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J. E. Cunningham

TO:

FROM: M. Benedict, MIT for Columbia-National Corp.

SUMMARY REPORT

ECONOMIC COMPARISON OF ZIRCALOY AND STAINLESS STEEL IN NUCLEAR POWER REACTORS

Columbia-National Corporation
Jointly owned by Columbia-Southern Chemical Corporation and National Research Corporation
70 MEMORIAL DRIVE, CAMBRIDGE 42, MASSACHUSETTS

SUMMARY REPORT

ECONOMIC COMPARISON OF ZIRCALOY AND STAINLESS STEEL IN NUCLEAR POWER REACTORS

by

Dr. Manson Benedict
Professor of Nuclear Engineering, MIT

for

Columbia-National Corporation

February 6, 1958

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ABSTRACT

SUMMARY REPORT - ECONOMIC COMPARISON OF ZIRCALOY AND STAINLESS STEEL IN NUCLEAR POWER REACTORS

by Dr. Manson Benedict

Use of zirconium (as Zircaloy) instead of less expensive stainless steel as structural material, fuel cladding, or fuel diluent in nuclear reactors makes savings possible through the use of uranium of lower enrichment and/or through reduction in the critical mass of uranium. Columbia-National has made a study of the relative economics of using Zircaloy versus stainless steel in five power-producing thermal reactors, chosen so as to span the entire range of fuel enrichment from natural to highly-enriched uranium. Break-even prices of Zircaloy were computed for each reactor, i.e., the price at which, with an annual return on capital investment of 15%, the lower cost of uranium inventory is just balanced by the difference in cost between Zircaloy and stainless steel. The reactors studies are:

	% U-235	Break-Even Zircaloy Price, per lb. Fuel Cladding	Permanent Parts
1- Natural Uranium, Heavy Water Reactor (Atomic Energy of Canada, Limited)	0.71	$104	$842
2- Sodium-Graphite Reactor (Atomics International)	1.8	57	592
3- Yankee Atomic Electric Reactor (Westinghouse)	2.6	51	-
4- Merchant Ship Reactor (Babcock & Wilcox)	3.64	44	141
5- Experimental Boiling Water Reactor (General Electric)	93	10	-

These studies indicate that Zircaloy should be used for permanent parts of commercial power-producing reactors fueled with uranium enriched up to at least 4% U-235. Zircaloy should be used to clad fuel elements of natural uranium. At prices of from $40 to $60 per pound for mill products it is definitely competitive with stainless steel for fuel cladding in slightly enriched reactors in which zirconium can be substituted

for stainless steel on approximately a volume-for-volume basis. This is the basis for the above break-even prices.

The break-even price is roughly inversely proporational to the volume of Zircaloy substituted for one volume of stainless steel.

The break-even price of Zircaloy decreases as the U-235 enrichment of the fuel increases, because neutron economy is less important with more highly-enriched fuels. Should the A.E.C.'s rental charge against the value of the entire inventory of uranium, now only 4% per year, be raised to a level more representative of commercial interest rates prevailing both here and abroad, the break-even price of zirconium would be increased sharply. This will also be the result if the price of enriched uranium is raised.

The break-even price of Zircaloy used for permanent reactor parts increases slightly with increasing load factor. For cladding it increases with decreasing load factor; this indicates that Zircaloy should be seriously considered for cladding fuel elements, as well as permanet parts, in reactors which are not likely to be operated at load factors of 80% or more.

For a reactor operating at a given power level, the break-even price of Zircaloy increases as it becomes possible to increase the life-time of the fuel in the reactor, i.e., as the fraction of fuel which is burned is increased, a higher price can be justified for the Zircaloy. The break-even price of Zircaloy also is higher with longer fuel life-time for a given burnup fraction, since the Zircaloy need not then be replaced so frequently.

A significant measure of the economic incentive to use Zircaloy in preference to stainless steel is the annual return on the incremental investment made when substituting Zircaloy for stainless steel. At the break-even price, the return is 15%. As the prices of Zircaloy mill products are reduced below the break-even price, the return on the incremental investment rises sharply.

1.0 Introduction

In most of the nuclear reactors being designed today for commercial power production, it is technically feasible to use either stainless steel or zirconium or one of its alloys as structural material, fuel cladding or fuel diluent. When used within the neutron flux of the reactor the low neutron-absorption cross section of zirconium gives that material an important economic advantage over stainless steel. Use of zirconium instead of stainless steel makes possible savings through the use of uranium of lower enrichment, through reduction in the critical mass of uranium, or through some combination of these cost-saving features. On the other hand, zirconium and its alloys cost more than stainless steel. The economic incentive to use zirconium instead of stainless steel will, therefore, depend on the relative magnitudes of the saving in fuel costs made possible with zirconium compared with the additional material cost incurred when zirconium is used in place of stainless steel.

In order to assist reactor designers in determining when it is advantageous to consider zirconium as fuel cladding or structural material in nuclear reactors, Columbia-National Corporation has undertaken a study of the relative economics of using Zircaloy or stainless steel in five representative power-producing thermal reactors. This report states the premises of the study and summarizes the principal results. Readers interested in details of the calculation method employed are referred to a second report[1)], which illustrates application of these methods to a specific reactor.

Section 2.0 of the present report describes briefly the five reactors considered in this study and summarizes the break-even price of

Zircaloy-2 found for each reactor. By break-even price is meant that price of Zircaloy at which the contribution to the cost of power due to Zircaloy and the less enriched fuel which may be used with Zircaloy just equals the contribution to the cost of power due to stainless steel and the more enriched fuel which must be used with stainless steel.

Section 3.0 discusses the assumptions made in evaluating the break-even price and illustrates how the break-even price would vary with changed assumptions.

Section 4.0 gives the annual savings in the cost of fuel and structural materials if Zircaloy at various prices was used in place of stainless steel. This section also shows the annual return on the incremental investment in Zircaloy over stainless steel made possible by the lower fuel costs obtainable with Zircaloy.

