Gross Energy Available through Light Water Reactors

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This CNR Report addresses the question of the maximum possible contribution (gross) to the U.S. energy supply via light water nuclear reactors. The nuclear promotional industry, inside and outside of the Carter Administration, has made it appear that light water reactors are sorely required, if we are to meet our energy "demand". The trivial energy contribution possible via light water technology is evident in the tabulations of this report. Considered here are:

--- Low, medium and high estimates of workable-grade uranium available in the U.S.

--- The electrical yield (kwhrs/e) gross per short ton U_3O_8 mined, with all supporting assumptions and calculations.

--- Lifetime U_3O_8 requirement per 1000-megawatt light water reactor.

--- Quads of energy (thermal and electrical) available through LWR technology; also in barrels of oil-equivalent.

--- The number of light water reactors fuelable within the estimated U_3O_8 supply.

--- The energy which would be lost to the economy if no further nuclear plants were initiated.

Except for explicit use of various estimates of the fuel supply, the calculations throughout this report are based upon the optimistic assumptions of the nuclear industry, in order to present the most favorable case for nuclear power. Even with this approach, nuclear power via light water technology is a trivial source of energy.

Following the tables is Appendix #1 which shows the calculations and assumptions from which the tables are derived.

Appendix #2 discusses some fundamental terms in the fuel issue, like ppm, MTU, yellowcake, etc.

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References:

1. Starr, Chauncey, "On the Distribution of Fissions in Light Water Reactors", Letter, dated May 12, 1976, to Committee for Nuclear Responsibility. (Dr. Starr is President of the Electric Power Research Institute, POB 10412, Palo Alto, CA 94303).

2. Perry, A.M., Letter, dated February 2, 1976 to Committee for Nuclear Responsibility. For extensive details, see the comprehensive report, "Net Energy from Nuclear Power", Rotty, Ralph M; A.M. Perry, D.B. Reister, Institute for Energy Analysis, IEA-75-3, November, 1975, Oak Ridge Associated Universities, Oak Ridge, TN.

3. Wilde, R.M., Nuclear Regulatory Commission Staff Testimony (quoted by P.M. Wood) in Hearings before the Atomic Safety and Licensing Board in the Matter of Gulf States Utilities Company (River Bend Station, Units 1 and 2), Docket Nos. 50-458, 50-459, second half of 1976.

4. Nuclear Regulatory Commission Staff Testimony, ibid. (Presented by P.M. Wood).

5. Lieberman, M.A., "United States Uranium Resources --- An Analysis of Historical Data", Science 192, Number 4238, 431-436, April 30, 1976.

6. "The National Energy Plan", April 29, 1977, Executive Office of the President, Energy Policy and Planning, Washington, D.C. 20500. (See also "Uranium Reserves, Resources, and Production", Energy Resources Council, June 15, 1976).

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Table No. 1

Number of 1000-Megawatt/e Plants Fuelable

INCLUDING those already built

Because the actual size of nuclear plants varies so much, for clarity one should discuss a standard size like 1000-megawatts (electrical).

Based on Assured Fuel Supply of 640,000 tons U_3O_8

	Plants at 70% Capacity Factor	Plants at 55% Capacity Factor*
Fuel performance at 100% of its "theoretical" yield**	105.5 plants	134.3 plants
Fuel performance at 75% of its "theoretical" yield	79.1 plants	100.8 plants
Fuel performance at 50% of its "theoretical" yield	52.8 plants	67.2 plants

Probable Fuel Supply of 1,130,000 tons U_3O_8 (Ref. 5).

	Plants at 70% Capacity Factor	Plants at 55% Capacity Factor*
Fuel performance at 100% of its "theoretical" yield	186.3 plants	237.1 plants
Fuel performance at 75% of its "theoretical" yield	139.7 plants	178.0 plants
Fuel performance at 50% of its "theoretical" yield	93.2 plants	118.5 plants

Exaggerated Fuel Supply of 1,840,000 tons U_3O_9 (Ref. 6).

	Plants at 70% Capacity Factor	Plants at 55% Capacity Factor*
Fuel performance at 100% of its "theoretical" yield	303.3 plants	386.1 plants
Fuel performance at 75% of its "theoretical" yield	227.4 plants	289.8 plants
Fuel performance at 50% of its "theoretical" yield	151.7 plants	193.0 plants

* At 55% capacity factor, more plants (highly inefficient) can be built than at 70% capacity factor, provided that refueling schedules are altered to prevent premature unloading of "unburned" fuel.

** "Theoretical" yield = 3.033×10^7 kwh(e) per short ton U_3O_8 mined.

NUMBERS IN BOXES: See reverse side of this sheet.

