal 12.5 KW average over a 10-year period) to its surrounding boiler-tube.

It was further noted that fresh, 24-KW canisters would each contain about 6 megacuries of radioactivity and that a 5-MW plant would contain some 1.5 billion curies. With responsible operators using well established high-level waste handling techniques, we foresee no problems in running such a plant. However, considerable shielding will be required (~5-ft of concrete or ~12-ft of water) to hold operator dose rates down to the few milliroentgen per hour levels typical at licensed facilities.

By a broad parametric survey of the annual costs of 5-MW plants, we found that an economically logical system should be fed with maximum-concentration, borosilicate-type, 4-year old, solidified wastes and should use these wastes for a period of ~10 years prior to discharge. Under these conditions, a minimum annual cost, 5-MW plant would use ~500 working canisters.

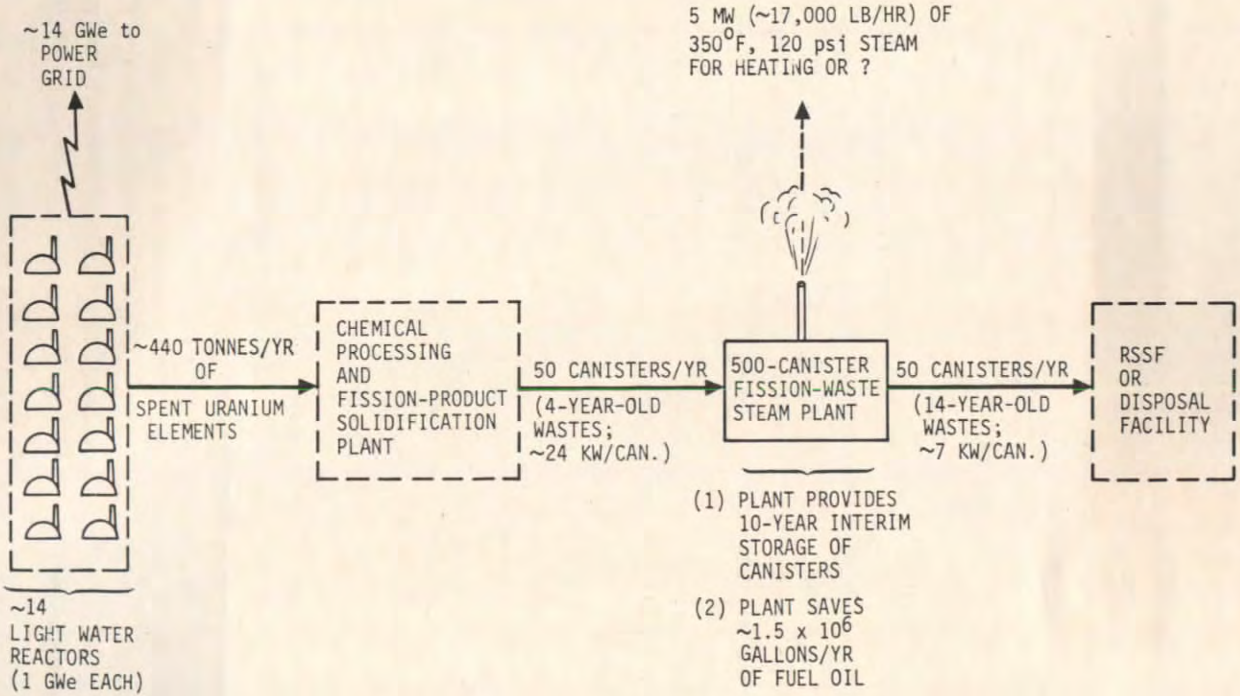
We found that a 5-MW plant could be built at a cost of ~1.8 M$ which could be authorized over a period of 3 to 4 years during which the plant's quarter-sections could be sequentially constructed. Competition of the 5-MW plant with oil-burners in today's oil market (25 to 50 cents per gallon) appears to be a distinct possibility. Even without receipts for the 10-year interim storage of canisters, such plants might compete with burners of ~45-cent per gallon oil. With such receipts, competition with ~33-cent oil is indicated for the 5-MW systems. If 10-MW plants were built instead of 5-MW systems, competition with 22-cent and 33-cent oil is indicated for the receipt and no-receipt cases, respectively.

To illustrate the role of a 5-MW steam plant in the overall fuel-cycle of the plant's fission-waste source-reactors, we have prepared Fig. 8. There we see that about 14 large (1-GWe) modern reactors of the light water type constitute the steady state source of fuel for a 5-MW fission-waste steam plant. This large bank of reactors annually discharges ~440 tonnes of spent-fuel which is fed to a chemical-processing/waste-solidification plant. This plant, in turn, annually feeds about 50 canisters (borosilicate-type wastes) to our 5-MW plant, which uses each canister for ten years and

Fig. 8

THE STEADY STATE SITUATION

(5-MW FISSION-WASTE STEAM PLANT OPERATION)



then forwards the used canisters to a passive storage or canister disposal facility.

