the role of HTGRs and FBRs in meeting the Energy Crisis

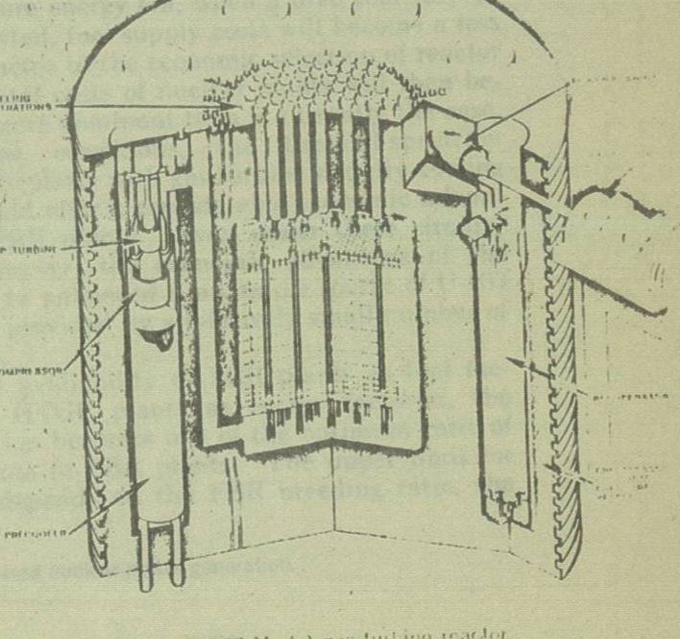

Fig. A 1000 Mw(e) gas turbine reactor

The fast breeder reactor uses a uranium cycle to refuel itself. However, its excess bred fuel can best be exploited in a high-temperature gas-cooled reactor, a thorium-cycle-based converter type. For this purpose, fissile feed material such as U-233 can be bred in thorium blankets around FBR cores. Thus both reactor types can be used to complement each other, a fortunate circumstance in the effort to successfully meet the long-range energy crisis.

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In considering the incentive for operating both fast breeders and HTGR's in a power program, see Fig 1, the first aspect requiring clarification concerns the extent to which an external supply of U-233 could benefit the thorium-uranium thermal reactor fuel cycle.

The precise extent of the benefit of being able to operate the HTGR system from the start on U-233 is a much more complex question than might be supposed, for the prime goal of minimal power cost inevitably involves compromise in design between conflicting issues. Thus, getting the most benefit from an improved starting fuel calls for complete design reoptimization. Indeed, this is one reason why having such fuel available from the start is much more advantageous than breeding it in during reactor life, for the latter approach largely precludes the design reoptimization necessary to extract full benefit. By looking at what we presently get with U-235 start-up and at some of the compromises involved in design for the alternative case, we may get some idea of the potential rewards of being able to design for the best fuel from the start.

The conversion ratio for present HTGR designs, when initially operating on U-235 without U-233 recycle, approaches a steady-state value of 0.60 after about 10 years of operation. Even when all the U-233 in the spent fuel is recycled and equilibrium is reached, a conversion ratio of only perhaps 0.7 is attained. This might seem surprising for an "advanced converter" which, in principle, could achieve near-unity conversion on the thorium U-233 cycle. It is, therefore, important to observe that these figures do not arise from inherent design limitations, but are simply the result of adjustment to achieve minimal power cost.

It turns out that, under prevailing conditions, it is more economical to take advantage of the HTGR core's special ability to achieve very high rating than to exploit its full potential as a near-breeder. Introduction of U-233 from the start changes this situation by providing increased conversion without corresponding loss of fuel rating. Indeed, the accompanying increase in effective fission cross-section and the improvement in age-peaking factors substantially raise the rating capability. Thus, while there will still be a new optimum conversion less than the ultimate, this value can be much higher than the present figure. This is illustrated by the fact that a simple change from U-235 to U-233 with appropriate fertile-to-fissile ratio adjustment alone would raise conversion by at least 0.1. The use of more frequent fueling or on-line refueling would allow another increment of about 0.05. The rapid rise of the "fuel amplification" term [1/(1-CR)], as unity conversion is approached, further acts to raise the optimum degree of breeding. It also makes the optimum much "flatter," allowing further breeding gain for little penalty.

