CHAPTER 15

The Course Ahead

When we lift ourselves from the routine of nuclear ship requirements, we can sense a great "nuclear era" ahead for commercial ships of all national flags. The specific direction will become more clear, of course, following the successful operation of the *SAVANNAH*. Already, though, numerous guideposts appear. For example, nuclear ships beyond the *SAVANNAH* could cater to those reactor designs capable of producing marine standard (superheated) steam; those reactors could be favored which are sufficiently flexible for adaptation to gas turbines; advanced reactor concepts employing "plasma thermocouple" loops could be considered for the direct conversion of fission energy to electricity for propulsion plant auxiliaries; and entirely new concepts involving thermonuclear (fusion) reactors could be envisioned. Over-all, the momentum of future effort will depend on how well we frame the technology of maritime nuclear science. A sound formulation of this science is a "must."

15-1 Nuclear Cost-Trend Down

The cost of the *SAVANNAH's* nuclear reactor and steam propulsion plant approaches the order of 13 million dollars.[*] This is exclusive of research and development, and special mock-ups and experiments to prove-out technical modifications of pressurized water reactors for merchant ships. Compared with oil ship propulsion plant costs, the *SAVANNAH's* nuclear plant is over *three times* more costly. In terms of $/shp, the *SAVANNAH's* power plant costs about $650/shp as against about $200/shp for oil ships. No one ever claimed that the *SAVANNAH* would be cost-wise competitive with comparable oil ships.

The *SAVANNAH*, we should remember, represents a cost reference or *starting point*. From this point onward, costs will go down (excluding inflationary effects, of course). Whereas significant cost improvement opportunities for oil ships have been pretty well exhausted, great opportunities lie ahead for nuclear ships. Significant improvements in power-

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[*] Ref: "Outlook for Nuclear Ship Propulsion," R. P. Godwin, *Management and Atomic Energy*, Atomic Industrial Forum, Inc., July, 1958, p. 204.

plant efficiency, plant weight, operating economy, and over-all ship productivity can be anticipated. With increasing experience with nuclear merchant ships, all factors indicate that nuclear costs unquestionably will trend downward (see Fig. 15-1).*

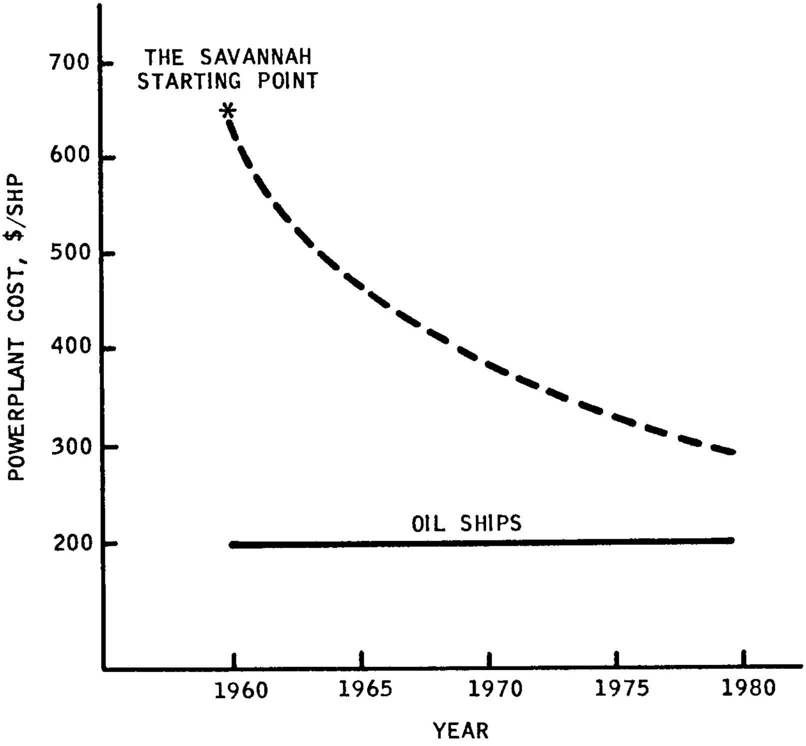

Fig. 15-1 Plausible Nuclear Ship Propulsion Cost Trend

The factors which support the Fig. 15-1 trend are:

(1) Refinements in nuclear plant design. The first of a kind is never the most refined model; successor plants gain from the experience of predecessors.