It is hoped that this report will give the reactor designer an understanding of the magnitude of the economic incentive to use Zircaloy or other zirconium alloys in place of stainless steel in nuclear reactors, and of the dependence of this incentive on reactor parameters and on the price of Zircaloy.

The studies on which this report is based were carried out by Messrs. George Jansen, Jr., Jacek Jedruch and the writer.

2.0 The Break-Even Price of Zircaloy in Representative Reactors

Table I lists the five reactors investigated in this study together with their principal features of interest and properties which affect the break-even price of Zircaloy. These five reactors were so chosen as to cover the entire range of U-235 enrichment in fuel from natural uranium (0.71% U-235), in the NPD Reactor, to fully enriched U-235 (93% U-235),

TABLE I

BREAKEVEN PRICE OF ZIRCALOY IN REACTORS

Name	NPD Reactor	Sodium-Graphite Reactor	Yankee Atomic Electric Reactor		Merchant Ship Reactor		General Electric Devel. Boiling Water Reactor
Developed by	AEC of Canada and Canadian G. E.	Atomics International	Westinghouse		Babcock & Wilcox		General Electric
Owner	Hydroelectric Power Comm. of Ontario	Consumers Public Power of Nebraska	Yankee Atomic Elec. Company		Maritime Commission and A. E. C.		G. E. & Pacific Gas & Electric
Megawatts - Electric	20	75	134		--		5
- Thermal	80	250	480		85		20
Load Factor	0.8	0.8	0.8		0.8	0.4	0.6
Materials Presently Specified							
Fuel Cladding	Zr	S.S.	S.S.		S.S.	S.S.	S.S.
Permanent Parts	Zr	Zr	--		S.S.	S.S.	--
Pounds Uranium in Fuel	14,140	53,800	53,500		19,400	19,400	43
% U-235 in Fuel	0.71	1.8	2.6		3.64	3.64	93
MWD per Ton	4,000	3,500	8,240		8,113	8,113	--
Burnup Fraction, β	0.0043	0.0037	0.0088		0.0087	0.0087	0.20
Reactivity Life-time, years, t	0.98	1.17	1.43		2.86	5.72	0.99 (S.S.) 0.57 (Zr)
FUEL CLADDING							
Form	0.567"OD tube	0.495"OD tube	0.305"ID tube		0.448"ID tube		Sheet
Thickness, mils S.S.	30	10	15	15	26.5	26.5	5
Zr	30	10	15	30	38	38	5
Pounds Zr per Fuel Charge	3,045	1,920	10,940	22,400	7,700	7,700	584
Pounds Zr Used per Year	3,120	1,646	7,740	15,850	2,760	1,380	1,026
Zr BREAKEVEN PRICE, $/lb	104	57	51	25	44	57	10
PERMANENT PARTS							
Form	3 1/4" & 3 5/8" tube	tube & sheet	----		Sheet	Sheet	----
Thickness, mils S.S.	40	35			} Equal	} Equal	
Zr	40	35					
Pounds Zr per Reactor	2,970	15,060			3,270	3,270	
Zr BREAKEVEN PRICE, $/lb	842	592			141	109	

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in the G. E. Developmental Boiling Water Reactor. The U-235 enrichment is one of the most important factors influencing the break-even price of Zircaloy.

2.1 NPD Reactor

The NPD Reactor, under development by Atomic Energy of Canada, Ltd., and the Canadian General Electric Company, will be the first power reactor using natural uranium as fuel to go into operation in the Western hemisphere. For successful operation on natural uranium, this reactor must use materials with low neutron absorption. Pressurized heavy water has been specified as coolant and moderator, and Zircaloy has been selected as structural material both for permanent parts of the reactor and for fuel cladding, which must be replaced around once a year with each new charge of fuel. The mechanical design of this reactor was recently modified so that individual cooling tubes now take the principal pressure stresses in the reactor instead of the external pressure vessel being subjected to these stresses. The break-even price study has been based on the former pressure-vessel design instead of the present pressure-tube design because detailed information on the present design was not available. This change would not have much effect on the break-even price of Zircaloy. This reactor is described in a pamphlet[2)] issued by the Canadian General Electric Company. Additional information on this reactor was kindly furnished by Dr. W. B. Lewis.

2.2 Sodium-Graphite Reactor

The reactor being developed by Atomics International under contract with AEC for the Consumers Public Power District of Nebraska is

cooled by molten sodium moderated by graphite and fueled with uranium slightly enriched in U-235. In this reactor a large amount of Zircaloy is specified for use in permanent cladding for graphite moderator blocks, and a smaller amount of stainless steel is specified for use in cladding for fuel elements, to be replaced at intervals of 1.2 years. The design for this reactor used in the present study was that reported by Starr[3)] at the Geneva Conference in 1955, which called for uranium fuel containing 1.8% U-235. The most recent design, which calls for using a somewhat richer fuel, has not been used in the present study. This would reduce the break-even price, somewhat.

2.3 Yankee Atomic Electric Reactor

The reactor being designed by Westinghouse for the Yankee Atomic Electric Company is cooled and moderated by pressurized light water and uses stainless steel as cladding for fuel elements, to be replaced at intervals of 1.4 years. Fuel consists of uranium oxide pellets enriched to 2.6% in U-235. Design information for this reactor has been obtained from Westinghouse Report YAEC-1[4)], kindly made available to us by Mr. Roger Coe of Yankee.

2.4 Merchant Ship Reactor

The Merchant Ship Reactor, under development by Babcock and Wilcox for the Maritime Administration and the AEC is also of the pressurized water type. It uses stainless steel both for permanent parts of the reactor core and as cladding for UO_2 fuel elements, to be replaced every 3 to 6 years, depending on the reactor load factor. Fuel for this reactor is to be enriched in U-235 to 3.64%. Design information for this reactor as of July, 1957, was kindly furnished by Dr. M. C. Edlund of

Babcock and Wilcox. Changes in specifications may be made before this reactor is actually built.