Table No. 1, continued

NUMBERS IN BOXES

52.8:	Since approximately 50,000 megawatts are already built, if fuel performance remains at 50% of theoretical yield, then no more nuclear plants can be fueled with the known 640,000-ton U_3O_8 reserve.
139.7:	This number turns out to correspond closely with the number of nuclear megawatts which the National Energy Plan (Ref. 6) proposes to have in operation by 1985. See Table 3. The Plan is obviously risky with respect to fuel for 140,000 Mw. If fuel performance and capacity factors remain as they are now (50% and 55% respectively), then only 118,700 megawatts will be fuelable, even if 1,130,000 tons of fuel are found.
303.3:	This number corresponds closely to recent statements by James Schlesinger that he is thinking of 300 presumably fuelable LWR's on line by the end of this century. This table shows that such talk is based on wildly optimistic assumptions about the fuel supply and fuel performance.

NOTE:

Not all of the uranium discovered in this country, and to be discovered in this country, belongs to the United States!

According to the General Accounting Office (GAO) report to Congress of July 7, 1976, entitled "Certain Actions that Can Be Taken to Help Improve This Nation's Uranium Picture", no one knows what fraction of U.S. uranium is already owned and will be owned by foreign investors. In 1974, at least 10% of all uranium exploration in this country was done by companies which were wholly owned by foreign companies or countries, with the right to export the fuel (p.18).

Additionally, some domestic companies are conducting joint ventures with foreign companies for uranium exploration. Under one such agreement, half the uranium discovered is to be controlled by the foreign investors (p.19).

"According to an ERDA official, foreign countries are exploring for uranium in this country because they believe there is more opportunity to recover and export uranium from the U.S. than from other countries which have rigid export requirements" (p.19).

Table No. 2

Energy Contributions from Nuclear Power

Based on Assured Fuel Supply of 640,000 tons U_3O_8

	Total Quads nuclear over 30 years		Average Quads nuclear per year	
Fuel performance at 100% of its "theoretical" yield	199.4 thermal	66.3 elec.*	6.6 thermal	2.2 elec.*
Fuel performance at 75% of its "theoretical" yield	149.4 thermal	49.7 elec.	5.0 thermal	1.66 elec.
Fuel performance at 50% of its "theoretical" yield	99.8 thermal	33.2 elec.	3.3 thermal	1.11 elec.

Share Possible from Nuclear, if U.S. Energy Consumption ≈ 91.65 Quads per Year

In 1976, total U.S. primary energy demand ≈ 75 Quads. Carter's prediction for 1985 ≈ 91.65 Quads.

	Thermal Quad basis	Elec. Quad basis
Fuel performance at 100%	7.2%	2.4%
Fuel performance at 75%	5.5%	1.8%
Fuel performance at 50%	3.6%	1.2%

Probable Fuel Supply of 1,130,000 tons U_3O_8

	Total Quads nuclear over 30 years		Average Quads nuclear per year	
Fuel performance at 100% of its "theoretical" yield	352.1 thermal	117.0 elec.	11.7 thermal	3.9 elec.
Fuel performance at 75% of its "theoretical" yield	264.0 thermal	87.7 elec.	8.8 thermal	2.9 elec.
Fuel performance at 50% of its "theoretical" yield	176.1 thermal	58.5 elec.	5.9 thermal	1.95 elec.

Share Possible from Nuclear, if U.S. Energy Consumption ≈ 91.65 Quads per Year

In 1976, total U.S. primary energy demand ≈ 75 Quads. Carter's prediction for 1985 ≈ 91.65 Quads.

	Thermal Quad basis	Elec. Quad basis
Fuel performance at 100%	12.8%	4.3%
Fuel performance at 75%	9.6%	3.2%
Fuel performance at 50%	6.4%	2.1%

*Producing electricity for purposes where electricity is required merits crediting as "thermal" Quads, since other fuels would otherwise be used at their thermal value.

Producing electricity for purposes where electricity is NOT required, but is merely used for its heat value to replace other fuels, deserves crediting ONLY as "electrical" Quads.

Table No. 2, continued

Exaggerated Fuel Supply of 1,840,000 tons U_3O_8

	Total Quads nuclear over 30 years		Average Quads nuclear per year	
Fuel performance at 100% of its "theoretical" yield	573.0 thermal	190.4 elec.	19.1 thermal	6.3 elec.
Fuel performance at 75% of its "theoretical" yield	429.8 thermal	142.8 elec.	14.3 thermal	4.8 elec.
Fuel performance at 50% of its "theoretical" yield	286.7 thermal	95.3 elec.	9.6 thermal	3.2 elec.

Share Possible from Nuclear, if U.S. Energy Consumption ≃ 91.65 Quads per Year

In 1976, total U.S. primary energy demand ≃ 75 Quads. Carter's prediction for 1985 ≃ 91.65 Quads.

	Thermal Quad basis	Elec. Quad basis
Fuel performance at 100%	20.8%	6.9%
Fuel performance at 75%	15.6%	5.2%
Fuel performance at 50%	10.5%	3.5%

Table No. 3

Jimmy Carter's Energy Plan proposes (p.71) to have a total of 138 nuclear plants (of various sizes) in operation as of 1985 without specifying the combined generating capacity in megawatts. However, the Plan does reveal the expected thermal energy (gross) to be yielded in 1985 by these plants: 7.71 Quads. From that figure, one can derive the total number of nuclear megawatts (or number of 1000-megawatt plants) which are proposed (below).

