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PREPRINT UCRL- 81600

Lawrence Livermore Laboratory

CUMULATIVE FUEL COMMITMENT FOR LIGHT WATER REACTORS
IS THERE A "URANIUM CRUNCH?"
THE FUSION-FISSION FUEL FACTORY CAN HELP

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September 11, 1978

MASTER

This paper was prepared for presentation at the 4th Course "Driven Magnetic Fusion Reactors", Erice, Italy, September 18-26, 1978

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Summary

It can cautiously be stated that there is not an imminent U.S. uranium crunch, because the installed capacity of fission reactors to 1990 is less than was anticipated. We have time for careful judgment and deliberation. We probably have until at least the year 2000 before beginning the phasing-in of a new technology to augment or replace the light water reactor. Consequently the fusion-fission hybrid appears to have strong potential as a fuel factory supplying fuel to the LWR industry. The hybrid relaxes some of the physics and engineering constraints on pure fusion and should be available somewhat sooner. The hybrid also integrates into the energy plan by supporting fission rather than replacing it. The hybrid seems like a good interface between the eventual pure fusion reactor and fission. The easing of the fission fuel demand under that which was anticipated, coupled with the high probability that available uranium resources are proportional to the price paid per pound (within limits) are likely, more than currently stated, serving to fusion's advantage by buying time for development.

"Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48."

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Installed Capacity for Nuclear Plants

Our principal reference is the August 1978 ANS list of nuclear plants.¹ From this listing it is seen that for the US the 1990 installed capacity $\cong 200$ GWe.

Since it is only 12 years until 1990, and it takes ~ 12 years to place a nuclear plant in operation, it is fairly certain that the installed capacity will not increase. It may, in fact, decrease due to cancellations or delays. However, we use 200 GWe as a reliable value. (The ANS US total is 195,678 GWe.)

We can assume some nuclear power growth rate per annum. In n years at i rate, the installed capacity after 1990 must be:

$$\text{Cap} = 200 (1 + i)^n.$$

Fuel Consumption

For a 1.GWe light water reactor with an 80% capacity factor, 171 tons of U_3O_8 are required per year. This is a conservative case. The HTGR with a higher conversion ratio would use only ~ 72 tons. We use the conservative case -- 171 tons.

Fuel Inventory

The inventory or initial core requirement of U_3O_8 per 1.GWe reactor is 480 tons.

Guaranteed Fuel Supply

Each new reactor coming on line must have a 30-year guarantee on fuel supply. If this were not the case, the utility would be highly reluctant to build it. The tonnage guarantee is 480 (initial core) plus 29 reloads (29×171).

Cumulative Fuel Commitment

The cumulative fuel commitment (CFC) is related, therefore, to the fuel consumption (FC), to the necessary inventory (I), and to the guaranteed fuel supply (GS).

If we take 1960 as a datum and declare that in that year the connected nuclear load was near zero, then the sum of the three areas under the curve represent the cumulative number of GWe years as a function of time. The total number of GWe years is

$$A + B + C \\ A + B + C \approx 100n \left[(1 + i)^n + 1 \right] + 3000.$$

At 171 tons of U_3O_8 required per GWe reactor per year, the fuel consumption is:

$$FC = (1.7 \times 10^4) n + 1 + (1 + i)^n + 5.14 \times 10^5$$

The total inventory, or the sum of the core requirements, of U_3O_8 at 480 tons per GWe is:

$$I = 200 (1 + i)^n \times 480 \\ = (9.6 \times 10^4) (1 + i)^n .$$

The guaranteed total fuel supply is, on the average, equal to the installed GW capacity x fuel consumption per GW-year x 1/2 the guarantee period.

$$GS = 200 (1 + i)^n \cdot 171 \times 30/2 .$$

Example: Let the growth rate $i = 5\%$, and n the number of years beyond 1990, be in 5 years steps until 2020. The data are shown in Table I.

Thus, as an example at time 1990 plus 20 years, or 2010, the connected load would be 530 GWe. This would require a fuel commitment of

3.13×10^6 tons of U_3O_8 including a fuel reserve that would sustain that total installed capacity for another 15 years. This could provide constant power to 2025, if somehow all plants were not retired. In the standard case of limited plant life and normal retirement, it would provide declining power at an average rate (3.3%/yr. for 30 year plant life) to the year 2040.