(2) Integration of nuclear plant components into the ship's hull. For example, the reactor containment shell and collision shielding would merge and become part of the ship's hull; the same is true of the hull reinforcement and refueling access.

(3) Less emphasis on overconservative designs. A greater understanding of, and confidence in, the benefits and hazards of nuclear power would ease the demands for overstringent safety precautions.

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* Ref: "Ship Propulsion," R. P. Godwin, *Nucleonics*, Sept., 1957, pp. 114-117.

(4) Standardization of certain nuclear plant features. For example, secondary shielding configuration and materials could be readily standardized; the same is true of nuclear instrumentation, automatic control consoles, mechanical control rods, radiation monitoring systems, etc.

(5) Greater emphasis on superheated steam from reactors. Already a nuclear superheat program is underway for land-based reactors from which feasible superheat designs could be extended to merchant ships.* Long ago, superheated steam proved its economy for oil ships.

(6) Installation of nuclear reactors into larger sized ships. Nuclear power is inherently a large capacity heat source which, in total plant size, is less sensitive to increased power requirements than corresponding oil plants.

(7) Use of nuclear power for higher speed ships. This involves a complete integration of the nuclear plant, finer hull forms, and greater power per propeller shaft. Surface speeds on the order of 35 knots are possible, but merchant ships as a class have not yet attained this speed. Nuclear power could help to close this unused speed gap while at the same time approaching oil-ship total costs.

Taking all factors into consideration, the only circumstance which would work against the downward nuclear costs would be the *absence of nuclear ship experience.* If no nuclear merchant ships beyond the *SAVANNAH* were built—or only a few—we could not acquire the necessary technical and operating experience to gauge the cost changes. We would then have only one point on the Fig. 15-1 curve, and all projections beyond this point would be purely speculative.

15-2 Dilemma over Development Costs

Fortunately, the maritime industry—both in the United States and abroad—has shown great interest in nuclear ship propulsion. Based on this interest and genuine technical study, several post-*SAVANNAH* nuclear ships have been proposed.†

One shipping company (the Isbrandtsen Co.) has proposed an important "first": that of constructing the first privately owned and operated nuclear merchant tanker.‡ The proposal is a joint venture between Isbrandtsen, the Ford Instrument Co. (reactor designers), and the Maryland Shipbuilding and Drydock Co. The unique feature of the proposal is the plan to short-cut costly developmental requirements by building a

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* Ref: "AEC Offers Development Contract on Superheat," *Nucleonics,* April, 1959, p. 18.

† Ref: "Nuclear Merchant Ships: A *Nucleonics* Special Report," *Nucleonics,* Nov., 1957, pp. 78-87.

‡ Ref: "Isbrandtsen Tanker to be Atom Powered," *Marine Digest,* Feb. 28, 1959.

helium-cooled, superheated-steam reactor (~950°F) into a separate hull section, then inserting this "reactor hull" into a conventional tanker hull (32,000 DWT) when all nuclear plant trials have been completed.* The sad feature of the proposal is that its success depends on . . . Government aid.

In fact, though many nuclear ship proposals have originated from private sources, all have this one feature in common: reliance on the Government for financial support. This arises from the legislative "built-ins" in the Merchant Marine Act of 1936 (direct ship construction and operating subsidies) and in the Atomic Energy Act of 1954 (direct support of nuclear research and development). From these Acts, we can virtually draw the conclusion that the number of nuclear merchant ships ever to be built will depend directly upon the extent of Government assistance!

To devise ground rules for Government assistance, the Maritime Administration and the Atomic Energy Commission have jointly nurtured a "Nuclear Ship Cooperative Program."† Behind this program is the recognition that, even though nuclear costs will trend downward, the near-term differences between nuclear and oil-ship costs are too great for private industry to bear alone. Also, the cooperative program recognizes that, though nuclear reactors are technically feasible for merchant ships, there is still a substantial gap between technical feasibility and the developmental effort required to assure reliability in a merchant ship environment. This raises the important question: "Who—fundamentally—should pay for nuclear merchant ship development costs: the Government or private industry?"