Relationship of Thermal Quads to Megawatt Design-Capacity of Nuclear Plants

Capacity Factor	Megawatt Rating	Annual Quads thermal from a single plant	Number 1000-meg (e) Plants Required to Produce 7.71 Quads (t) per Year
70%	1,000 Mw	0.063 Quads	122.4 Plants
60%	1,000 Mw	0.054 Quads	142.8 Plants
55%	1,000 Mw	0.0495 Quads	155.8 Plants

At recent Nuclear Regulatory Commission hearings, expected capacity factor has been stated by the NRC as 60%.

Table No. 4

Energy to Be Lost to the Economy

if no ADDITIONAL nuclear plants are initiated

Assumptions:

1.) 1,130,000 tons U_3O_8 are the ultimate U.S. reserve from suitable ore.

2.) Fuel performs at 75% of its theoretical yield in LWR's.

3.) Plants operate at 70% of their rated capacity.

4.) Enrichment "tails" are 0.2% instead of 0.3%.

Total number fuelable 1000-Mw plants = 139.7, or 140,000 Mw (Table 1).

BUT many of them have already been built. We now have 63 plants "operable" with a combined capacity of about 50,000 Mw, plus about 30,000 additional Mw underway = 80,000 Mw.

140,000 Mw minus 80,000 Mw operable and underway = 60,000 Mw.

Thus only 60 ADDITIONAL plants @1000 Mw can be considered at all. And even these are risky with respect to fuel supply.

Since 140 plants @1000 Mw would consume the entire 1,130,000 tons of fuel, a decision NOT to build 60 of them (a "ban" on new nuclear construction) would mean a maximum loss of 43% (60 ÷ 140) of the energy which 140 plants could deliver. 140 plants could deliver 8.8 thermal Quads per year, because that is the yield from 1,130,000 tons fuel (Table 2).

Thus Quads per year lost by a "ban" = 43% of 8.8 Quads = 3.8 Quads.

Annual U.S. energy consumption in 1985 = 91.65 Quads (Carter Plan).

3.8 Quads/yr lost by a nuclear "ban" = 4.1% of total (3.8 ÷ 91.65).

Conclusion:

Loss of 3.8 Quads/yr from initiating NO additional nuclear plants is a negligible 4.1% loss.

Increment of 3.8 Quads/yr from new nuclear construction would solve only 4.1% of the country's supply problem.

This utterly trivial amount of energy can not possibly justify the common scaremongering about the effects of a ban on new nuclear construction! In fact, even this trivial increment of energy will be non-existent if fuel-performance remains poor, or if less than 1,130,000 tons of fuel are found.

Table No. 4

Energy to Be Lost to the Economy

if no ADDITIONAL nuclear plants are initiated

Assumptions:

1.) 1,130,000 tons U_3O_8 are the ultimate U.S. reserve from minable ore.
2.) Fuel performs at 75% of its theoretical yield in LWR's.
3.) Plants operate at 70% of their rated capacity.
4.) Enrichment "tails" are 0.2% instead of 0.3%.

Total number fuelable 1000-MW plants = 139.7, or 140,000 Mw (Table 1).

BUT many of them have already been built. We now have 63 plants operable with a combined capacity of about 50,000 Mw, plus about 30,000 additional Mw underway = 80,000 Mw.

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Appendix 1

The Electrical Yield in Kwhrs (e) per Short Ton U_3O_8 Mined:

There are two methods for estimating the "theoretical" yield of electrical power (via light water reactors) per ton of U_3O_8 mined.

The first method is based upon assuming that some fraction of U-235 in the reactor is utilized in one pass through the reactor (no reprocessing). That fraction "burned" is generally quoted as between 70% and 73.3%. We shall utilize the mid-range value of 71.7%.

Then it is necessary to know how many fissions ("bonus fissions") are contributed by nuclides other than U-235. The other potential contributors are U-238, Pu-239, Pu-241. Starr (Ref. 1) has estimated that under the best conditions of fuel burn-up, the distribution of fissions is:

52 from U-235
40 from Pu-239 and Pu-241 combined
8 from U-238.

This means that the energy per U-235 fission must be supplemented by 48 $\div$ 52 , or 0.923 for energy from the combined fissions of U-238 plus plutonium nuclides.

The second method is more empirical and is based upon the best yield of energy observed for light water reactors (not their usual operating yield). Perry (Ref. 2) has suggested 30,000 megawatt-days thermal per metric ton of 3.0% enriched fuel, barring premature fuel-discharge due to fuel failures. This value can be translated directly to the "theoretical" or "design" expectation of energy yield.

We shall develop both methods here.

Method 1.

Step 1: Losses in milling

Ore is mined containing one short ton U_3O_8. Wilde (Ref. 3) has suggested that "mill losses may conservatively be taken at 10%". The lost uranium-235 ends up in the mill "tailings".