2.5 General Electric Developmental Boiling Water Reactor

This reactor has been designed, built, and operated by the General Electric Company to provide experimental data on the characteristics of a boiling-water reactor system. For fuel, it uses a powder compact of UO_2 and stainless steel, clad with stainless steel sheet. The uranium is fully enriched (93% U-235). This reactor was chosen for this study because complete design information was available and its characteristics were representative of other fully enriched reactors, such as the Army Package Power Reactor, for which complete design information was not available at the time of this study. Design data for the G. E. reactor was obtained from references 5) and 6).

The study showed that the break-even price of Zircaloy ($10 per pound) was so low that its use would never be economic in this reactor. Hence, the question whether it would really be mechanically feasible to fabricate a powder-compact fuel element from Zircaloy instead of stainless steel does not have to be faced.

In all other types of reactors operating conditions are such that it is technically feasible to use Zircaloy or stainless steel interchangeably, both in fuel cladding and in permanent parts of the reactor.

2.6 Factors Which Affect Break-Even Price

The principal factors listed in Table I which affect the break-even price of Zircaloy are the % U-235 in fuel, the burnup fraction β, the fuel reactivity life-time t, and the relative thicknesses of stainless

steel and Zircaloy used when one material is substituted for the other. By burnup fraction is meant the fraction of uranium atoms (U-238 as well as U-235) which are converted to fission products by the time the fuel is discharged from the reactor. The burnup fractions listed in the table are those claimed to be feasible by the reactor designers. The reactivity life-times have been obtained from the burnup fraction β, rated thermal power P, load factor L, uranium inventory in metric tons U and an assumed heat of fission Q = 0.938 MWD/ton by t(years) = βQU/365LP.

2.7 Comparison of Break-Even Price in Different Reactors

The lower part of Table I gives data for the break-even price of Zircaloy (1) when used in fuel cladding, to be replaced at the end of each fuel life of stated duration, and (2) when used in permanent parts of the reactor which are assumed to last as long as the reactor. The form and amount of Zircaloy used in each way is given. The amount of Zircaloy required and the break-even price refer to Zircaloy in the form of mill products (sheet or tubing) of the specified dimensions. It has been assumed that in fabricating reactor parts from mill products a yield of 90% may be secured with Zircaloy and 100% with stainless steel.

As this table shows, the break-even price of Zircaloy when used in fuel cladding is much lower than when used in permanent parts of the reactor. This is because one cannot afford to pay as much for Zircaloy when new material must be bought with each charge of fuel as when it need be bought only once in the life of the reactor. The break-even price, both in fuel cladding and in permanent parts, decreases in reading from left to right in this table. This is due principally to the increased % U-235 in fuel; other things being equal, the higher the

% U-235 in fuel, the lower the break-even price.

When Zircaloy is used in fuel cladding, the break-even price for the NPD Reactor, using natural uranium fuel, is $104 per pound. This is so high that the decision of the Canadians to use Zircaloy in this reactor is amply justified. In the other reactors, using uranium enriched above the natural abundance, the break-even price of Zircaloy in fuel cladding is $57 or less. The present price of Zircaloy tubing of a size suitable for fuel cladding is in the range of $40 to $60 per pound. In the G. E. Developmental Boiling Water Reactor, the break-even price of $10 per pound is so low that one can conclude that it would never pay to use Zircaloy for fully enriched reactors.

When Zircaloy is used in permanent parts of the reactor, the break-even price ranges from $842 per pound in the NPD Reactor to $109 per pound in the Merchant Ship Reactor. These values are so high that one may conclude that Zircaloy should be used as permanent parts in reactors fueled with slightly enriched uranium, at least up to 4% U-235.

Most of the break-even prices given in Table I are based on the substitution of one volume of Zircaloy for one volume of stainless steel. The break-even price is roughly inversely proportional to the volume of Zircaloy substituted for stainless steel. This generalization is illustrated by the two cases for the Yankee Reactor listed in this table, in which the break-even price drops from $51 per pound for 15-mil Zircaloy tubing to $25 per pound for 30-mil tubing.

The first three reactors listed in Table I will be used in large, central-station power plants at a load factor of around 0.8. The load factor of the Merchant Ship Reactor, on the other hand, is more

uncertain, and may be lower. For this reason, break-even prices have been given for load factors of 0.8 and 0.4 for this reactor.

3.0 Discussion of Assumptions and Their Effect on the Break-Even Price

The principal assumptions on which these break-even prices have been based and the effect of these assumptions on the price are sketched below.

3.1 Substitution Conditions

Conditions assumed held constant when Zircaloy is substituted for stainless steel are:

1) the reactor's inventory of U-238,
2) the burnup fraction, i.e., the fraction of uranium in spent fuel which has been converted to fission products, and
3) the reactivity of spent fuel.

When these conditions are held constant in the substitution of Zircaloy for stainless steel, the U-235 content of fresh fuel may be reduced. Calculation of the magnitude of this reduction is an important step in evaluating the break-even price.

Except where otherwise noted, it has been assumed that one volume of Zircaloy may be substituted for one volume of stainless steel.

3.2 Value of Materials

Stainless steel has been valued at $5 per pound in place in the reactor. For every dollar per pound increase in this price, the break-even price of Zircaloy is increased by about the same amount. The price of cobalt-free stainless steel is much greater than $5 per pound. When Zircaloy is considered as a substitute for cobalt-free stainless the

break-even price of Zircaloy is correspondingly higher.

The value of uranium as a function of enrichment has been taken from the AEC's price schedule which values natural uranium at $39.27 per kg. and highly enriched uranium at $17 per gm. U-235. Both the cost of uranium in fresh fuel and the credit for uranium in spent fuel have been evaluated from this schedule. The break-even price of Zircaloy is roughly proportional to the value of uranium.