The situation has created a dilemma. There is general agreement that we cannot pioneer a large-scale nuclear merchant fleet on the one *SAVANNAH* vessel alone. There is agreement also that the *SAVANNAH* will help solve many of the practical problems to pave the way for the general acceptance of nuclear merchant ships. But beyond these two points, agreement diverges. The Government feels that its nuclear responsibilities are to check out the basic technical concepts of reactor prototypes only, and that it is up to private industry to adapt these proven concepts to merchant ships. Toward this end, the Government has made available to industry a vast amount of nuclear data and information. The maritime industry, on the other hand, feels that the adaptation costs provide too great a gap between private economic incentives and return on capital investment. Both sides are right . . . and so the dilemma persists.‡

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* Using the now common "jumboizing" technique for lengthening tankers.

† Ref: "Merchant Ship Program under Study by MA-AEC," *Nucleonics*, June, 1958, p. 20.

‡ Ref: (1) "Ship Aid Program Sunk," *Nucleonics*, March, 1959, p. 19.
(2) "Administration Splits on Prompt Ship Program," *Nucleonics*, April, 1959, p. 23.
(3) "Wanted: Nuclear Clipper Ships—Now," *Nucleonics*, April, 1959, p. 85.

15-3 Maritime Nuclear Science Foundation?

Very possibly, one way out of the dilemma may be through some form of cooperative Maritime Nuclear Science Foundation. A nonprofit organization could be established whereby all maritime interests could contribute funds for the advancement of nuclear ship science. These funds would be tax deductible for those corporations and individuals contributing them. The disbursement of the funds would be supervised by representatives of both industry and the Government. The Government would provide no direct funds on its own, but would assist through providing a cooperative forum for the easement of overstringent regulation, and through the general coordination of regulatory safeguards.

"All maritime interests" could be construed to mean: ship operating companies, shipbuilding companies, reactor engineering companies, nuclear equipment manufacturers, marine equipment vendors, marine insurance underwriters, maritime labor unions, interested individuals . . . in short, everyone interested in the development of a nuclear merchant marine.

The sole purpose of a Maritime Nuclear Science Foundation would be to pursue those technical concepts which would ultimately lead to economically feasible nuclear ships. The presumption is that the end purpose of science is to define the technology that would benefit man under an environment of world peace and trade.

It is conceivable that a nonprofit organization could comprise experimental facilities (e.g., reactor critical assemblies, fuel element testing labs, etc.), *floating* test cells (consisting of nuclear plants in partial ships' hulls), training facilities (for nuclear merchant mariners), reference libraries (on nuclear ship propulsion), a standards and specifications forum, and other normally nonprofit technical activities. If necessary to do so, complete "first-of-a-type" nuclear ships could be built with nonprofit funds. Subsequently, the ships could be leased or sold to private shipping companies. Beyond the first nuclear ship of each type, it would be anticipated that private financing (with profits taxable) would take over.

15-4 Flexible Reactor Designs

One of the disconcerting features of nuclear propulsion is the number of technically feasible reactor types available. When a private ship owner selects one type of reactor, he has committed himself for 20 or more years ahead. During this period, he can anticipate many reactor modifications and changes. Whereas on one hand he must standardize reactor plant design to keep costs down, on the other he must be sufficiently flexible to avoid nuclear obsolescence.

The most likely area where flexible design would pay off is the reactor core itself. The core—consisting of fuel elements, control elements, and support structure—has to be taken out and replaced periodically, anyhow.

So, we would do well to keep an open mind to nuclear core changes that would up-grade the efficiency and capability of the over-all power plant.

For example, we may want to modify the core to develop superheated steam, and we may want to try out gaseous controllants. We could then design a new core in *two parts*: core-within-a-core (see Fig. 15-2). The inner core would retain the mechanical control rods, but would be redesigned and refueled for dry steam flow. The outer core would retain its former type of fuel elements and coolant, but the mechanical control rod passages would be replaced with gas control tubes. The gas controllant manifolding could be led up through the former mechanical rod openings in the reactor vessel head, and tied in to an otherwise unmodified reactor plant.