Therefore, per short ton U_3O_8 mined, we end up with 0.9 short tons U_3O_8 at the end of the milling step.

Step 2: Conversion to UF_6 and back to UO_2

It is estimated that the combined losses in these steps is 1.5% of the fuel. Therefore, we end up with 98.5% of initial uranium.

$\therefore$ (0.985) x (0.9) = 0.8865 short tons U_3O_8 equivalent.

Step 3: Losses to "tails" during enrichment

In preparing 3.0% U-235, some U-235 is left in the "tails" of the enrichment plant. Currently as much as 0.3% U-235 is the concentration in the "tails". Since this wastes uranium, we shall assume (to give nuclear power every advantage) that additional enrichment facilities will be built if the U.S. goes on with nuclear expansion, that we will then leave the "tails" at 0.2% rather than 0.3% (which produces a 19.8% saving of fuel), and on that basis, we calculate the loss of U-235 in enrichment tails:

By the law of conservation of mass, the U-235 comes out of the enrichment plant either in the enriched product or in the tails. Let us assume 100 tons of uranium go into the enrichment step.

Let x = tons of enriched uranium produced (3% U-235)

100 - x = tons of depleted uranium in tails (0.2% U-235)

0.0071 = fraction of feed uranium that is U-235.

$\therefore$ 100(0.0071) = 0.03x + (0.002)(100 - x). Conservation of U-235.

0.71 = 0.03x + 0.2 - 0.002x

0.028x = 0.51

x = 18.2 tons; 100 - x = 81.8 tons.

We started with 100 x 0.0071, or 0.71 tons U-235.

In the enriched fraction, we now have:

(18.2)(0.03) = 0.546 tons U-235

So, $\frac{0.546}{0.71}$ = 0.769, or 76.9% of the U-235 survives the enrichment step.

From step 2, we had left 0.8865 short tons of U_3O_8 with its U-235 content. Since we say that 76.9% of the U-235 survives the enrichment step, it is the same as saying:

(0.769) x (0.8865), or 0.6817 short tons U_3O_8 equivalent get into the reactor cycle.

Step 4: Energy per short ton U_3O_8 in the reactor step

1 short ton U_3O_8 $\longrightarrow$ 2000 pounds U_3O_8
1 pound U_3O_8 $\longrightarrow$ 454 grams U_3O_8
$\therefore$ 1 short ton U_3O_8 $\longrightarrow$ 908,000 grams U_3O_8
The uranium fraction of U_3O_8 is 0.848
$\therefore$ 1 short ton U_3O_8 $\longrightarrow$ (908,000)(0.848), or
769,984 grams uranium.
U-235 is 0.0071 of natural uranium.
$\therefore$ 1 short ton U_3O_8 $\longrightarrow$ (769,984)(0.0071), or
5466.9 grams U-235

But, from step 3, our original short ton of U_3O_8 is down to 0.6817 short tons after enrichment and reconversion to UO_2 fuel (3.0% U-235). Therefore:

U-235 entering reactor cycle = (0.6817)(5466.9), or
3726.8 grams U-235

Step 5: U^{235} Utilization in the reactor

The estimate is (in the introduction of this Appendix) that 71.7% of the U-235 gets utilized in the reactor, if there is no premature unloading of the fuel. Therefore:

(3726.8)(0.717) = 2672.1 grams U-235 utilized in the reactor per original short ton of U_3O_8 mined.

Step 6: Fraction of U^{235} undergoing fission

Some U-235 is utilized in a non-productive manner, by capturing neutrons to produce non-fissionable U-236. The remainder is fissioned. Starr (Ref. 1) estimates for the U-235 used up, 81% of the U-235 fissions, while 19% does not, because it goes to U-236. Therefore:

(0.81)(2672.1), or 2164.4 grams U-235 undergo fission per short ton of U_3O_8 mined.

Step 7: Energy from fission

The fission of one gram U-235 yields 0.92 megawatt-days of thermal energy (from first principles of physics).

1 megawatt-day $\longrightarrow$ 24,000 kilowatt-hours (thermal)

$\therefore$ Fission of 1 gram U-235 $\longrightarrow$ (0.92)(24,000), or 22,080 kwhrs (t)

Therefore:

Fission of 2164.4 grams U-235 $\longrightarrow$ (2164.4)(22,080), or 4.779×10^7 kwhrs, thermal.

But, for every U-235 fission, we have 0.923 "bonus fissions".

$\therefore$ (0.923)(4.779×10^7) = 4.411×10^7 kwhrs thermal from bonus fissions.

Final total thermal yield = $4.779 \times 10^7 + 4.411 \times 10^7$
= 9.19×10^7 kwhrs thermal from our original short ton of U_3O_8 mined.

Step 8: Thermal to electrical conversion

Generally a value of 0.33 is taken as the electrical energy obtained per thermal energy-unit produced in light water reactors.

$\therefore$ (9.19×10^7)(0.33) = 3.033×10^7 kwhrs electrical from our original short ton of U_3O_8 mined.