Another feature of present limitations is the slow U-233 buildup associated with low-conversion operation. The available U-233 content of fuel recycled from HTGR's started on U-235 never, in fact, amounts to more than about one-third of the total fissile feed requirements of these reactors. Thus restricted, HTGR's do not fully exploit the U-233 advantage. Availability of U-233 from a high-gain breeder would, therefore, provide a route for eventually making use of the full, undiluted benefits of U-233.

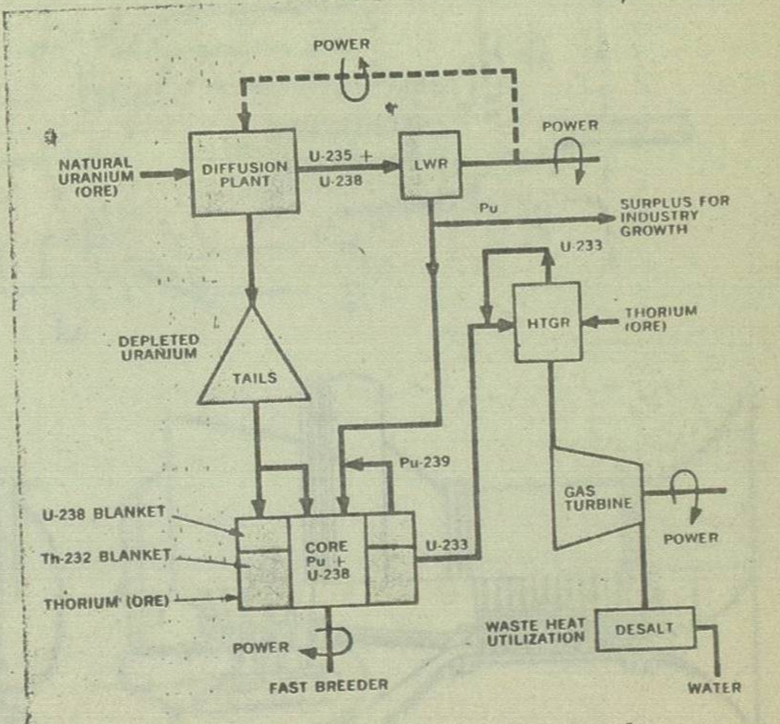
Optimal Association of FBR's and HTGR's

Systems analysis studies by the USAEC and national laboratories have had, as an objective, the determination of the probable energy growth patterns by power plant type, based on projected national energy requirements, resource availability assumptions, and power plant economic assumptions. The results of these studies have contributed, probably unwittingly, to the impression that one type of nuclear power plant will triumph over all other candidates. However, the ultimate emergence of the FBR as the predominant source of energy in these analyses should not be too surprising in view of the assumptions and the constraints applied. The most influential assumptions in the studies were probably: (*a*) the relative capital cost data for different reactor types, (*b*) the value of U_3O_8, and (*c*) the type of bred fuel allowed from the FBR plants and the disposition of this fuel. The last point is particularly important in the very long range. In all cases, it was assumed that excess plutonium was bred from natural or depleted uranium blankets. While plutonium is, of course, the most ideal fuel for fast-spectrum reactors, thermal-spectrum reactors would be expected to profit more from the production of U-233 in thorium blankets. The higher conversion ratio attainable with U-233 would also allow a larger number of thermal-spectrum reactors to be supported by a fixed source of bred fuel.

In the future energy era, when a bred fuel surplus can be expected, fuel supply costs will become a less important factor in the economic selection of reactor types. Capital costs of nuclear plants will then become even more dominant than is currently the case. Under these conditions, the thermal-spectrum HTGR, particularly with gas turbine and dry-cooling towers, should offer a considerable economic advantage over FBR plants. Even under these circumstances, however, the economic advantage of the HTGR can be enhanced if an ample source of U-233 feed fuel is provided by a relatively small number of FBR plants.

