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ABSTRACT

A short introduction to fusion-fission hybrid systems is provided, touching on: (a) basic technological characteristics; (b) potential applications; (c) relevance of environmental considerations in the development rationale for hybrids. References to the more technical literature are supplied.

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Fusion-Fission Hybrid Reactors: A Capsule Introduction

John P. Holdren

Fusion-fission hybrids are systems wherein a fusion-reactor core is surrounded by a fission blanket. The fusion core may be either a magnetically confined plasma or an inertial-confinement system wherein compression and heating of the fusion fuel is provided by lasers, electron beams, or ion beams. The fission blanket may be designed to exploit fast-neutron fission, thermal-neutron fission, production of fissile isotopes from fertile ones, or a combination of these.

Hybrid systems have been receiving increasing attention in the world nuclear community, particularly in the United States and the Soviet Union (1-6), in connection with three quite distinct applications: (a) the use of hybrids as self-contained, base-loaded electricity generating stations; (b) use of hybrids primarily as producers of fission fuels for use in separate pure-fission reactors; (c) use of hybrids for the transmutation of long-lived radioactive wastes, primarily by fast-neutron fission of the actinides.

Base-load electricity generation

In the self-contained, electricity-generation application, the primary function of the fission blanket is to multiply the energy yield obtainable from the 14 MeV neutrons produced by deuterium-tritium fusion reactions in the core. Increasing the energy yield per neutron opens the possibility of significant net energy production in a device whose fusion core by itself would be a marginal energy producer or even a net energy sink. In this role of the hybrid, then, the idea is that the fission blanket enables fusion technology to find useful application before an economic pure-fusion system

becomes available. Since energy multiplications of about a factor of 10 appear to be achievable in conceptual fission blankets that have been analyzed, the requirement on the Lawson criterion for energy break-even ($n\tau \approx 10^{14}$ for pure fusion, where n is the fuel number density in ions per cc and τ the confinement time in seconds in the fusion plasma) can be relaxed by about a factor of 10 below what would be required in a pure fusion system.

Attaining this relaxation of the Lawson requirement exacts a significant price in technical complexity (hence presumably construction costs) and in the loss of potential environmental advantages of pure fusion.

With respect to complexity, meeting the elaborate requirements of fusion and fission subsystems (injection, heating, confinement, and tritium breeding for fusion; refueling for fission; cooling and heat removal for both), in the close proximity required for reasons of neutron economy, poses formidable difficulties which are unlikely to be overcome cheaply. (For a specific conceptual design, see e.g., Ref. 7.)

With respect to environment, reliance on fission for the bulk of the energy production means the hybrid reactor's radioactivity inventory, after-heat, fissile material production, and long-lived radioactive wastes are essentially those of a fission system. Hybrids might have a significant safety advantage compared to some pure fission reactors, however, in terms of accident pathways: specifically, a hybrid's fission blanket will be subcritical (incapable of a self-sustaining chain reaction) in its operating configuration and possibly can be designed to be subcritical under all accident conditions as well; also, the power density in the fission blanket may be able to be made low enough to alleviate emergency cooling requirements substantially. Neither of these potential advantages is automatic (8). In some designs a blanket that is subcritical in normal operation could become

critical in accidents involving loss of coolant and severe geometric reconfiguration. Also, achieving energy multiplication high enough to make a power-producing hybrid really interesting may require a high power density in the blanket.

Hybrids as fuel producers

In this application, the primary function of the fission blanket is to produce fuel for use in physically separate pure fission reactors. The breeding reactions of interest are $^{238}\text{U} \rightarrow ^{239}\text{Pu}$ and $^{232}\text{Th} \rightarrow ^{233}\text{U}$. Although many designs would produce both power and fuel, it is not essential that a hybrid intended for the fuel-production mode produce net electrical power as well; a negative net electrical power balance in the hybrid could be made up from the pure-fission power grid to which the hybrid was supplying fuel. This is what is meant by a "symbiotic" relation between hybrids and pure-fission reactors.

Even if hybrid technology proved too expensive to be attractive in the self-contained, electricity-generation role, it might well be affordable in the fuel-producing role. This is so because one large fuel-producing hybrid could supply 5 to 10 fission converter reactors (say, light-water reactors or high-temperature gas-cooled reactors) of similar thermal power rating with make-up fuel. Alternatively, fuel-producing hybrids might be used in a fission breeder-reactor economy to reduce the effective doubling time and thus increase the rate at which installed generating capacity in breeders could be expanded. The fuel-producing role for hybrids also has the advantage that hour-to-hour and day-to-day reliability are less critical than for an electricity-producing reactor tied directly into the power grid. This is an especially important consideration for a new technology that might be expected to have unpredictable reliability while bugs are being worked out.

Hybrids optimized for the fuel-producing role (with fissions in the blanket deliberately suppressed) can have somewhat smaller inventories of fission products and lower blanket power densities than electricity-producing hybrids. Safety ramifications must be analyzed in a systems sense, however. Two possible "systems" safety ramifications of fuel-producing hybrids are: (a) hybrids could permit the pure-fission reactors in the system to be high-temperature gas-cooled reactors (HTGRs) or heavy-water moderated CANDUs (for example) instead of liquid-metal fast breeder reactors (LMFBRs), or low-breeding-ratio LMFBRs instead of high-breeding-ratio ones, which would be important if certain converter reactors or low-gain breeders were deemed safer than high-gain breeders; (b) hybrids might permit the use of the $^{232}\text{Th} \rightarrow ^{233}\text{U}$ fuel cycle where otherwise $^{238}\text{U} \rightarrow ^{239}\text{Pu}$ was required, which would be important if the thorium cycle were deemed safer than the plutonium cycle (e.g., in respect to safeguards against production of nuclear explosives (9)).