This value, 3.033×10^7, or 30.33 million kilowatt hours electrical per short ton U_3O_8 mined is what we shall call the "theoretical" yield in the light water reactor.

Theoretical Energy Yield per Ton vs. Actual Yield:

The figure 30.33 million kwhrs (e) is "theoretical" in the sense that this is the energy yield to be obtained if all design criteria are fulfilled.

Thus if 71.7% of the U-235 is not utilized or "burned", the yield will fall. If the "tails" in enrichment are 0.3% instead of 0.2%, the yield will fall. If the "bonus fissions" have been overestimated (and they may be), the yield will fall.

It appears that the actual fuel performance on the average to date has been approximately 50% of its theoretical yield, according to testimony and tables presented by the Nuclear Regulatory Staff in the second half of 1976 (Ref. 4).

Method 2.

Direct Estimate from Claimed Empirical Results

Perry has estimated 30,000 megawatt-days, thermal, per metric ton 3% enriched uranium, barring premature discharge of fuel.

1 metric ton $\rightarrow$ 1,000 Kg.

At 3% U-235, (1,000)(0.03) = 30 kilograms U-235, or
30,000 grams U-235

In step 4 of Method 1 (above), we estimated that 3762.8 grams U-235 at 3% enrichment enter the reactor cycle per short ton U_3O_8 mined.

Therefore, if 30,000 grams U-235 $\longrightarrow$ 30,000 megawatt-days thermal, it follows that

3762.8 grams U-235 $\longrightarrow \frac{3762.8}{30,000} \times 30,000 = 3762.8$ megawatt-days thermal,

per original short ton U_3O_8 mined.

1 megawatt-day $\longrightarrow$ 24,000 kwhrs

$\therefore$ (3762.8)(24,000) = 9.03×10^7 kwhrs thermal
per original short ton U_3O_8 mined

Utilizing the factor of 0.33 for conversion of thermal to electrical, we have

$(0.33)(9.03 \times 10^7) = 2.98 \times 10^7$ kwhrs electrical per
original short ton U_3O_8 mined...

in good agreement with Method 1.

Confusion over the term "megawatt-days of burn-up"

Some observers carelessly use megawatt-days of "burn-up" to describe fuel performance in reactors. It is extremely important to point out that 30,000 megawatt-days thermal is a design value which applies if there is no premature discharge of fuel and if we start with 1 metric ton of 3.0% enriched uranium. It should be self-evident that if lower or higher enrichment is utilized (and both occur frequently in commercial light water reactors), the design expectation is different from 30,000 megawatt-days thermal per metric ton of fuel metal.

It is therefore far preferable to speak of "fuel duty" or performance in terms of kwhrs per original short ton of U_3O_8 mined, than to speak of megawatt-days per metric ton of enriched fuel, the latter being so dependent upon extent of enrichment.

Reconciliation with Our Previous Estimates:

In 1976, C.N.R. presented some estimates of the gross electrical yield, kilowatt-hours (e), per short ton U_3O_8. Four parameters have been revised in this report.

(1). The fraction of U-235 going to fission (vs. "duds" going to U-236) is reduced from 85% to 81%, which conforms with the "dud"-fraction (19%) used by the Electric Power Research Institute (Ref. 1).

(2). The bonus fissions from U-238 plus plutonium nuclides are here taken as 92.3% of U-235 fissions instead of 43% of U-235 fissions, because that appears to conform with the values observed for burn-up at design levels (Ref. 1).

(3). The loss of U-235 in enrichment tails is here taken as 0.2%, whereas earlier we used 0.3% tails. Actually, 0.3% corresponds better with current practice, but to present nuclear power prospects most favorably again, we are assuming sufficient additional enrichment capacity will be built to permit going to 0.2% tails---a development which should increase energy-yield per short ton U_3O_8 mined by a full 19.8%.

(4). An estimated loss of 10% of the U_3O_8 in mining-plus-milling is used in this report, whereas this loss was not included earlier.

Lifetime U_3O_8 Requirement per 1000-megawatt Reactor:

If we are to calculate the number of plants fuelable by any estimated U_3O_8 supply, it is necessary to know the U_3O_8 requirement for the lifetime of one plant.Three factors are essential to specify:

(1). The expected average capacity factor. If a plant could operate at full power every hour of every day, it would be operating at 100% "capacity factor". Expected capacity factors are discussed as percents, which makes it possible to confuse these values with fuel performance at some percent of its theoretical energy yield. These are not the same.

(2). The lifetime of the plant. In 1976, we assumed a 40-year lifespan for nuclear plants; the nuclear industry no longer expects them to last 40 years. So this report uses 30 years. Therefore each plant will use only 75% as much fuel as calculated earlier. (However, the effective capital cost of nuclear power increases by 33% with this adjustment).