With the availability of FBR plants as fuel factories and HTGR plants as energy factories, the basic question becomes one of the optimum ratio of HTGR plants to FBR plants. The upper limit for this ratio depends on the FBR breeding ratio, the

Fig. 1 Integrated nuclear power generation.



HTGR conversion ratio, and the rate of growth of new energy requirements. For an FBR breeding ratio of 1.5 and an HTGR conversion ratio of 0.9, approximately four HTGR plants can be supported by one FBR plant, assuming energy generation has reached a steady-state condition, i.e., no growth. While the growth of electrical energy is currently at a rate of about 7 percent per year, one would expect that over the period of 100 years or more, some asymptotic energy generation level will be reached, after which the level of energy generation will stabilize. In 50 years from now, the rate of growth of electrical energy is expected to be between 3 and 4 percent per year. For a growth rate of 3 percent per year, the ratio of HTGR to FBR plants would be about two to one.

The optimum balance between HTGR and FBR plants has still further ramifications. If the capital cost advantage of the HTGR over the FBR is significantly large, as it indeed might be, then further advantages may be realized with the system by operating the HTGR off its economically optimum condition in order to increase the conversion ratio still further and allow an even larger number of the still more economic energy plants relative to the fuel-producing plants.

Another variant in operating strategy might involve the optimization of load assignments to the FBR and HTGR plants. Generally, the overall load factor for the entire energy system would probably be less than 70 percent. By operating the FBR plants at their maximum availability, say 80 percent, the production of fuel could be maximized, again allowing a larger fraction of the total number of power plants to be the lower-cost HTGR plants.

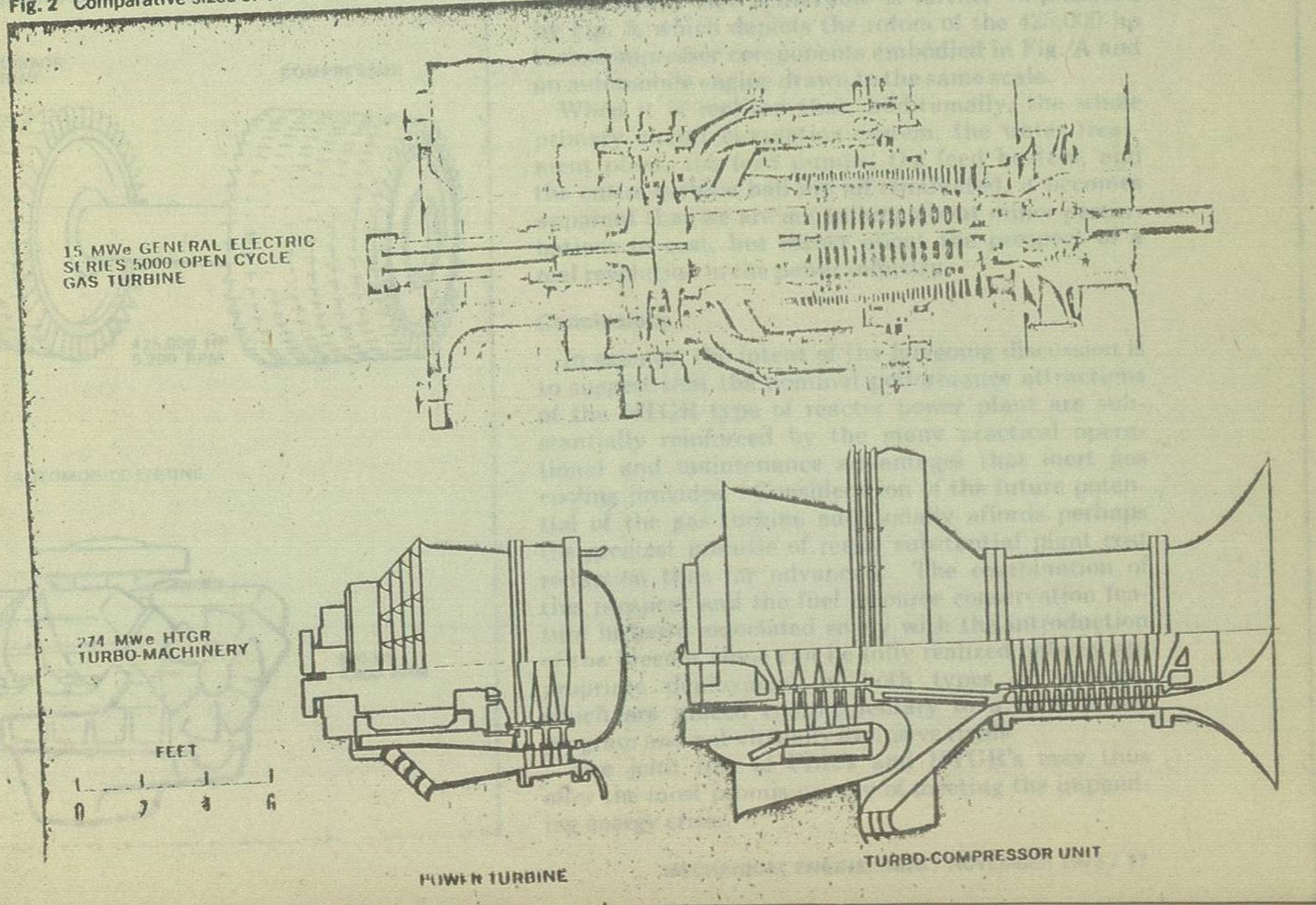
With an HTGR conversion ratio close to unity, relatively modest changes in operating strategies can lead to quite significant economic rewards.

