FIG. 4. Tubing cross section of intentionally hydrided reference sample, showing hydride redistribution which occurred under thermal gradient, after 1600 hr of testing. The uniform hydrogen content before redistribution was 140 ppm (150 ×).

ziracaloy-2 tubing and that containing hydrogen concentration gradients (such as that in Fig. 3) will be reported at a later date.

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Breeding Potential of Thermal Reactors

The breeding potential of thermal reactors was recently reviewed by Chernick and Moore (*1*). A number of the statements made in this review concerning the depletion of uranium reserves, the need for breeder reactors, and the breeding potentialities of certain reactor systems are open to question and should not be left unchallenged.

One of the principal arguments usually advanced in discussions concerning the necessity for developing breeder reactor systems may be referred to as the conservation argument. Essentially, this argument states that unless breeders are developed, economically recoverable reserves of uranium ore are insufficient to significantly extend U. S. energy resources. The key to the validity of such an argument lies in part in the definition of the term "economically recoverable uranium reserves." It has become somewhat of a common practice to arbitrarily limit economically recoverable reserves to those which can be recovered at less than twice present cost (*1*). This definition was apparently originated by Putnam and has no firmer basis other than being a convenient point of division in his analysis (*2*). In actuality, the price that a future nuclear power reactor economy will be willing to pay for uranium ore (and therefore a definition of "economically recoverable") is highly speculative since it will depend upon the state of nuclear technology and the cost of various alternative sources of energy. For example, at the present time demonstrated nuclear technology permits us to utilize less than 0.5% of the total uranium available, and to achieve useful heat outputs of the magnitude of 5000 Mwd of heat per ton of uranium. If this is arbitrarily taken as the standard, and using present uranium prices of $10/lb of U_3O_8, we might define "economically recoverable" uranium as that which gives a "heat value" of 2.5 kwd/cent. Now if we are able to increase our utilization by a factor of 10 (not improbable since we would still only be utilizing 5% of the total uranimum available) we could pay 10 times as much per pound of uranium and not exceed our definition of economically recoverable uranium.

The term "significantly extend" in the basic argument also requires more precise definition.

Table I presents recent data on uranium reserves in the United States as compiled by the U. S. Atomic Energy Commission's Division of Raw Materials (*3*). The various reserve categories of U_3O_8 lie in two price regions, one of

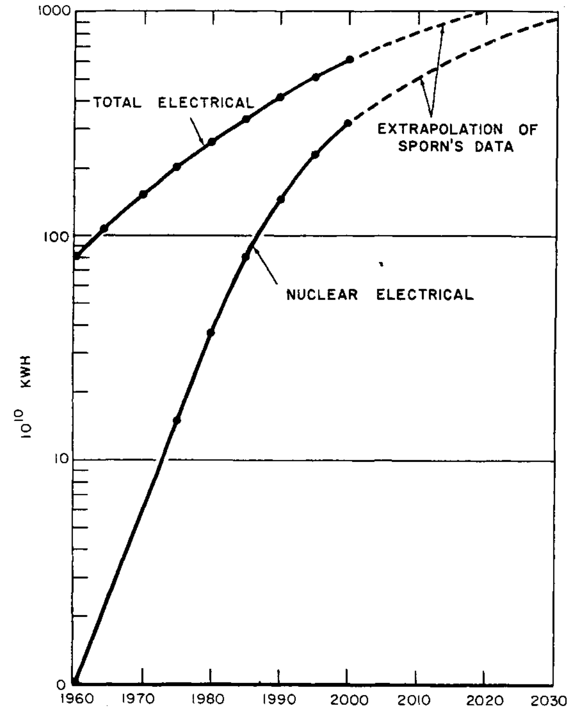

FIG. 1. Projected U. S. total electrical and nuclear electrical power growth.

TABLE I

UNITED STATES URANIUM RESERVES

Reserve category	Present cost ($/lb U_3O_8)	Status	U_3O_8 (short tons)	^{235}U content (kg × 10^6)
A	10 or less	Known	230,000	1.27
B	10 or less	Assumed additional	300,000	1.75
C	10 or less	Possible additional	530,000	2.92
D	30–60	Known	6,000,000	33.0
E	30–60	Assumed additional	6,000,000	33.0

TABLE II

CUMULATIVE RESERVE LIFETIME: ELECTRICAL CONSUMPTION COMPLETELY NUCLEAR, URANIUM RECYCLE[a]

Reserve Category	Thermal mwd potential × 10^8	Electrical kwh potential × 10^{12}	Cumulative lifetime (years)
A	7.05	5.07	5.3
B	9.15	6.59	10.3
C	16.2	11.7	16.7
D	183	132	46.1
E	183	132	61.1

[a] This table does not represent a realistic case but is merely presented as a means of comparison with reference (*1*).