Plutonium in spent fuel has been credited at $30 per gm., the AEC's present "buy-back" price. This price has little effect on the break-even price of Zircaloy, since the yield of plutonium is not greatly changed by the substitution of Zircaloy for stainless steel.

3.3 Fabrication Yields

The yield of stainless steel in the reactor from stainless steel mill products has been taken as 100%. The yield of Zircaloy in the reactor from Zircaloy mill products has been taken as 90%, a value recommended to us by Westinghouse. This yield is based on a tubular fuel element containing fused uranium oxide pellets.

The break-even price of Zircaloy mill products is roughly inversely proportional to this yield. The break-even price of Zircaloy mill products for fabrication yields different from the 90% used in this report is shown in Figure 1. In these calculations Zircaloy scrap from fuel element fabrication has been given a credit of $3 per pound; this credit has little effect on the break-even price.

3.4 Fuel Fabrication and Processing Costs

It has been assumed that fuel element fabrication costs per kg. of uranium would be the same for fuel elements clad with Zircaloy as for

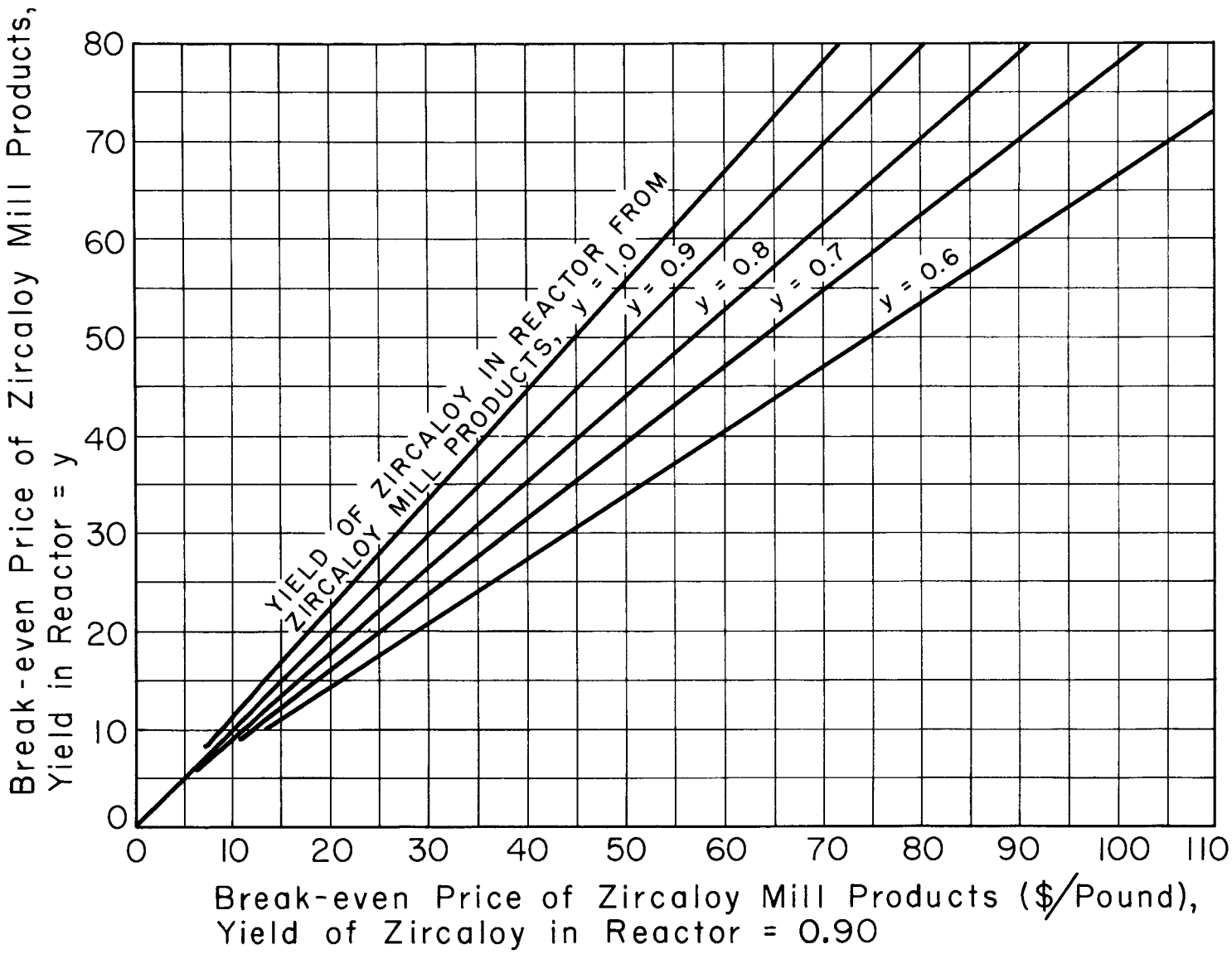

FIGURE I - EFFECT OF YIELD OF ZIRCALOY IN REACTOR FROM ZIRCALOY MILL PRODUCTS ON BREAK-EVEN PRICE

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those clad with stainless steel, exclusive of the cost of the cladding and fabrication losses. These fabrication costs are not well known at the present time. With the assumption that they are equal for the two materials, and the assumption that the same fraction of uranium is converted to fission products with the two materials, the fabrication costs cancel out in evaluating the break-even price and need not be known.

Similarly, it has been assumed that the cost of reprocessing fuel elements per kg. of uranium is the same for elements clad with Zircaloy as for those clad with stainless steel. This is true in the schedule of reprocessing charges currently in use by the AEC. With the assumption that the same fraction of uranium is converted to fission products with the two materials, the fabrication costs also cancel out of the break-even price and need not be stated.

3.5 Inventories

For purposes of computing rental charges on uranium, the uranium inventory of the reactor system has been assumed to be made up of the following components:

a) the uranium fuel charge in the reactor,

b) spare fuel elements, containing 10% of the uranium in the fuel charge, and

c) uranium corresponding to a holdup of one year in fuel fabrication, cooling and reprocessing.