The Role of the HTGR

Since fast breeders produce more fissile material than they consume, being, in this sense, "fuel factories," and at the same time operate at temperatures allowing efficient power generation, the need for any other kind of reactor at all might be questioned. If fuel cycle costs were the only factor to be considered, a power program dependent entirely on fast breeders would certainly appear attractive. However, far more must be considered in determining real total system economy, and it is this latter criterion, and not just fuel costs or even global fuel conservation issues, that really determines the acceptability of a particular reactor system.

Total nuclear power costs are dominated by capital charges, and, in the case of the efficient FBR/HTGR breeding system combinations we are discussing, this would be even more evident. A prospective fuel cycle cost of approximately 1 mill/

Fig. 2 Comparative sizes of turbomachinery.



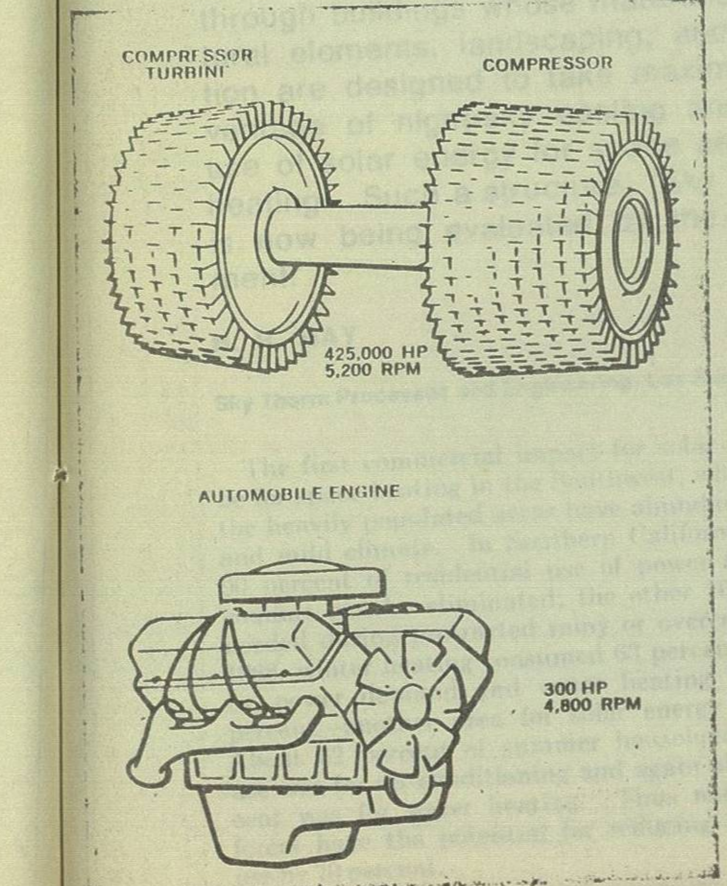
kwhr, for example, would amount to less than 12 percent of the generating costs associated with a plant having a capital cost of $400/kw. A modest capital cost increase can thus easily wipe out a large fuel cost advantage. Furthermore, even a small outage time has the same effect, for by far the greater part of operating cost is independent of whether or not such a plant is working.

