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February 1978

UWFDM-240

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## Notes on Fusion Hybrid Reactors

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February 28, 1978

The D-T fusion process produces four times as many neutrons per unit of energy as the fission reaction. Further, fusion neutrons have an initial energy of 14.1 MeV as compared with an average fission neutron energy of about 2 MeV. For these reasons, fusion reactors can be attractive fuel factories for the production of fissile material. Many studies in recent years have examined different types of hybrids.<sup>(1,2)</sup> We outline in this note a combination of hybrid reactors and light water fission reactors (LWR) which minimizes alterations and technology developments in the present fission industry, extends our fissile fuel reserves by a large amount, is proliferation resistant, and may permit adequate time for deliberate decisions on fuel reprocessing and physically secure fuel production centers. The hybrid is treated here primarily as a fissile fuel factory and enrichment facility, first without and then with fuel reprocessing. Other converter reactors can be considered but we emphasize the LWR because it is presently the workhorse of the U.S. nuclear industry.

### A. The Hybrid System as a Fuel Factory Without Reprocessing

Natural uranium occurs as 0.7%  $^{235}\text{U}$  in  $^{238}\text{U}$ . This fissile fuel reserve can be increased by at least a factor of 4 without reprocessing by using a hybrid reactor to enrich either natural uranium or completely fertile fuels such as  $^{238}\text{U}$  or thorium to ~3-4% fissile material. The proliferation resistance of the system described here comes about because the fissile fuel occurs only in highly radioactive fuel assemblies. These assemblies are shipped

from the hybrid to the fission reactor and are returned after use as spent fuel to storage. If such protection from theft and diversion is acceptable (and we elaborate on this shortly ) then either the thorium-<sup>233</sup>U cycle or the uranium-plutonium cycle should be acceptable. We first consider the use of thorium as the fertile material and discuss the acceptability of using the <sup>238</sup>U-<sup>239</sup>Pu cycle in part C.

The process proposed is outlined on Fig. 1 and involves four steps:

1. The fabrication of fertile ThO<sub>2</sub> fuel assemblies in a form directly usable in an LWR. Other convertor reactors may be included but the integration with existing U.S. industry is more complicated.

2. The irradiation of the fuel assemblies in a hybrid reactor to enrich the fuel to 3-4% as required for the LWR.

3. The transfer of irradiated assemblies as units directly to LWR's and burning of the fuel.

4. Storage of the spent fuel until a decision is made on reprocessing or permanent storage or both. If feasible, one can insert the spent assemblies into the hybrid to re-enrich the fuel and burn it further in the fission reactor. This possibility depends upon the importance of fission product buildup to LWR performance and the radiation damage to both the fuel and the cladding.

The attractive features of this cycle are the following:

1. The system is resistant to diversion because fissile material occurs only inside highly radioactive fuel assemblies. Only fresh fertile material is fed to the hybrid and, upon removal, the fuel pellets contain fission products that are highly radioactive and