For two other growth rates of 2.5% and 7.5%, we have the following:

TABLE II

i = 2.5%	YEAR					
	1995	2000	2005	2010	2015	2020
2.5% n =	5	10	15	20	25	30
$(1 + i)^n$	1.3	1.28	1.45	1.64	1.85	2.1
Conn. Load GW	226	256	290	328	370	420
Consumption $\times 10^5$	4.39	6.47	8.85	11.6	14.8	18.5
Inventory $\times 10^5$	1.08	1.23	1.39	1.57	1.78	2.02
Guaranteed Fuel $\times 10^5$	5.8	6.57	7.44	8.41	9.49	10.8
Cum Total LWR $\times 10^5$	11.3	14.3	17.7	21.6	26.1	31.3
i = 7.5%						
7.5% n =	5	10	15	20	25	30
$(1 + i)^n$	1.44	2.06	2.96	4.25	6.1	8.75
Conn. Load GW	288	412	592	850	1220	1751
Consumption $\times 10^5$	4.66	6.09	12.7	20.5	32.9	52.6
Inventory $\times 10^5$	1.39	2.0	2.85	4.1	5.88	8.44
Guaranteed Fuel 10^5	7.39	10.6	15.2	21.8	31.3	44.9
Cum. Total LWR	13.4	18.7	30.8	46.4	70.1	106

Part of the strategy in easing the cumulative commitment for U_3O_8 may be to use (after 1990) reactors that are more neutron conservative and more efficient. Fuel consumption (as U_3O_8) in a HTGR is ~ 72 tons per GWe year, instead of 171 tons for the LWR. The U_3O_8 inventory is about the same.

Reserves and Resources

The estimated United States resources of U_3O_8 are highly uncertain. Recent values range from a low of approximately 2×10^6 tons to values as high as 10×10^6 . Resources of 25×10^6 tons at \$100/lb U_3O_8 were cited by the AEC as recently as 1970. Since that time, investigators tend to accept lower values.²

It is a historical fact that resources more often than not are generally underestimated. This is due to the fact that there is no incentive to establish much more than a thirty-year resource. Anticipation of needs beyond thirty years for ongoing businesses is generally not given much attention. It is too far off to worry about. The reserves related as they are to near term operations, as opposed to the longer term resources, seem to have a more tangible base since by definition (as defined jointly by the U.S. Bureau of Mines and the U.S. Geological Survey) they are "in hand" and represent the fraction of the resource delineated by adequate exposure at the surface, or in drill holes or excavations available under present technology and current economic and political conditions. Even so, caveats on price, politics and technology in this definition lend some uncertainty to reserve amounts. Witness our uncertainty about reserves of natural gas. Uranium reserves are given as a function of price, currently \$50/lb. of U_3O_8 . If the price were higher, the reserve would be higher. Higher prices would also serve as an incentive for new discoveries, thereby increasing the resource.

Related to this argument of 'higher price--higher resource' is the estimate that the cost of electricity from LWR's increases only about 0.6 mils/kWh per \$10/lb increase in the price of U_3O_8 .³ Thus, U_3O_8 at \$150/lb would increase bus bar costs about 6 mils per kWh over the \$50/lb price. This 6 mil differential is about the same as the differential fuel cost between the lower cost nuclear and coal in the year 2000, (see Pacific Gas & Electric Company, US cost data Table III attached) which suggests that the added fuel cost can be accommodated. If this higher allowable fuel cost is acceptable, then the known resources and reserves of U_3O_8 should increase as a result of the price

incentive. A resource value of 4×10^6 tons of domestic U.S. U_3O_8 would thus appear to have a reasonable base. Moreover, imports from Africa and Australia may provide the main source of U_3O_8 since these countries have large supplies. On this basis, which is not fact but reasonable supposition, we may assume low, moderate and high availability values for U_3O_8 of 2, 4 and 8×10^6 tons and estimate the consequences. The cumulative fuel commitment as a function of time for various growth rates are plotted in Figures 1 and 2 for LWR's and HTGR's.