TABLE III

CUMULATIVE RESERVE LIFETIME: REALISTIC NUCLEAR ELECTRICAL CONSUMPTION, URANIUM AND PLUTONIUM RECYCLE (C. R. = ⅔)

Reserve Category	Thermal mwd potential × 10^8	Electrical kwh potential × 10^{12}	Cumulative lifetime (years)
A	2.12	15.2	33
B	27.4	19.8	41
C	48.5	35.0	49
D	549	396	~90
E	549	396	~105

$10.00 or less per pound of U_3O_8 and the other at $30 to $60/lb. Since the present cost of uranium ore is between $8 and $10 per pound, this indicates that uranium reserves are available in deposits from which they could be recovered at approximately present costs and in deposits from which the uranium could be recovered at three to six times present costs. For this analysis, it will be assumed that an insignificant amount of uranium is available at between $10 and $30/lb of U_3O_8, although projections by others estimate a significant amount of ore in this reserve category (*4*). Ore costing more than $60/lb is also neglected even though these reserves are extremely large (*4*, *5*). The term status in the table refers to the degree of certitude associated with the existence of the amount of the reserve. A "known" reserve is one that is currently under development or planned for development; and "assumed additional" reserve represents undeveloped reserves based upon specific geologic evidence; "possible additional" reserves represent probable reserves based upon general geologic data and past discovery experience. The quantities of reserves listed under each category appear conservative if an intensive exploration program is initiated (*3*, *4*).

Table II presents the thermal mwd potential of each reserve category based upon the assumption that the non-usable tails ejected by the diffusion plants are 0.22% of U^{235} content. This appears to be conservative because if the price of uranium ore tends to increase, the U^{235} tails composition would tend to decrease since the nuclear power reactor economy could afford to pay more for the cost of separative work. The electrical kwh potential is based upon the arbitrary assumption that 10% of the available U^{235} is used for nonelectrical production. This arbitrary figure is low for the immediate future and appears high for the long-term future with the over-all figure of 10% probably being conservative. An average thermal efficiency of $33\frac{1}{3}\%$ was also assumed. By compounding these conservative assumptions, it appears that the electrical kwh potential is low. The last column of the table lists the cumulative number of years that each successive reserve category will serve the nuclear power economy based upon the unrealistic assumption that the total electrical generating capacity is completely nuclear. This electrical generating capacity is based upon the projected U. S. total electrical power growth presented in Fig. 1 as given by Sporn (*6*). It should be noted that Table II is based upon the unrealistic case of only uranium recycle, i.e., the conversion ratio of all the reactor plants within the nuclear power reactor economy is zero.

Therefore, from a review of Table II it is seen that statements such as "U. S. uranium reserves at twice present cost show that there is insufficient U^{235} to supply total U. S. power demands over the next five years" (*1*) are somewhat misleading and are only true under pessimistic assumptions for reserve category A which consists of our known reserves at present costs. Inclusion of other reserve categories significantly changes the situation. A more important consideration in this unrealistic case exists in both the assumptions that the total U. S. electrical generating capacity is completely nuclear and that no plutonium is recycled. Consideration of a realistic power reactor economy system will drastically change the situation.

Figure 1 also presents the projected U. S. nuclear electrical power growth as given by Sporn. This is much larger in the later years of the projection than data recently presented by Zebrowski (a factor of $2\frac{1}{2}$ greater in the year 2020) (*4*). Hence, Sporn's nuclear growth rate might be optimistic. However, the use of Sporn's data as well as the most probably realistic case of plutonium recycle results in the data present in Table III. An effective conversion ratio of $\frac{2}{3}$ has been assumed in this tabulation which is defined here as the effective amount of Pu^{239} and Pu^{241} produced in all the reactors of the power reactor economy system divided by the amount of U^{235} consumed in the system. By an "effective amount" of plutonium is meant the amount either burned *in-situ* in the power reactor economy system or available for reactor through-put after a single cycle of operation. It appears that this assumed value of conversion ratio is conservative (low) for the long-term future. It also should be noted that breeder systems on the plutonium cycle and thorium systems have not been taken into account.

Comparison of the lifetimes for reserve category A as presented in Tables II and III show that the realistic case extends the lifetime by over a factor of 6 based upon compounding conservatisms. Hence, this is a minimum factor. Similar considerations apply to the cumulative lifetimes for the other reserve categories with the difference factor decreasing as the projected nuclear power growth curve approaches the projected total electrical growth curve. The conclusion that may be drawn from these comparisons is that statements implying a very rapid depletion of our uranium reserves can be highly misleading unless they are well qualified.

Another conclusion to be drawn from Table III is the apparent need for reactors of high conversion ratio since an increase in the conversion ratio increases the cumulative lifetime of each reserve category. Hence most of the fertile U^{238} could be utilized if the conversion ratio of the system of reactors was of the order of unity. In addition, with the development of economic high conversion ratio thorium systems, thorium resources also could be used to extend the capabilities of nuclear fission energy.

Before closing it should be noted that any implication that one breeder system is necessarily more economical than another (*1*) is premature. In fact it is difficult if not impossible to demonstrate that any one concept is more economical than another. Economics is a complicated interplay of capital, fuel, and operating costs. Since the nuclear part of a plant represents a small part of the total plant cost, and nuclear fuel costs, if we project a few years into the future, represent less than two mills/kwh, the most important attribute of a nuclear reactor is apt to be the low maintenance or operating costs. This figure will not be known with any degree of certainity for a good many years.

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