The Hybrid System as a Fuel Factory Without Reprocessing

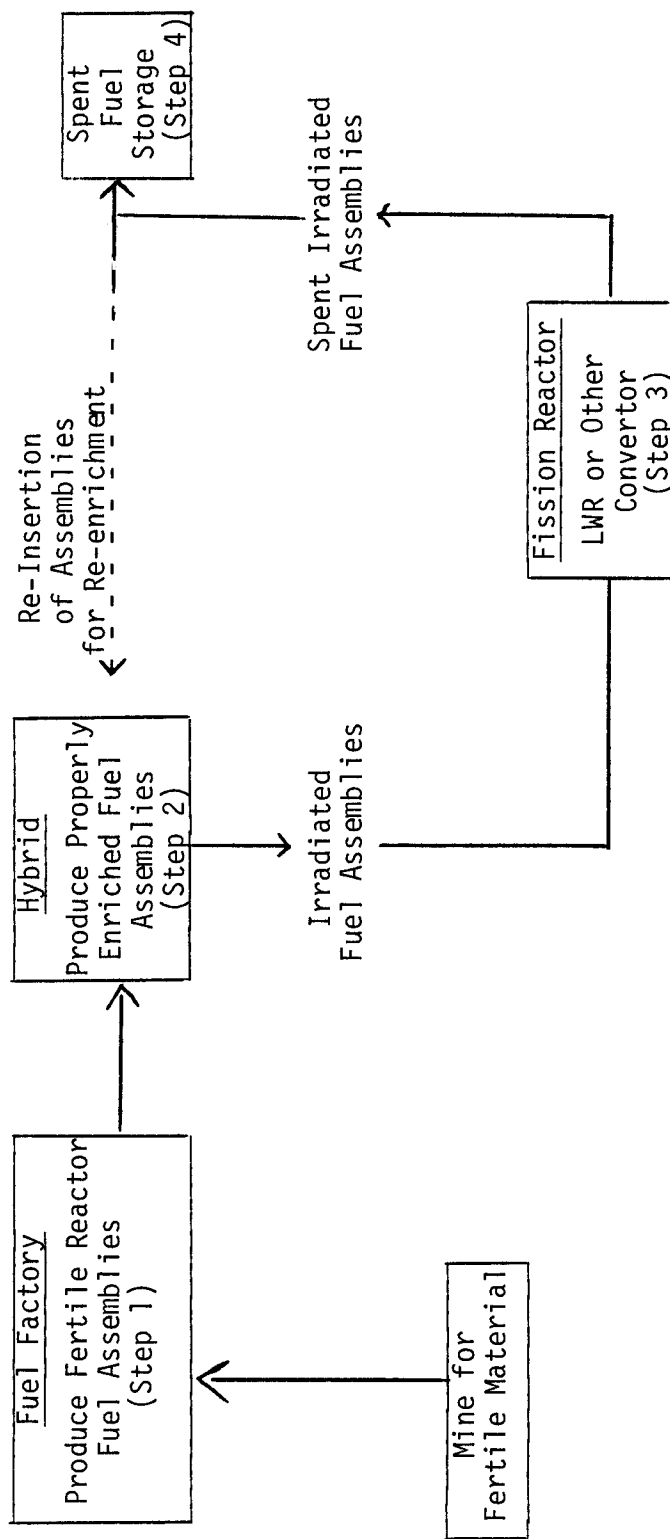


Fig. 1

Note: The Fusion hybrid provides fuel for only 1-2 fission reactors without reprocessing.

the pellets themselves are contained in rod assemblies with highly activated cladding. Access to the fissile material is thus very difficult making the entire cycle proliferation resistant. Feiverson and Taylor<sup>(3,4)</sup> have argued elsewhere that spent or highly irradiated fuel is self-protecting.

Such assemblies weigh approximately half a ton and the radiation is so strong as to provide a lethal dose of gamma radiation in just a few seconds. They argue that stealing irradiated assemblies would require heavy cranes, tons of shielded containers, and a large vehicle for transporting the stolen, shielded assemblies. Further, such thieves must still perform the very dangerous and technically difficult task of separating the  $^{233}\text{U}$  from the fuel. While these obstacles may not be as formidable as isotopic enrichment, they are nevertheless quite severe.

The presence of fissile material only in highly radioactive assemblies should eliminate the need to denature the  $^{233}\text{U}$  fuel by adding roughly six times as much  $^{238}\text{U}$ . It is true that without denaturing, the highly radioactive fuel assemblies will contain  $^{233}\text{U}$  which can be chemically separated, albeit with the difficulties described above. However, in denatured fuel, some of the  $^{238}\text{U}$  is converted to chemically separable Pu. Feiverson and Taylor consider the highly radioactive nature of the spent fuel to be adequate protection and we would argue that the highly radioactive nature of the fuel assemblies coming from the hybrid are likewise protected from theft and diversion. One could of course denature the fuel for added protection but the additional  $^{238}\text{U}$  displaces thorium in the fuel and lowers the conversion ratio for producing  $^{233}\text{U}$ .

2. The fissile fuel reserves are extended substantially. If the average LWR fuel enrichment is assumed to be 3%, the fissile fuel reserves are extended by  $4.3 \times$  (Thorium Resources/Uranium Resources). According to Staatz and Olsen,<sup>(5)</sup> the occurrence of thorium is widespread but the resources are not well known because present demand is low. The demand in 1968 was for only about 125 tons of  $\text{ThO}_2$ . Estimates of the thorium content of the earth's crust range from 6 to 13 ppm. Identified world thorium resources recoverable primarily as a by-product or co-product are about 1.4 million tons, one-third of which occurs in a deposit near Elliot Lake, Canada. The general understanding is that large additional resources would be found with additional exploration. If we assume the thorium resources are no larger than the uranium resources, the fissile fuel supply is extended by a factor of 4 to 5 without reprocessing.

3. The extension of the fission fuel supply using the hybrid produces additional time that can be used to make deliberate decisions on issues such as internationally controlled, physically secure fuel production and fuel reprocessing centers.<sup>(3,4)</sup>

4. The use of LWR assemblies in the hybrid followed by direct transfer to the fission reactor appears to be the simplest method of integrating the hybrid with U.S. industrial and utility LWR experience. Significant retrofitting or abandonment of existing LWR facilities should not be required. One will however need to handle irradiated assemblies in the process of loading the fuel, something that is not now required.