As we have noted, our plant's power is only about 1/100 per cent of the large fission-power of all its source reactors. However, it does annually utilize the energy equivalent of ~1.5 million gallons of fuel-oil, each 1-ton canister yielding the energy equivalent of 100 times its weight in oil toward this annual fuel-oil savings. And, perhaps equally important, the steam plant provides ~10 years of interim storage (in a military secure facility) for the highly radioactive canisters. This latter, of course, relieves the day-to-day cost burden of the passive storage facilities at all times of our plant's existence.

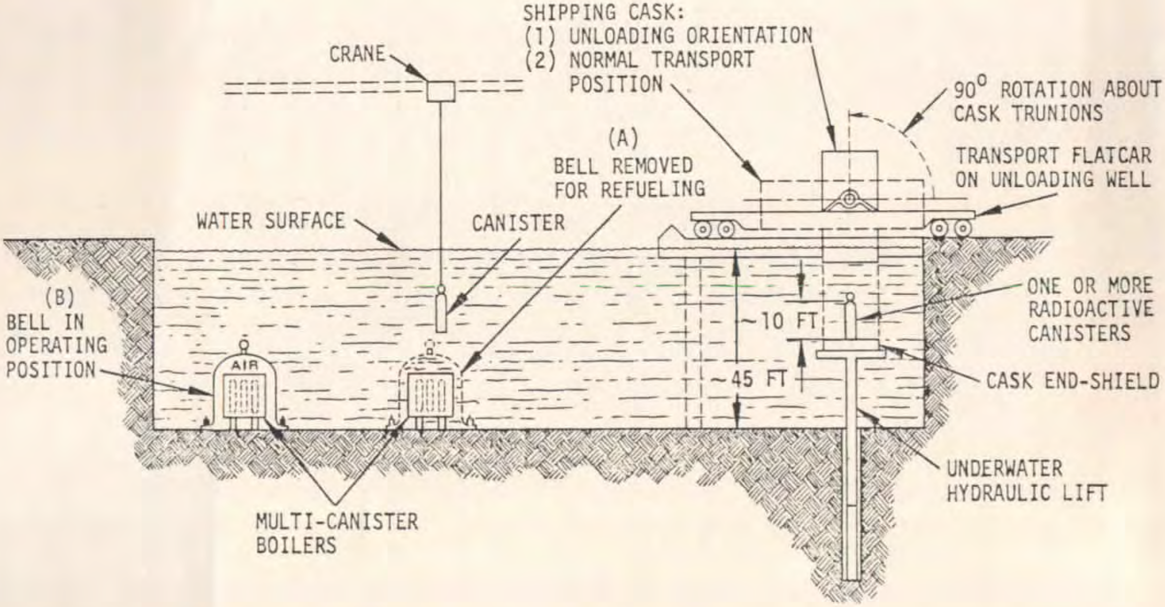
6.2 On Future Pursuit of the Concept

In the course of our iterative probings for a basic design philosophy, we had noted the potential economies of systems which would be totally--rather than partially--shielded by water. An example of such a system is the "diving bell" concept illustrated in Fig. 9. It may be noted that almost all past experience in handling solid high-level wastes (such as spent-fuel elements from reactors) has come from manipulations under water-shielding. Also, the Atlantic Richfield Hanford Company, in conjunction with the Kaiser Engineers, indicate (in their AEC-sponsored studies) that their Water Basin Concept would have about one-half of the capital cost of their next cheapest concept; namely, the all-concrete shielded Air-Vault Concept [9]. Indeed, we have noted that by going from our earlier all-concrete shielding concepts to an only partially water-shielded concept, a nominal 25 percent saving in capital costs might be realized.

For such reasons, we believe and have recommended that a follow-on study should be undertaken on systems which would utilize total water shielding.

FIG 9

A WATER-SHIELDED CONCEPT
OF
THE FISSION-WASTE STEAM PLANT
("DIVING BELL" CONCEPT)



REFERENCES

1. Hollis, H.D., Characterization of Energy Usage on Military Bases, a U.S. Army Facilities Engineering Support Agency Paper, Fort Belvoir, Virginia, 22 October 1974.

2. Safonov, G., Fission-Product Energy for Heating, Quarterly Technical Report for Period 29 March 1974 to 29 June 1974, RDA-TR-6800-001, June 1974.

3. Safonov, G., Fission-Product Energy for Heating, Interim Technical Report for Period 29 March 1974 to 29 September 1974, RDA-TR-6800-002, September 1974.

4. Safonov, G., Fission-Product Energy for Heating, Quarterly Technical Report for Period 29 September 1974 to 29 December 1974, RDA-TR-6800-003, December 1974.

5. Bolme, D.W., The Potential of Using Mixed Fission Products as a Source of Energy, BNWL-1115, June 1969.

6. Renzetti, J. L., Process Steam Generation by Reactor Wastes, a Pennsylvania State University Master's Thesis, March 1973.

7. Nuclear Industry 1973, WASH 1174-73, a USAEC publication.

8. Private Communication, Fort Belvoir's M. Greenberg to G. Safonov, 4 September 1974.

9. Retrievable Surface Storage Facility Alternative Concepts Engineering Studies, ARH-2888 REV, Atlantic Richfield Hanford Company/Kaiser Engineers, July 1974.