(3). Fuel performance relative to its theoretical yield.

a.) 30-year lifetime; 70% capacity factor ; fuel performance 100% of theoretical

$$(0.7)(1000 \text{ Mw})\frac{(1000 \text{ kw})}{\text{Mw}}\frac{(24 \text{ hrs})}{\text{day}}\frac{(365 \text{ days})}{\text{year}}(30 \text{ years}) \longrightarrow$$

$$(0.7)(10^6)(8.760 \times 10^3)(30) \longrightarrow$$

1.84×10^{11} kilowatt-hours output in 30 years.

Theoretical yield per short ton U_3O_8 mined = 3.033×10^7 kwhrs (e)

Therefore under these conditions, each plant requires

$$\frac{1.84 \times 10^{11}}{3.033 \times 10^7} \text{ or } 6{,}067 \text{ short tons } U_3O_8$$

b.) 30-year lifetime; 55% capacity factor ; fuel performance 100% of theoretical

Obviously if the nuclear generating plants operate much more poorly than designed, e.g., at 55% capacity factor instead of 70%, the U_3O_8 requirement per plant for 30 years will be less, provided the refueling schedule is revised to take the much poorer performance into account.

At 55% capacity factor, electrical output in 30 years is

$$(0.55)(1000\ \text{Mw})\ \underline{(1000\ \text{kw})}\ \underline{(24\ \text{hours})}\ \underline{(365\ \text{days})}\ (30\ \text{years}) \longrightarrow$$
$$\phantom{(0.55)(1000\ \text{Mw})}\ \text{Mw}\qquad \text{day}\qquad \text{year}$$

$$(0.55 \times 10^6)(8.76 \times 10^3)(30) \longrightarrow$$

$$1.445 \times 10^{11}\ \text{kilowatt-hours output in 30 years.}$$

Therefore under these conditions, each plant requires

$$\frac{1.445 \times 10^{11}}{3.033 \times 10^7} \text{ or } 4,764 \text{ short tons } U_3O_8 \text{ mined.}$$

Number of Plants Fuelable:

Illustrative Calculations

a.) If nuclear plants operate with fuel performance at 100% of theoretical yield, how many plants (operating at 70% capacity factor) can be fueled with the assured U.S. reserve of 640,000 tons of fuel? How many, if plants operate at 55% capacity factor?

At 70% capacity factor, it takes 6,067 tons U_3O_8 mined to supply one plant for a 30-year lifetime. Therefore, for 640,000 tons reserve of U_3O_8:

$$\text{Number of plants fuelable} = \frac{640,000}{6,067}, \text{ or } \underline{105.5 \text{ plants.}}$$

At 55% capacity factor, it takes 4,764 short tons U_3O_8 mined to supply one plant for a 30-year lifetime. Therefore, for a 640,000-ton reserve of U_3O_8:

$$\text{Number of plants fuelable} = \frac{640,000}{4,764}, \text{ or } \underline{134.3 \text{ plants.}}$$

b.) Nuclear plants have thus far operated with fuel performance at about 50% of "theoretical" energy yield. With that performance, how many plants would be fuelable from a reserve of 640,000 tons U_3O_8?

For operation with fuel performance at 50% of its theoretical energy yield, a plant at 70% capacity factor requires much more U_3O_8. Indeed, one plant requires 6,067 x 2, or 12,134 tons U_3O_8 for a 30-year lifetime. Therefore, from 640,000 tons U_3O_8,

$$\text{Number of plants fuelable} = \frac{640,000}{12,134}, \text{ or } \underline{52.7 \text{ plants.}}$$

c.) If there are fewer fuel failures in the future, fuel performance in nuclear plants will rise. If we assume that fuel performance on the average reaches 75% of its theoretical energy yield, how many plants would be fuelable with the assured supply of 640,000 tons U_3O_8?

For fuel performance at 75% of its theoretical energy yield instead of 100%, a plant at 70% capacity factor requires 100 ÷ 75 as much fuel, or 1.33 x 6,067, or 8,069 tons U_3O_8 for a 30-yr. lifetime. Therefore, from 640,000 tons of U_3O_8

$$\text{Number of plants fuelable} = \frac{640{,}000}{8{,}069}\text{, or } \underline{79.3 \text{ plants.}}$$

Quads (and oil-equivalent) from Nuclear Power

In describing an energy economy, one finds two units in common use. The first is the "Quad", which is the abbreviation for 10^{15} British Thermal Units, or 10^{15} BTU's. The second unit is the barrel of oil equivalent.

In order to express the energy contribution of nuclear electric power plants in a set of units comparable to those for other energy sources, it is necessary to convert kilowatt-hours to Quads or to barrels of oil equivalent.

First, one Quad represents 180,000,000 barrels of oil. (That is the conversion from a General Electric handbook; a Federal Energy Administration handbook uses 172,000,000 barrels per Quad. The difference is not great considering variations in the energy-content of crude oil).