What really sells a nuclear power plant, then (particularly one of the new generation), is the cost of building it and the likelihood that it can be kept going, as indicated by demonstrably simple maintenance, as well as confidence in reliability. These issues, together with factors affecting freedom of site choice, are what really count. It is in these areas that the prospects of the fast breeder are less clear, and indeed require extensive further study.

The issues raised are largely matters of practical engineering, rather than physics, and are concerned not only with the capital cost and other characteristics of presently constructed types of plant, but, more importantly, with the impact of future requirements and technical developments. Prominent among the latter are the increasing pressures of environmental factors and the possibilities offered by successful adaption of the closed-cycle gas turbine to the needs of nuclear power.

The connection between these last two factors is simply that, because of the inherently much higher mean temperature level of the gas turbine's heat reject, it can be much more readily adapted to the needs of dry cooling. In fact, about ten times less air (correspondingly heated to ten times the temperature rise permissible with a steam plant) suffices to dispose of the gas turbine's heat. Thus, the advent of the closed-cycle gas turbine, practically adaptable only to the HTGR's high gas temperature, is of particular importance to the solution of heat-rejection problems and thereby provides a much wider freedom of site choice.

Fig. 3 Turbocompressor rotors for 250-Mw nuclear gas turbine.



Even in the absence of a dry cooling requirement, the attractions of the direct-cycle nuclear gas turbine in terms of plant simplification and capital cost savings are impressive and add greatly to the prospect of the capital cost reduction so essential to achievement of really economic nuclear power.

A second, perhaps less dramatic, but certainly more appropriate, illustration of the compactness typical of closed-cycle machinery is provided by Fig. 2, which compares the size of such a system with that of a representative open-cycle system as presently used for power peaking duty. In this case, the striking point is the enormous increase in power for roughly similar size brought about mainly by the pressurization of the closed-cycle's exhaust.

Fig. A conveys something of this potential by illustrating graphically the extreme compactness of the closed-cycle gas turbine, which allows its complete incorporation into spaces in the reactor vessel that were needed to house solely the boilers of a steam nuclear power system. The degree of the reduction in machinery size achievable is further emphasized by Fig. 3, which depicts the rotors of the 425,000-hp turbocompressor components embodied in Fig. A and an automobile engine drawn to the same scale.

When it is realized that, additionally, the whole primary circuit circulation system, the water treatment plant, the feed pumps, the feed heaters, and the entire turbine hall are all eliminated, it becomes apparent that we are not talking about minor perturbations to cost, but rather about the prospect of a real revolution in the power industry.

Conclusions

In essence, the intent of the foregoing discussion is to suggest that the nominal performance attractions of the HTGR type of reactor power plant are substantially reinforced by the many practical operational and maintenance advantages that inert gas cooling provides. Consideration of the future potential of the gas turbine additionally affords perhaps the greatest promise of really substantial plant cost reduction thus far advanced. The combination of this prospect and the fuel resource conservation feature hitherto associated solely with the introduction of the breeder alone can be fully realized only by appropriate deployment of both types of systems, which are indeed complementary to a total power program and not virtually exclusive rivals.

The joint role of FBR's and HTGR's may thus offer the most promising way of meeting the impending energy crisis.