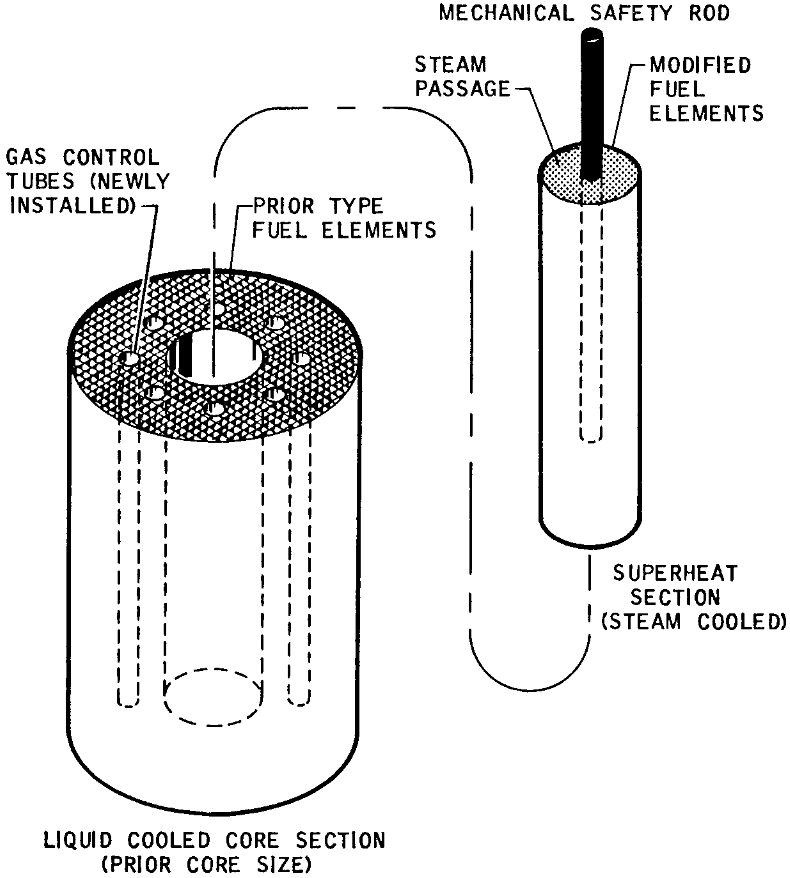

Fig. 15-2 Typical Reactor Modification Scheme: Core-within-Core

Sometime later, we may want to install a bank of "plasma" thermocouples in the superheat section of the core.* We could use these thermocouples to generate direct electrical power for miscellaneous shipboard loads. If successful, we might do away with one or more of the turbogenerators.

The plasma thermocouple is a thermoelectric cell consisting of a central hot cathode (electrically positive) surrounded by a (relatively) cold anode (see Fig. 15-3). The lower end of the cell contains a pool of liquid cesium. The cathode is a bare nuclear fuel rod (possibly UC_2: uranium carbide). The anode is a material, such as copper, which is an excellent conductor of both heat and electricity. The anode and cathode are electrically insulated, using possibly Al_2O_3: artificial sapphire.† The cell is evacuated to on the order of 10^{-5} mm Hg (mercury), and is cooled by an externally circulating (electrically neutral) medium. This cell coolant medium, in turn, is cooled by the normal reactor coolant.

The liquid cesium in the plasma cell is vaporized by the ambient reactor heat. This cesium vapor occupies the entire cell and engulfs the uranium cathode and copper anode. Neutrons from the main portion of the reactor fission the cathode, whereupon the fragments flying apart, the new neutrons, and the fission gammas and betas all *ionize* the cesium vapor. The positive ions flow to the copper anode; the negative ions to the cathode. The result: an electrical current flows in an external circuit.‡

Before the plasma nuclear-electric device would be used aboard ship, it would have to be appropriately developed. Though technically feasible now, its adaptation to merchant ships is many years away.

15-5 Plasma Reactor Possibilities

One of the refreshing features of nuclear propulsion is that new technical possibilities continually unfold. When one reactor concept is perfected—or is nearly so—a successor concept follows to open entirely new vistas of application.

For example, talented minds are taking the plasma thermocouple concept and racing one stride further . . . to a plasma reactor.** The principal end product of such a reactor would be direct electrical power of larger output capabilities than possible with a bank of plasma thermocouples. Conceivably, nuclear ships could use a plasma reactor, as a separate piece of equipment from the main propulsion reactor, to generate all of the

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* A "plasma" is a dense gas of electrically charged (ionized) particles.

† Al_2O_3 is both an excellent conductor of heat and an excellent electrical insulator.

‡ Current levels on the order of 50 amp/cm^2 of anode surface (voltage levels of 5 volt/cm^2) have been obtained in laboratory experiments. Reported electrical conversion efficiencies are on the order of 15%, but with further research and development these efficiencies are expected to improve.