The Question of Growth Rate

The growth rate of 7.5% for base load electric nuclear plants starting with 200 GWe in 1990 is probably not achievable or realistic, at least under the present U.S. pressures on licensing, site selection, etc. From a manufacturing-construction standpoint, however, this rate is within the capability of industry. The 5% rate is about equal to the historical rate for total energy. It is also about equal to the National Energy Plan of 4.6% through 1985.⁴ The ERDA extension of the NEP is 3.9% from 1985 to 1990 and 3.7% after 1990. Two and one-half percent rate is quite low, but may prevail. If we use 5%, then without the help of the more effective HTGR, the "crunch" on uranium would not occur until around 2015 provided that the estimates resources of U_3O_8 are $\sim 4 \times 10^6$ tons. With the help of the HTGR the time would be extended to 2025. If we factor in logical advances in technology, such as laser isotope separation, so as to decrease the tails assay from $\sim 0.3\%$ to say 0.15% and include spent fuel reprocessing, then more energy can be made available per pound of U_3O_8 . Spent fuel assays commonly are ~ 0.8 to 0.9% with initial fuel assays of ~ 2.8 -3.5%. There is improvement that is possible for this fuel cycle, further decreasing the annual fuel consumption and extending the time. All things considered, the time period around 2015 seems to be conservative.

Whether the time is 2015 or some number of years beyond that, the fact remains that we must plan ahead. We must allow not less than 20 years in advance of this date for a substitute to begin to take up the slack. Generally it takes at least this amount of time for a new technology to have any measurable influence. This time requirement for

the energy producers is illustrated in Figure 3. It can be seen that oil, for instance, starting in about 1880 took until about 1905 to capture 5% of the market. Natural gas started even more slowly, but from about 1920 to 1940 achieved a 5% market penetration. Coal fared somewhat better. The technology-intensive nuclear industry took 20 years to acquire 2.5% of the total; or, since nuclear is all base load electrical, it is more correct to say it took 20 years to provide 10% of the electrical energy.

Even with the 20-year allowance considered, there does not seem to be any great urgency in the pursuit of the fission breeder reactor. The breeder is at the commercial state if breeders in Europe are accepted. It certainly will be commercial in the U.S. by ~1995 when it would be required to begin entering the market. For fusion as a new energy source, there is the implication that if a commercial prototype is available ~2000, it will be time enough. If the U_3O_8 resource proves higher than the 4×10^6 tons, or if we use the fuel judiciously, then would be able to have even more development time. Demonstration of higher resources ($>4 \times 10^6$ tons) or doing a better job with what we have is a two-fold benefit for pure fusion; it buys time, which may be sorely needed, and it defers deployment of the breeder. Demonstration of moderate resources ($\sim 4 \times 10^6$ tons) defers the deployment of the breeder and may give time for the fusion hybrid fuel factory which would supply fuel to the light water or high temperature gas cooled reactors. Low resources ($\sim 2 \times 10^6$ tons) places more urgency on deployment of the breeder at an earlier time (~ 1980) and could hamper both pure fusion and the hybrid.

Recent Trends

There is another factor to consider and that is the growth rate of fission plants particularly in the U.S. has slowed drastically. This is illustrated in Figure 4. The growth rate in the 1990 period is negligible when compared to a growth rate of 30% between 1970 and 1975 and 12% between 1975 and 1980. At 200 GWe connected load in 1990 if we were to try to recoup a growth rate of 5%, it would be necessary to place orders or preliminary letters of intent today since overall construction time is ~12 years. The orders are not being placed.

In comparing these estimates on fuel requirements to previous calculations made in the late 60's and early 70's to justify the breeder (i.e., the suggestion of a uranium crunch 2000), the points to recognize are that there has been a much lower overall growth rate in fission reactors during the period 1970 - 1990 than was anticipated, and the growth rate is really at a standstill now. None of the early analysts had the benefit of knowing, with almost certain reliability, that the installed capacity in 1990 would not be more than 200 GWe. For instance, in the AEC document, WASH 1139, dated February, 1974, it was estimated that there would be from 850 to 1400 GWe nuclear plants in the year 2000. Using the 200 MWe by 1990, if we take a steep but rather unlikely growth rate of 7% per annum, then the installed capacity will be slightly less than 400 GWe in the year 2000. This is roughly two to four times less than was previously anticipated and can do nothing but ease the "crunch" on uranium.

References

1. List of World Nuclear Power Plants -- American Nuclear Society News, August 1978 issue.
2. Domestic Uranium Requirements, R. W. Brown, R. H. Williamson, Policy and Evaluation -- U.S. Department of Energy, presented at the Uranium Industry SEminar, October 26, 1977, Grand Junction, CO.
3. Benedict M 1971 "Electric Power from Nuclear Fission," Proceedings of the National Academy of Sciences 68 pp. 1923 - 1930.
4. Executive Office of the President. The National Energy Plan, April 29, 1977.