In accordance with present AEC accounting practice, all of this uranium is valued at the composition it had when charged to the reactor.

For purposes of computing annual charges on cladding material, the value of its inventory is assumed made up of the following components:

a) one-half of the cladding in the reactor,

b) spare fuel elements containing 10% of the cladding in a full reactor charge, and

c) cladding corresponding to a holdup of one-half year in fuel fabrication.

Cladding material is treated differently from fuel, because it is assumed that during irradiation cladding depreciates in value linearly from full value in fresh fuel to zero value in spent fuel. This is why charges are levied on the value of only half of the inventory of cladding in a reactor charge, and none on cladding in spent fuel.

3.6 Interest Charges

A rental charge of 4% per year is made against the value of the entire inventory of uranium in fuel fabrication, reactor cooling, reprocessing and spare fuel elements. This is the AEC's present rental charge. Figure 2 shows how the break-even price in the Yankee Reactor would be affected by changes in this rental charge. It is worth noting that the break-even price of Zircaloy would be substantially higher if the rental charge were higher than 4%, as would be the case if enriched uranium were produced under ordinary commercial conditions.

In the prices given in Table I, an annual charge of 15% per year has been made on the undepreciated value of the working inventory of stainless steel and Zircaloy; this is near the average rate for utility financing. The effect of changes in this rate is shown in Figure 3 for those reactors where this effect was studied. This plot, on semi-log paper, shows that the annual charge on investment has little effect on

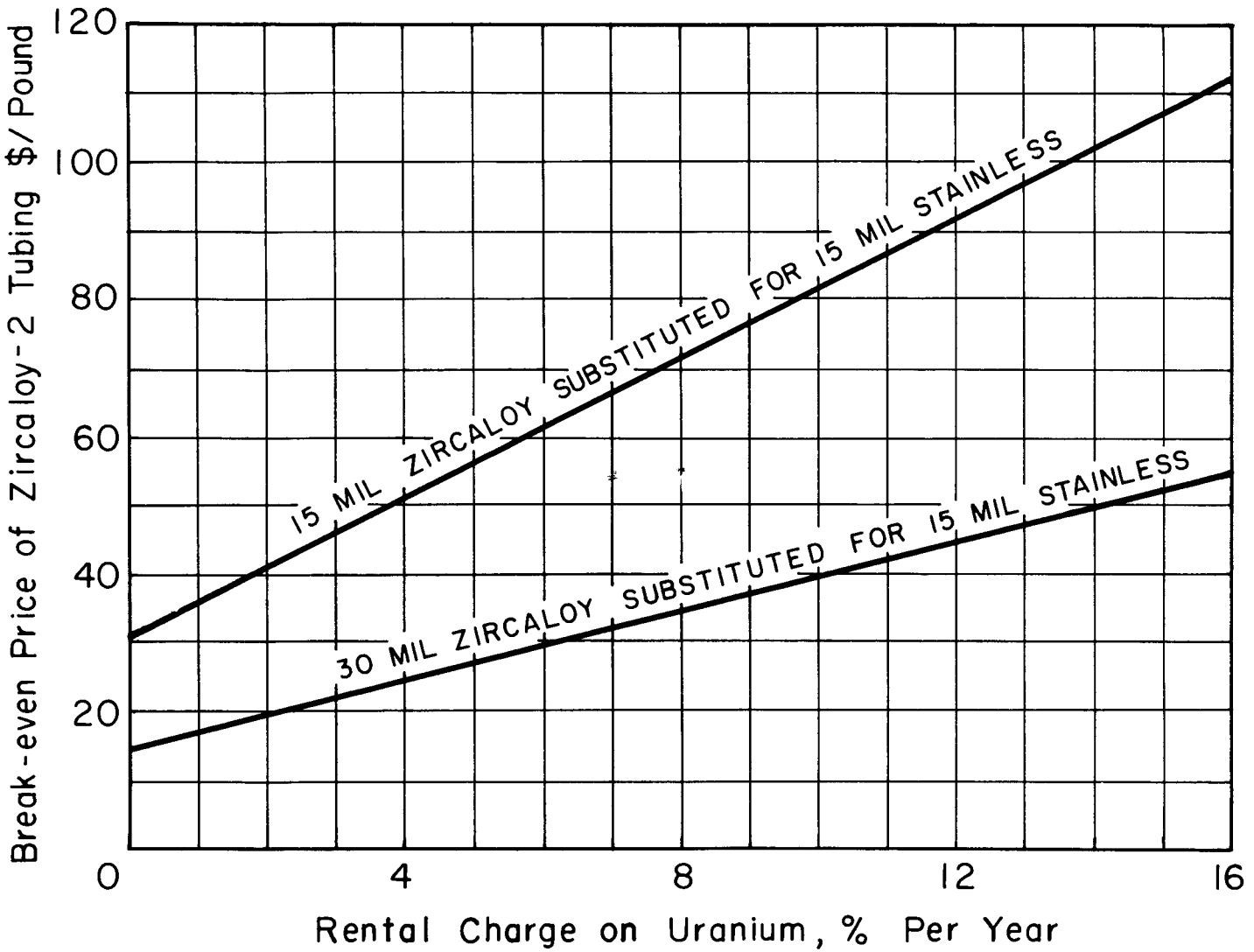

FIGURE 2-EFFECT OF AEC'S RENTAL CHARGE FOR URANIUM ON BREAK-EVEN PRICE OF ZIRCALOY-2 TUBING USED TO CLAD FUEL IN YANKEE REACTOR