Thus, when the National Energy Plan (April 1977) reports the 1976 U.S. primary energy demand as 37 million barrels of oil equivalent per day, we convert to Quads as follows:

$$\frac{37{,}000{,}000}{180{,}000{,}000} = 0.2056 \text{ Quads per day}$$

$$\underline{\text{Annual}} \text{ energy use} = \frac{(0.2056 \text{ Quads})}{\text{day}}\frac{(365 \text{ days})}{\text{year}}$$

$$= 75.0 \text{ Quads per year}$$

Next, a 1000-megawatt plant at 70% capacity factor produces

$$(0.7)(1000 \text{ Mw})\frac{(1000 \text{ kw})}{\text{Mw}}\frac{(24 \text{ hrs})}{\text{day}}\frac{(365 \text{ days})}{\text{year}}\text{, or } (0.7 \times 10^6 \text{ kw})(8760 \text{ hours}),$$

or 6.132×10^9 kilowatt-hours electrical per year.

<u>1 Kilowatt-hour is equivalent to 3415 BTU.</u>

Therefore, a 1000-megawatt plant at 70% capacity factor has an annual energy output, electrical, of $(6.132 \times 10^9 \text{ kwhrs}) \left(\frac{3{,}415 \text{ BTU}}{\text{Kwhr}}\right)$

or, 2.094×10^{13} BTU electrical per year.

But 1 Quad $= 1 \times 10^{15}$ BTU

$$\therefore \text{Annual Output, electrical} = \frac{2.094 \times 10^{13}}{1 \times 10^{15}} = 0.02094 \text{ Quads.}$$

$$\text{Annual output, thermal} = \frac{1}{0.33} \times \text{Annual output, electrical}$$

(2/3 of annual output is waste heat).

$$\therefore \text{Annual output, thermal} = \frac{1}{0.33} \times 0.02094 = 0.063 \text{ Quads thermal.}$$

<u>Lifetime outputs per plant (30 years):</u>

Quads, electrical, (30)(0.02094) = 0.628 Quads

Quads, thermal, (30)(0.063) = 1.89 Quads

<u>In barrels of oil equivalent</u>

$$\text{Annual output, electrical} = (0.02094 \text{ Quads}) \left(\frac{180{,}000{,}000 \text{ barrels}}{\text{Quad}}\right)$$

$$= 3.77 \times 10^6 \text{ barrels of oil}$$

$$\text{Daily output, electrical} = \frac{3.77 \times 10^6 \text{ barrels}}{3.65 \times 10^2 \text{ days}}$$

$$= 1.033 \times 10^4 \text{ barrels or oil per day,}$$

or about 10,000 barrels per day.

$$\text{Annual output, thermal} = (0.063 \text{ Quads}) \left(\frac{180{,}000{,}000 \text{ barrels}}{\text{Quad}}\right),$$

$$= 11.34 \times 10^6 \text{ barrels of oil}$$

$$\text{Daily output, thermal} = \frac{11.34 \times 10^6 \text{ barrels}}{3.65 \times 10^2 \text{ days}},$$

$$= 3.11 \times 10^4 \text{ barrels of oil per day,}$$

or about 30,000 barrels per day.

Appendix 2

Some realities about uranium ore:

There is a very great deal of uranium on earth, including uranium in sea water. This fact is often used to obscure the fundamental truth that there is an extremely small amount of uranium in discovered deposits which are worth working for nuclear plants of the types currently at hand.

Obviously, in general the richer an ore is in its uranium content, the more likely it is to be worth working. On the other side, for ores poor in uranium, there are limits to what can be used for nuclear power: (a) energy limits, and (b) absurdity limits.

(a) Energy Limits: If an ore is of too low a grade in uranium content, the energy required to mine, mill, convert, and enrich the uranium can exceed the energy obtainable from such uranium in light water reactors. Probably most of the uranium in the world falls into this class. Use of such uranium sources would represent a drain on the nation's energy supply, not an increment. Nevertheless, unless there is careful monitoring, such a practice could occur!

(b) Absurdity limits: In some instances, it can be shown that a low-grade uranium ore still could yield more energy out in LWR's than the combined energy inputs required for mining, milling, enrichment, etc.

In principle, such an ore could be considered as a potential source of fuel for light water reactors. In practice, however, it could be an absurdity to consider such a source.

One of the ostensible advantages of nuclear power over coal is the elimination of the requirement for mining and transporting "billions of tons" of coal. Rarely mentioned by nuclear salesmen is the fact that this advantage is true only for the high-grade uranium ores, which are rare indeed. The poor but abundant ores (like Tennessee Shale, at 60 to 70 ppm) could require about TWICE as much mining as would coal to get the same amount of net energy via LWR's. No rational society would tolerate a mining industry both huge and toxic by comparison with coal mining for such a poor energy yield compared with coal.

Grades of Ore, "ppm"

The most meaningful estimate of grade is the term "parts per million" by weight, or p.p.m. With rare exceptions, any other grading system can be reduced to the p.p.m. system, and of course the p.p.m. system is directly translatable to the percentage system. Thus, we can tabulate some uranium contents of ores in both systems:

Ore grade in ppm Uranium	Ore grade in % Uranium
10,000 ppm	1%
1,000 ppm	0.1%
100 ppm	0.01%
10 ppm	0.001%

An ore containing 1,000 ppm uranium means exactly that: out of every 1,000,000 units of ore mixture by weight, 1,000 units are uranium.