5. The manufacturing of fresh fertile fuel pellets can proceed without the handling problems inherent in the use of a radiation spiking material such



as  $^{60}\text{Co}$ . This avoids any legal or safety issues associated with the deliberate addition of dangerous materials.

The major disadvantage of this system is that it does not take full advantage of the fertile fuel reserves. To achieve a fuel supply measured in thousands of years, rather than just a few hundred, fuel reprocessing is essential. Without reprocessing, one hybrid reactor is only able to supply fissile fuel to between 1 and 2 LWR's which has the economic impact of increasing the effective fuel cost. With reprocessing, more than 5 LWR's can be fueled from one hybrid, depending on the conversion ratio of the LWR or other converter.

#### B. The Hybrid System as a Fuel Factory with Reprocessing

The cycle described in part A can be extended to include reprocessing. The system described here is particularly attractive for use in the structure outlined by Feiverson and Taylor<sup>(4)</sup> of regional internationally controlled, physically secure fuel production and reprocessing sites combined with many national converter reactors "outside the fence". The process we consider now involves the four steps outlined in Fig. 2.

Step 1. The fabrication of fresh  $\text{ThO}_2$  fuel assemblies in a form directly usable in an LWR or other convertor reactor. This step will also involve the fabrication of enriched fuel assemblies at the secure site using fissile fuel from the reprocessing step. We propose that such fuel be only partially enriched (for example, to just 2% even though about 3-4% is required) and that the hybrid be used to produce the required additional enrichment. The fuel assemblies are irradiated in the process which makes them highly radioactive. As argued earlier, denaturing with  $^{238}\text{U}$  or spiking the fresh fuel should not be required.