Hybrids for transmutation of radioactive wastes

The most dangerous long-lived radioactive wastes from fission fall principally into two categories: fission products of medium weight and half-life near 30 years (dominated by ^{90}Sr and ^{137}Cs), and heavy elements (the actinides) formed by absorption of neutrons in fuel isotopes and by the subsequent chains of radioactive decay. (Among the most troublesome actinides are 458-year ^{241}Am , 7950-year ^{243}Am , 24,400-year ^{239}Pu and 2 million year ^{237}Np .) The possibility of reducing the longevity of the hazard of fission products and actinides by bombarding them with fusion neutrons has now been studied in some detail (5,10).

The absorption of fusion neutrons by ^{90}Sr and ^{137}Cs produces isotopes of somewhat shorter half-life and/or lower radiological toxicity, but the neutron fluxes needed to achieve these transmutations at a useful rate

are formidably high (in the range of 10 megawatts of neutron power per square meter). Even if a hybrid could be designed to produce such neutron fluxes and to withstand the associated materials damage, the long exposure times required to transmute the fission products imply the accumulation of very large fission-product inventories in the hybrids themselves (larger than in pure-fission power reactors).

More promising is the use of fusion neutrons to fission the long-lived actinides, thereby converting them into still very toxic but substantially shorter-lived fission products. This process could lead to useful reductions in overall hazard lifetime at neutron fluxes that seem likely to be achievable (around 1 megawatt of neutron power per square meter). A hybrid reactor designed for this purpose would contain at any given time a very high inventory of dangerous actinides, however, and accident pathways for such hybrids will have to be scrutinized very carefully to determine whether this scheme is desirable. Another factor in such a determination is the extra handling and shipment of actinides that might be involved in comparison to alternative waste-management schemes. Since actinides also can be "burned up" in place in fast-neutron pure-fission reactors (with a loss of breeding of new fissile fuel), it might be preferable to do that and make up the loss of breeding by using hybrids in their fuel-producing role (5).

Concluding observations

The rationale for developing hybrids (or any other new energy source) presumably consists of potential advantages over alternative systems with respect to one or more of the following characteristics: fuel supply (abundance and dependability of access), cost of delivered energy, timing, and environmental and social characteristics. The LMFBR, which seems closer to commercial demonstration than either pure fusion or fusion-fission hybrids, would by itself

solve the fuel supply problem for many thousands of years, if it proves economic and environmentally acceptable; pure fusion reactors, if practicable, would solve it for even longer; so there is little advantage in this respect for fusion-fission hybrids. With respect to cost of delivered energy, it is also hard to make a compelling argument for fusion-fission: the capital costs of hybrids, which will dominate the energy cost, are quite uncertain but likely for basic engineering reasons to be higher than those of pure fusion.

With respect to timing, however hybrids have the potential advantage over pure fusion of being deployable sooner, and the potential advantage over LMFBRs of permitting a more rapid expansion of nuclear capacity (owing to higher breeding ratio). The importance of these rationales is controversial. The possible early availability of hybrids, and the related "stepping stone" argument that learning from hybrids will bring about pure fusion sooner, are in my view rather weak rationales for hybrid development unless hybrids are better than alternative "interim" technologies in other respects. The hybrid's advantage for rapid expansion of nuclear capacity seems to me to be weakened considerably by the increasing likelihood of slower electricity growth in the industrial nations where the main market for this sophisticated technology lies, and, in some countries, by the accumulating inventory of plutonium from converter reactors, which makes the LMFBR's low breeding ratio less of a liability.

To the extent that the rationale for hybrids on grounds of fuel supply, cost, and timing is perceived as marginal, then the environmental and social characteristics in comparison to alternative technologies take on increased importance. In evaluating environmental as well as other characteristics of hybrids, it is essential to determine the appropriate "yardsticks" against which hybrids should be compared. The answer depends on which of the possible

roles of hybrids is under discussion. In the electricity-production role, the appropriate comparisons are with pure fission and pure fusion reactors (and in a broader context with non-nuclear generating technologies); in the fuel-production role the comparison is with mining and enrichment or with pure-fission breeders; and in the waste-transmutation role the comparison is with other waste-management schemes.

Characteristics of hybrids that are relevant to evaluating environmental risks in any such comparison are: (a) radioactive inventories, including tritium, neutron-activation products, fission products, and actinides (a special category of which is the fissile isotopes of safeguards concern); (b) pathways for release of the inventories, relevant to which are criticality behavior, response to loss of coolant or coolant flow, other forms of stored energy, "geometrical" aspects (seams, welds, valves, lengths of pipes), and the amount of transport and handling of radioactive materials that is required; (c) systems aspects, including impact of hybrid technology on fuel choices and fission-reactor mix within the nuclear system as a whole. Detailed work on these characteristics is still largely missing. It should be undertaken without delay if fusion-fission hybrids are to be taken seriously as an additional option for the medium-term and long-term phases of the energy future.

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