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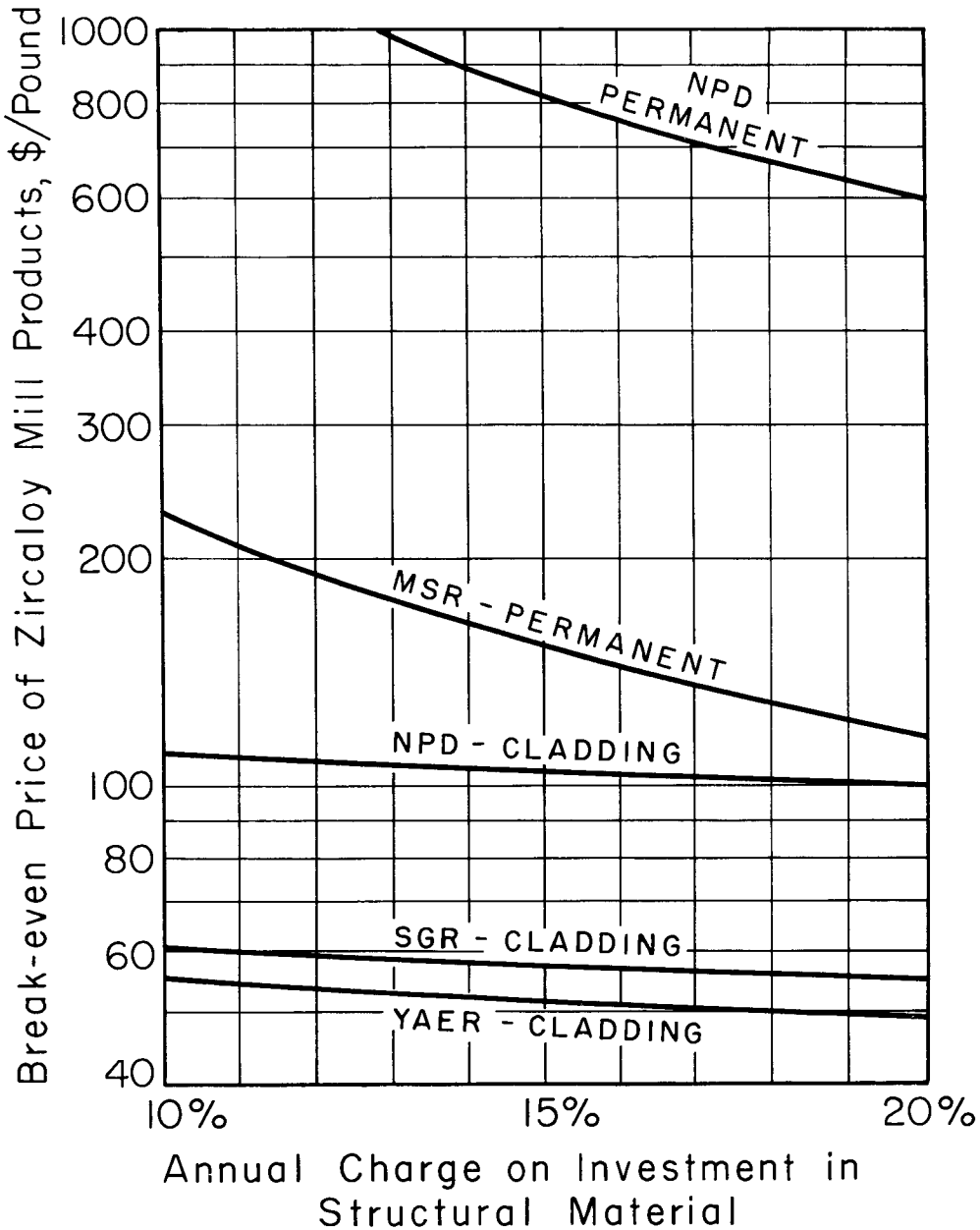

FIGURE 3
BREAK-EVEN PRICE OF ZIRCALOY VS. ANNUAL CHARGE ON INVESTMENT IN STRUCTURAL MATERIAL.

VOLUME-FOR-VOLUME SUBSTITUTION.

the break-even price of Zircaloy when used in fuel cladding replaced with each charge of fuel, but has an important effect on Zircaloy when used in permanent parts of the reactor.

The reason for this is simple. In these reactors fuel is replaced once every year or two, so that makeup charges are from 50 to 100% of the value of working inventory; variations in annual charges on investment between 10 and 20% then have only a slight effect on the overall economics. However, for permanent parts of the reactor there are no makeup charges, and the charges on investment are the whole charge against structural material. Under these conditions, the break-even price is approximately inversely proportional to the annual charge on investment. Decrease of this charge from 20 to 10% almost doubles the break-even price.

3.7 Substitution Ratio of Zircaloy for Stainless Steel

Except where otherwise noted in this report, it has been assumed that one volume of Zircaloy may be substituted for an equal volume of stainless steel, e.g., 15-mil Zircaloy tubing may be substituted for 15-mil stainless steel tubing. The break-even price of Zircaloy is very nearly inversely proportional to the volume substitution ratio of Zircaloy for stainless. For instance, if 30-mil Zircaloy is substituted for 15-mil stainless steel, the break-even price is about half the value when 15-mil Zircaloy is so substituted. Figure 4 is a chart giving the break-even price for a volume substitution ratio (R) different from unity in terms of the break-even price for unit volume substitution ratio.