TABLE I

i = 5%	YEAR					
	1995	2000	2005	2010	2015	2020
n =	5	10	15	20	25	30
$(1 + i)^n$	1.28	1.63	2.08	2.65	3.39	4.32
Conn Load GWe	256	326	416	530	678	864
Consumption x 10^5 tons	4.55	7.15	10.5	15.2	21.7	30.4
Inventory x 10^5 tons	1.23	1.56	2.0	2.54	3.25	4.15
Guaranteed Fuel x 10^5 tons	6.57	8.36	10.7	13.6	17.4	22.2
Cum. Total (LWR) x 10^5 tons	12.4	17.1	23.2	31.3	42.4	56.8

Table III

GENERALIZED POWER PRODUCTION COSTS
FOR VARIOUS TYPES OF GENERATING FACILITIES

	Nuclear 2x1200 MW	Coal		Combined Cycle 400 MW	Gas Turbine 4x75 MW	Geysers Geothermal 110 MW
		FCD(1) 2x800 MW	W/O FGD 2,300 MW			
1977 Cost Plus ADC(2)						
Plant \$/kW	243	761	544	264	178	323
Step-up & Switching	20	20	20	15	15	15
Transmission	30	10	30	10	0	35
Total \$/kW	293	791	594	289	193	358
Total Completed Cost						
1980 \$/kW	878	804	604	320	215	396
1985	1159	1061	797	412	271	522
1990	1529	1400	1051	541	354	689
Fixed Charge Rates	15.3	15.4	15.0	15.5	15.3	15.0
Fuel Type	Uranium	Coal	Coal	Distillate	Distillate	Natural Steam
Fuel Costs \$/ MWh(1)						
1977	73	125	122	263	263	65
1980	87	149	145	370	370	80
1985	116	199	194	530	530	90
1990	156	267	260	743	743	102
2000 *	279	477	466	1462	1462	147
Fuel Inventory (Days)	-700	90	90	60	10	--
Average Heat Rate	10,300	9,700	9,250	8,600	11,500	22,000
O & M Cost Fixed (\$/kWyr)	2.8	5.8	4.3	5.0	.5	2.7
Variable (Mills/kWh)	0	.5	.1	.4	1.6	.1
Peak Transmission Loss %	1.4	-.4	2.0	-2.0	-5.7	3.8
Average	.1	.5	1.9	-.7	-2.2	3.5
35 Year Levelized Power Prod. Costs for Plants Completed in 1985						
Fixed \$/kWyr	201	193	147	90	43	87
¢/kWhr @ 70%CF	3.3	3.2	2.4	1.5	.7	1.4
Variable ¢/kWhr	2.1	3.6	3.3	9.4	12.6	2.9
Total	5.4	6.8	5.7	10.9	13.3	4.3
35 Year Levelized Costs on a 1977 Constant \$ Basis(3)						
¢/kWhr, 10% CF	--	10.8	8.4	8.3	7.4	5.4
30	4.3	4.6	3.8	5.4	6.0	2.6
50	2.9	3.4	2.8	4.8	5.7	2.0
60	2.5	3.1	2.6	4.7	5.6	1.9
70	2.3	2.9	2.4	4.6	5.6	1.8
80	2.1	2.7	2.3	4.5	5.6	1.7

(1) FGD = Flue Gas Desulfurization (Scrubbers)

(2) ADC = Allowance for Funds During Construction

(3) Cost with effects of general escalation factored out

$$* 1 \times 10^6 \text{ Btu} - 1.05 \times 10^9 \text{ joules} = 292 \text{ kw hr}$$

$$\frac{(477 - 279)}{292} = 6.8 \text{ mills/kw hr}$$

**CUMULATIVE COMMITMENT FOR U_3O_8 AS A FUNCTION OF TIME FOR
VARIOUS GROWTH RATES IN THE USE OF 32% EFFICIENT LWR**

FIGURE 1

**CUMULATIVE COMMITMENT FOR U_3O_8 AS A FUNCTION OF TIME
FOR VARIOUS GROWTH RATES IN THE USE OF 40% EFFICIENT
HIGH TEMP. GAS COOLED REACTORS.**

CALENDAR YEAR
FIGURE 2

THE CONTRIBUTION OF VARIOUS ENERGY SOURCES
AS A FUNCTION OF TIME FOR THE U.S.

FIGURE 3

CUMULATIVE NUMBER OF NUCLEAR POWER PLANTS IN THE UNITED STATES FROM 1960 TO 1992

DATA AS OF AUG. 77

SOURCE: AMERICAN NUCLEAR SOCIETY

FIGURE 4