The Hybrid System as a Fuel Factory with Reprocessing

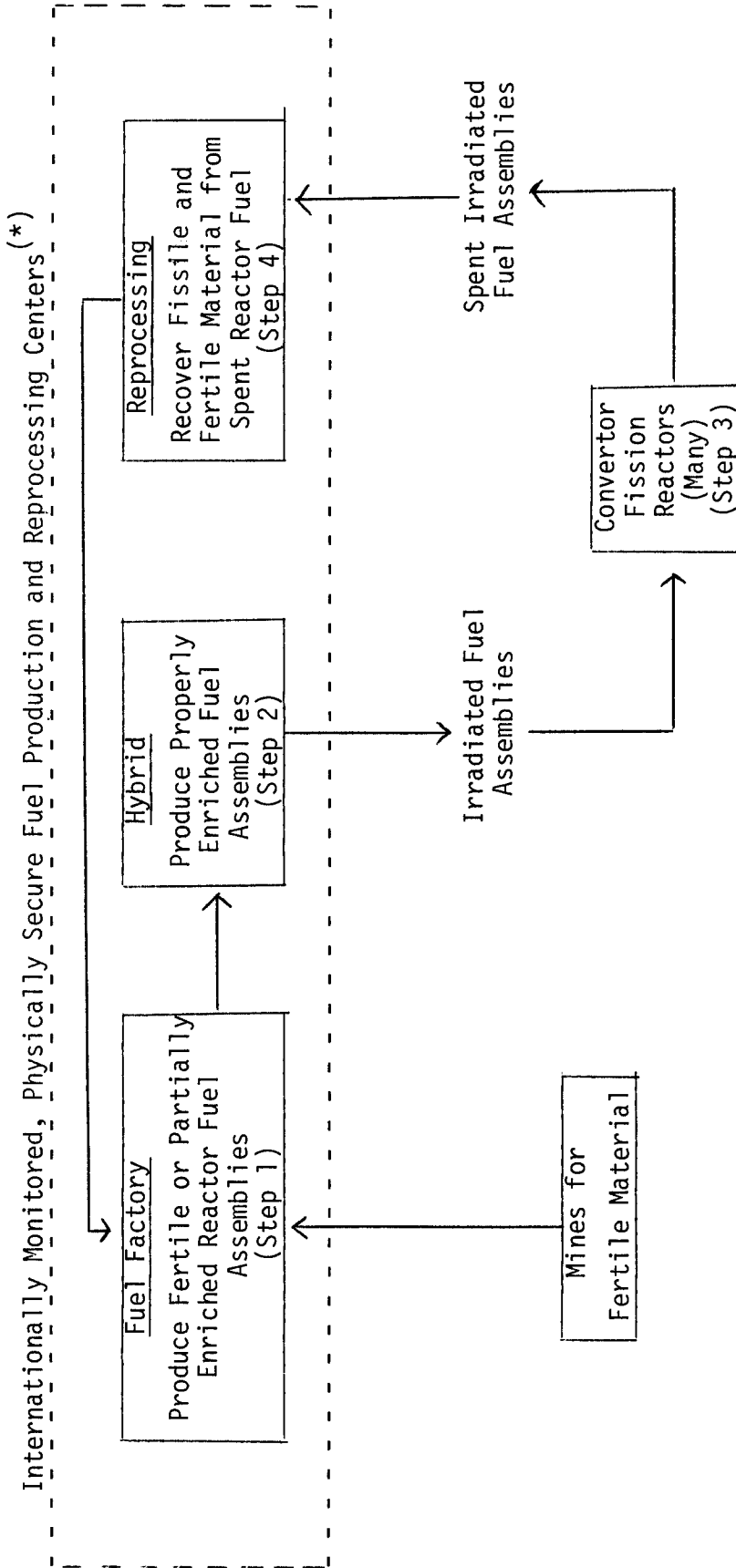


Fig 2.

Note: One hybrid supplies fuel for many (5 or more) fission reactors, depending on their conversion ratio.

(\*) Such a center is proposed by Feiverson and Taylor.<sup>(3,4)</sup> In their proposal, a Pu fueled LMFBR is used as the breeder of <sup>233</sup>U.

Step 2. Irradiation of converter reactor fuel assemblies in a hybrid reactor to produce the required fissile enrichment. Including reprocessing, one hybrid should be sufficient to fuel more than 5 convertor reactors.

Step 3. Burn the fuel in a convertor reactor.

Step 4. Ship the spent fuel assemblies back to the physically secure site for reprocessing. The reprocessing plant removes fission products and sends fissile material to the fuel factory for fabrication into new fuel assemblies.

In designing the hybrid blanket, it can be useful to include a  $^{238}\text{U}$  fission zone for neutron multiplication. This zone would be most effective when enriched with Pu. One can reprocess this fuel to burn the Pu in fission reactors, such as the LMFBR, located on the secure sites.

The advantages of this approach are the following:

1. The fuel supply is measured in terms of the fertile material abundance. All estimates show such fuel supplies will last for thousands of years.

2. Fuel shipped to and from convertor reactors is always highly radioactive and would be resistant to diversion and reprocessing for the reasons described earlier.

3. The convertor reactor need not be restricted to an LWR although using these reactors will minimize the need to develop additional fission reactor technologies.

### C. The Uranium-Plutonium Cycle

It has been argued that spent or highly radioactive fuel is its own self-protection and we summarized earlier the arguments of Feiverson and Taylor. These arguments are that stealing highly radioactive fuel assemblies would require heavy cranes, tons of shielded containers, and large

vehicles for transporting the stolen shielded containers. Even if successful, the next step of recovering the fissile material from the highly radioactive fuel is a difficult and dangerous job. The sum of these protective barriers is considered sufficient to deter diversion from a denatured  $^{233}\text{U}$  cycle in which Pu generated from the  $^{238}\text{U}$  occurs in chemically separable form in spent fuel.

In the systems outlined in parts A and B, the fusion hybrid reactor is used to enrich the fuel that is sent to the fission reactors. The fuel is rendered highly radioactive in the process. We have argued that this fuel is likewise self-protected and that denaturing, which leads to Pu in the spent fuel, is not necessary. It is important to recognize that this self-protection would extend to any fissile material and, in particular, should be equally applicable to  $^{233}\text{U}$  or to Pu. Therefore, the two fission-fusion hybrid combinations outlined in parts A and B could be based on the  $^{238}\text{U}$ -Pu cycle. The major advantages of using the U-Pu cycle are that the well established and large uranium reserves could be fully utilized and that we would be able to employ the well-established technology associated with uranium fuel.

#### D. Comments

Clearly, the limited fission-fusion hybrid combination outlined in part A or the expanded combination outlined in part B requires the development of fusion to the point where it is a reliable technical system. Advances have been rapid in recent years and energy breakeven experiments are planned for the early 1980's. Success in these experiments should make it feasible to construct an initial hybrid test facility by 1990 or somewhat

thereafter. A detailed scenario for this was described elsewhere several years ago.<sup>(6)</sup> The most important point is that the connection of successful fusion physics to a near term goal based on either of the fission-fusion hybrid combinations described here should be considered in national decision-making. To know we can do something, even if it has not yet been done, is important. On the other hand, until an engineering prototype of a hybrid is shown to be technically feasible, maintaining options such as the LMFBF as insurance seems only prudent.

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