3.8 Load Factor

Except where otherwise stated in this report, it has been assumed

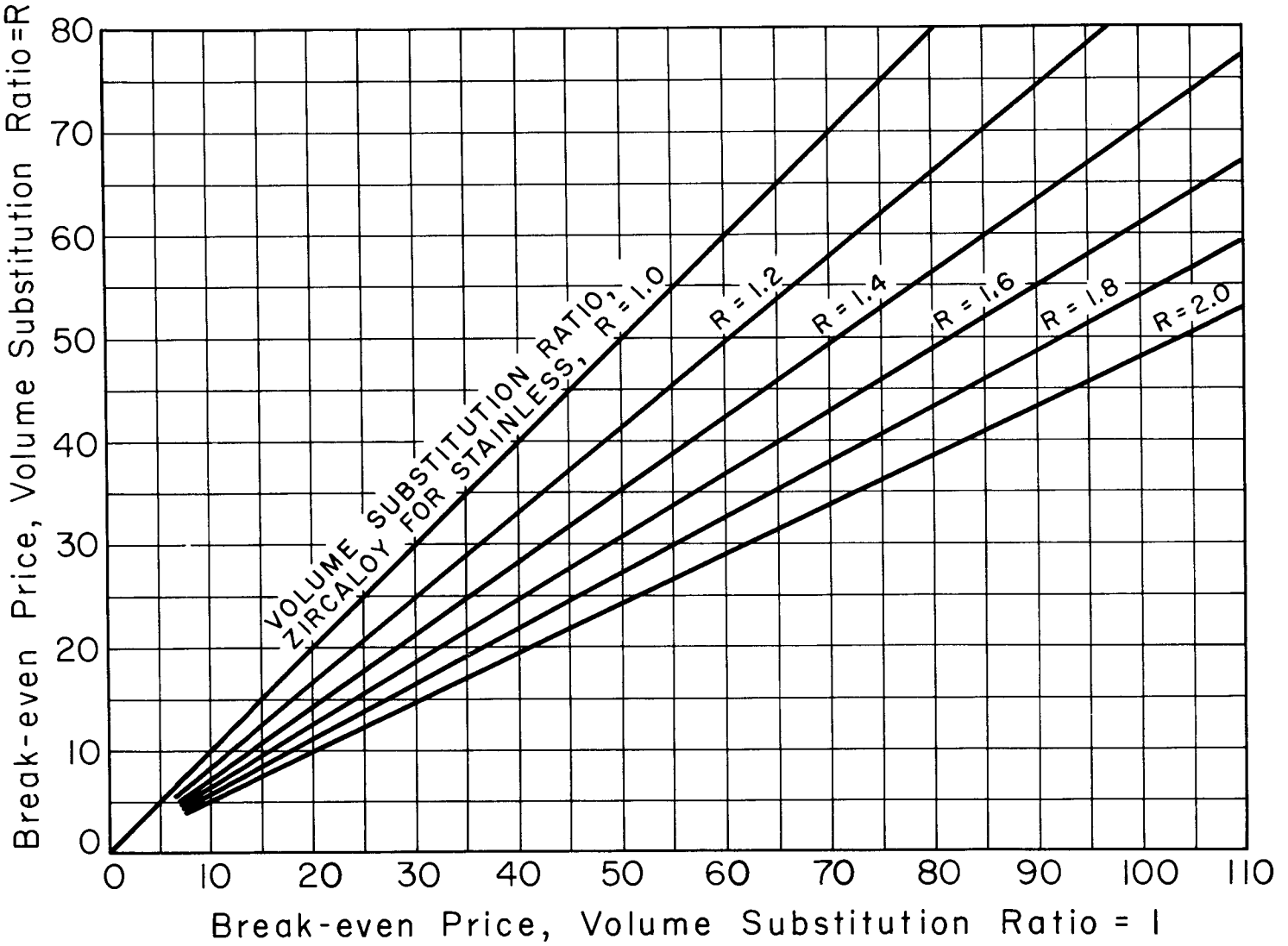

FIGURE 4 - EFFECT OF ZIRCALOY TO STAINLESS SUBSTITUTION RATIO ON BREAK-EVEN PRICE OF ZIRCALOY

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that each reactor operates at a load factor of 80%, a representative value for large, base-load, central-station power plants. Since the Merchant Ship Reactor may operate at lower load factors, the effect of changes in load factor on the break-even price of Zircaloy in this reactor has been investigated and is shown in Figure 5.

The reason for the increase in break-even price of Zircaloy used for permanent reactor parts with increasing load factor is that more fuel is then put through the reactor and the annual savings made possible by the use of Zircaloy are greater. Since the amount of Zircaloy in the reactor is independent of load factor, its break-even price is higher, the higher the load factor.

When Zircaloy is used for fuel cladding, to be replaced with each charge of fuel, the amount of Zircaloy used per year increases with load factor proportionately more rapidly than does the annual savings. Then the savings per pound of Zircaloy, and the break-even price, decrease with increasing load factor, as shown in Figure 5. The trends shown in this Figure suggest that if the load factor of this reactor is expected to be substantially under 80%, Zircaloy should be considered seriously for fuel cladding, as well as for permanent parts.

3.9 Flux Ratio

When the structural material is in a higher average neutron flux than the uranium fuel, the reduction in neutron absorption possible when Zircaloy is substituted for stainless steel will be greater, and the break-even price will be higher. In fact, the break-even price is approximately proportional to the ratio of the average flux in structural material to the average flux in fuel. The values for this flux ratio