** Ref: "Plasma Reactor Promises Direct Electrical Power," Colgate and Aamodt, *Nucleonics*, August, 1957, pp. 50-55.

ship's electrical needs. Instead of turbogenerators as we now know them, we would have, possibly, "fission-plasma generators."

A conceptual arrangement of a fission-plasma *reactor* is shown in Fig. 15-4. The concept is essentially one of a long cylinder of refractory material (graphite) surrounded by a neutron reflector and moderator (D_2O: heavy water). One end of the cylinder is a fission chamber; the other end is a magnetic field. Gaseous fissionable fuel (possibly UF_6) is introduced at the fission end until nuclear criticality is achieved. The resulting fission "explosion" creates an overpressure (shock) wave which drives the gas to the other end of the cylinder. Just behind the shock front, some of the

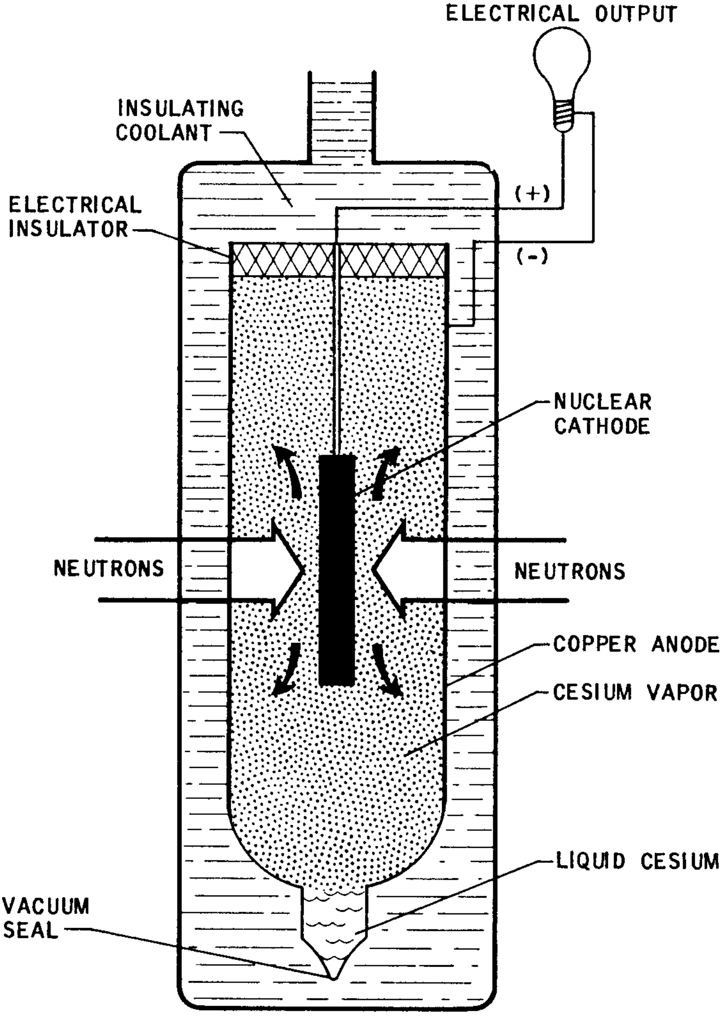

Fig. 15-3 Basic Principle of the Plasma Nuclear Thermocouple

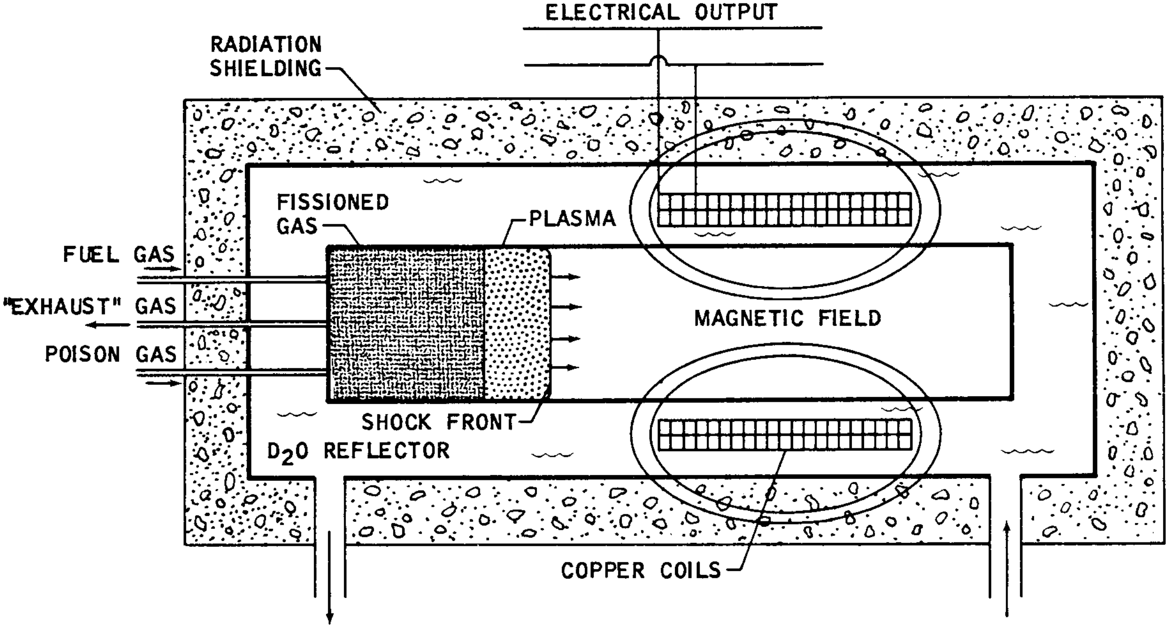

Fig. 15-4 Basic Principle of Fission-Plasma Reactor: Direct Electricity

fuel gas becomes highly ionized into a plasma. As this plasma "plug" passes through the magnetic field, electrical current is generated. As current is generated, the magnetic field increases, thereby compressing the plasma and forcing it back to the fission end again. Thus, the fissionable gas and its plasma oscillate back and forth, directly converting the fission energy to electrical energy.

Carrying the fission-plasma concept even further, a *fusion*-plasma reactor can be conceived. Fusion reactions, or, more properly, thermonuclear reactions, have captured the imagination of nuclear scientists the world over.* Here, in fusion, man is probing the very processes of solar and stellar energy which have existed for billions of years.

Whereas fission is the splitting apart of heavy atoms of matter, fusion is the bringing together of light atoms of matter. These light atoms are the "fusion fuel." These fuels are hydrogen (H^1), deuterium (H^2), and tritium (H^3). The end product of the fusion reaction is helium (He^4). Though several fusion reaction chains are required to produce helium, the net result is a synthesis of He^4 from four atoms of hydrogen or from two atoms of deuterium. (The most practical fusion fuel is deuterium.) The driving force of the fusion reaction is a 100-million-degree temperature—hence, the term *thermo*-nuclear. This, apparently, is what happens in the sun and stars.