High grade uranium ore deposits are those above 1,000 ppm of uranium. Ore deposits over 5,000 ppm are virtually unknown. Ores between 100 and 500 ppm have not been found in this country. Below 100 ppm, we are approaching the level where one mines as much uranium ore as coal to get the same amount of net energy.

Fuel Pellets, and Invisible Waste

It is not commonly understood that a very large amount of toxic waste is created in the process of converting uranium ore to those neat little "fuel pellets" of UO_2 featured so often in nuclear commercials, side by side with a carload of coal.

<u>For ores of 1,000 ppm, from ground to reactor, a concentration-factor of about 5,000 is required for uranium, as shown below:</u>

1 ton UO_2 pellets loaded into reactor $\longrightarrow$ 0.88 tons of uranium; the rest is oxygen.

The enrichment step (to 3.0%, with 0.2% tails) has concentrated the uranium 5.49-fold (100 ÷ 18.2). So before enrichment, we had

(5.49)(0.88) = 4.83 tons of uranium.

At 1,000 ppm, the ore mined is 1,000-fold the final uranium content.

(1,000)(4.83) = 4,830 tons of ore mined.

With 10% loss in mining and milling, and 1.5% loss in conversion steps:

$$(4{,}830)\left(\frac{10}{9}\right)\left(\frac{100}{98.5}\right) = (4{,}830)(1.11)(1.015)$$

$$= 5{,}442 \text{ tons of ore mined per ton of } UO_2 \text{ pellets fed into a reactor.}$$

When the nuclear industry is using ores of 500 ppm, there will be nearly 11,000 tons of radioactive waste (mostly in the mill tailings) for every single ton of UO_2 loaded into a reactor. Though they don't get moved, one could "picture" them in carloads too.

"Yellowcake" and Other Oxides

In the mining and milling of uranium ores as generally practiced in the U.S., the final product shipped from the mill is a uranium oxide (one of several possible oxides) which is bright yellow, which accounts for the trade name "yellowcake".

Yellowcake is essentially pure U_3O_8. Uranium reserves are often referred to in short tons of U_3O_8, whether or not the uranium is actually present in that oxide form.

Two other oxides of uranium are encountered in discussions: UO_2 and UO_3. UO_2 is the actual final form of uranium used in the manufacture of nuclear fuel pellets. UO_3 is not commonly encountered.

For most discussions, the key point is the ability to convert quantities between uranium metal and its two common oxides, namely U_3O_8 and UO_2.

Uranium constitutes 84.8% of U_3O_8 by weight; oxygen is 15.2%. Therefore, to convert U_3O_8 tons to uranium, multiply by 0.848. To convert uranium to U_3O_8, multiply by 1.18.

Uranium constitutes 88.1% of UO_2. Therefore, to convert UO_2 tons to uranium, multiply by 0.881. To convert uranium to UO_2, multiply by 1.14.

Uranium Hexafluoride (UF_6) is only of importance in that it is the gaseous compound actually used in the current form of diffusion enrichment plants. Following enrichment, the hexafluoride is converted back to UO_2 in general.

Descriptions of Ore Discoveries

It is important to be sure in a discussion to specify whether one is referring to ore, or to a purified uranium compound derivable from such an ore.

Thus a "find" of an ore body of an estimated 10 million tons sounds like the solution to the uranium shortage, but it can be simply trivial. Suppose the ore discovered is 200 ppm uranium! Then 10,000,000 tons of ore means only 2,000 tons of uranium, a miniscule amount.

Sometimes a discovery is even reported in pounds! But what seems huge in pounds is quickly reduced by a factor of 2,000 when converted to short tons.

While on the subject, we must give attention to the variety of "tons" encountered in the nuclear fuel literature.

1 short ton = 2,000 pounds
1 long ton = 2,240 pounds
1 metric ton = 1,000 kilograms
Since 1 kilogram = 2.2 pounds
1 metric ton = 2,200 pounds, close to the long ton.

One metric ton is labeled as 1 tonne.

"M.T.U"

The abbreviation will commonly be encountered, 1 M.T.U., meaning 1 metric ton of uranium. It is important to ascertain whether a specific reference is to 1 MTU of natural uranium (meaning the uranium is 99.3% U-238, and 0.7% of the fissionable U-235), or to enriched uranium (meaning uranium enriched to 2%, 3%, or more in U-235). The literature is exceedingly sloppy in specifying enriched uranium when this is meant.

But if a meaningful discussion of nuclear fuel is to take place, we must have specified the degree of enrichment of the uranium in U-235 content. Trying to figure out the energy which can be yielded by "1 M.T.U." is simply hopeless unless it is clearly specified that the uranium is not enriched at all (contains the 0.71% U-235 found in nature), or is enriched to 2%, 3%, 3.7%, or whatever.

There is no single "standard" degree of enrichment. However, one commonly encounters 3.0% or 3.2% enrichment in discussions of fuels for Pressurized Water Reactors.