15-6 Man's Continuing Quest

The problems associated with the attainment of a successful man-made fusion process are both enormously difficult and of unprecedented nature. But the potentialities of eventual success are of transcending importance.

Foremost of the promising considerations is that, in contrast to a fission reactor, there would be comparatively little radioactive waste from a fusion reactor. The principal waste—helium—is a stable, harmless, and non-radioactive gas. A second promising consideration is that a fusion reactor would be inherently safe. The fusion fuel is fed into the reactor as needed (it is not built in, in excess of criticality as in the case of fission reactors) and hence there would be no possibility of a runaway fusion reactor.

A third consideration of promise is direct electrical conversion into *great quantities* of power. This possibility arises from the fact that with, say, deuterium as a fuel, more than two-thirds of the fusion energy is transformed directly into fast-moving charged (ionized) particles. These ionized particles are the fusion plasma. On transiting a magnetic field, the fusion-plasma generates electrical power much the same as in the fission-plasma reactor . . . but to a greater magnitude. With this possibility—someday—we may find on nuclear merchant ships *electrically driven* propeller shafts.

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* Ref: (1) "Geneva 1958: Fusion," *Nucleonics*, Sept., 1958, pp. 66-71.
(2) "Controlled Fusion," A. S. Bishop, *Nucleonics*, Sept., 1957, pp. 128-130.

And, finally, there is the impressive consideration that if a fusion reactor can be proven feasible, man will have tapped a source of fuel which is virtually without limit. The oceans of the world contain enough deuterium to satisfy all propulsion requirements for hundreds of millions of years to come.

We do not know the limit of man's creative imagination. Nuclear technology—and nuclear ship propulsion in particular—provides a fertile field for man's continuing quest for ever more perfect power sources.