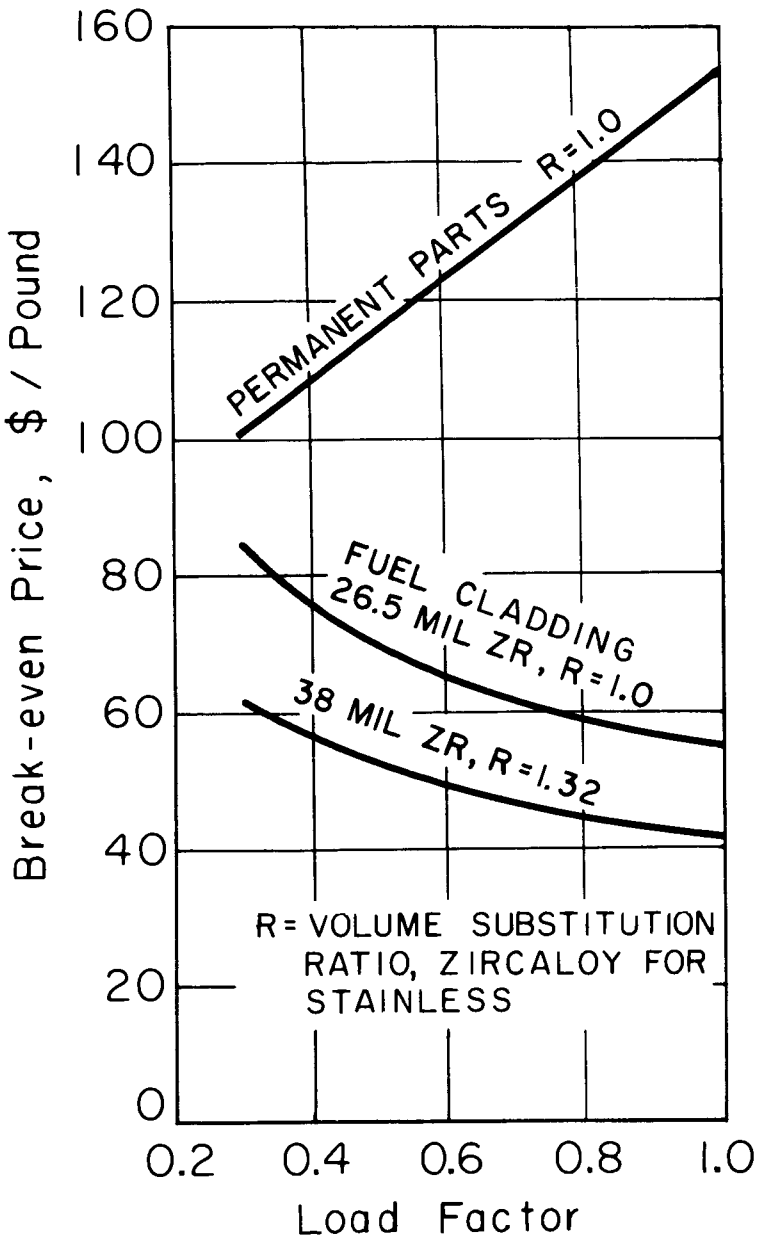

FIGURE 5
EFFECT OF LOAD FACTOR ON BREAK-EVEN PRICE OF ZIRCALOY MILL PRODUCTS IN MERCHANT SHIP REACTOR.

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used for each of the reactors studied is given in Table II.

TABLE II

Reactor	NPD	SGR	YAER	MSR	GEDBWR
Ratio of flux, structural material to fuel					
Permanent Parts	1.21	2.36	--	1.05	--
Cladding	1.04	1.00	1.005	1.00	1.01
Fraction of structural material in flux					
Permanent Parts	0.90	0.71	--	0.95	--
Cladding	0.95	1.00	0.87	0.95	1.00

3.10 Structural Material Outside of Core

In several of the reactors studied, structural material extends out of the core of the reactor into regions where there is no neutron flux. Since this extra material must be paid for but saves no neutrons and does not contribute to reduction in fuel costs, the break-even price of Zircaloy is lower the more structural material is outside of the neutron flux. Table II gives the fraction of structural material assumed to be within the neutron flux of each reactor studied. The break-even price is approximately proportional to this quantity.

3.11 Physical Properties

Table III gives the physical properties assumed for Zircaloy-2 and stainless steel.

TABLE III

PHYSICAL PROPERTIES OF ZIRCALOY-2 AND STAINLESS STEEL

	Zircaloy-2	Stainless Steel
Molecular Weight, M	91.01	54.2
Density, gm/cm^3, ρ	6.50	8.03
Neutron absorption cross section at 2200 m/sec., σ	0.206 b	2.79 b

Effective cross sections for uranium - 235 ($\hat{\sigma}_{25}$) and other fuel components were obtained from the correlation of C. H. Westcott[7], in which allowance is made for the effect of temperature of thermal neutrons and the effect of epithermal neutrons. The break-even price of Zircaloy is roughly proportional to the factor:

$$\frac{\dfrac{\sigma s \rho ssMzr}{R \rho zrMss} - \sigma zr}{\hat{\sigma}_{25}}$$

R is the volume substitution ratio of Zircaloy for stainless steel, and the other symbols have been defined above.

3.12 U-235 Enrichment Burnup Fraction, and Rate of Burnup of Fuel

The break-even price of Zircaloy is strongly dependent on the operating conditions of U-235 enrichment, burnup fraction and rate of burnup of fuel. In Table I, comparison of the break-even prices among the five reactors studied gives some idea of the effect of changes in these conditions on break-even price but is not very informative because it is difficult to sort out the effect of one variable from another when all are changed at the same time. Moreover, differences in flux ratios,

effective cross sections, and other variables among these reactors further obscure any trends. Consequently, a separate study has been made of the change in break-even price when operating conditions are changed one-at-a-time in the same reactor. Figures 6 and 7 show the main results of this study, made in Mr. Jacek Jedruch's S. M. Thesis in Nuclear Engineering at M. I. T.[8] The study refers to fuel cladding in the Sodium-Graphite Reactor. As these figures show, the break-even price decreases with increasing enrichment, increases with increasing burnup fraction, and decreases with increasing fraction burned up per year.

The prices shown in Figures 6 and 7 were developed for the Sodium-Graphite Reactor. However, the results are approximately correct for other slightly enriched reactors with volume-for-volume substitution of Zircaloy for stainless steel. This may be seen by comparing the price calculated for the Yankee Reactor (Table I) with the price for the Sodium-Graphite Reactor (Figure 6) at the same burnup fraction, % U-235 and rate of burnup:

Reactor	Yankee	Sodium-Graphite
Burnup Fraction	0.0088	0.0088
% U-235	2.6	2.6
Fraction Burned up per Year	0.0062	0.0062
Break-even Price, $/lb.	51	55
Source of Data	Table I	Figures 6 and 7 extrapolated

These Figures are recommended for use as a general correlation of the break-even price of Zircaloy when substituted volume-for-volume for stainless steel fuel cladding in slightly enriched reactors. As

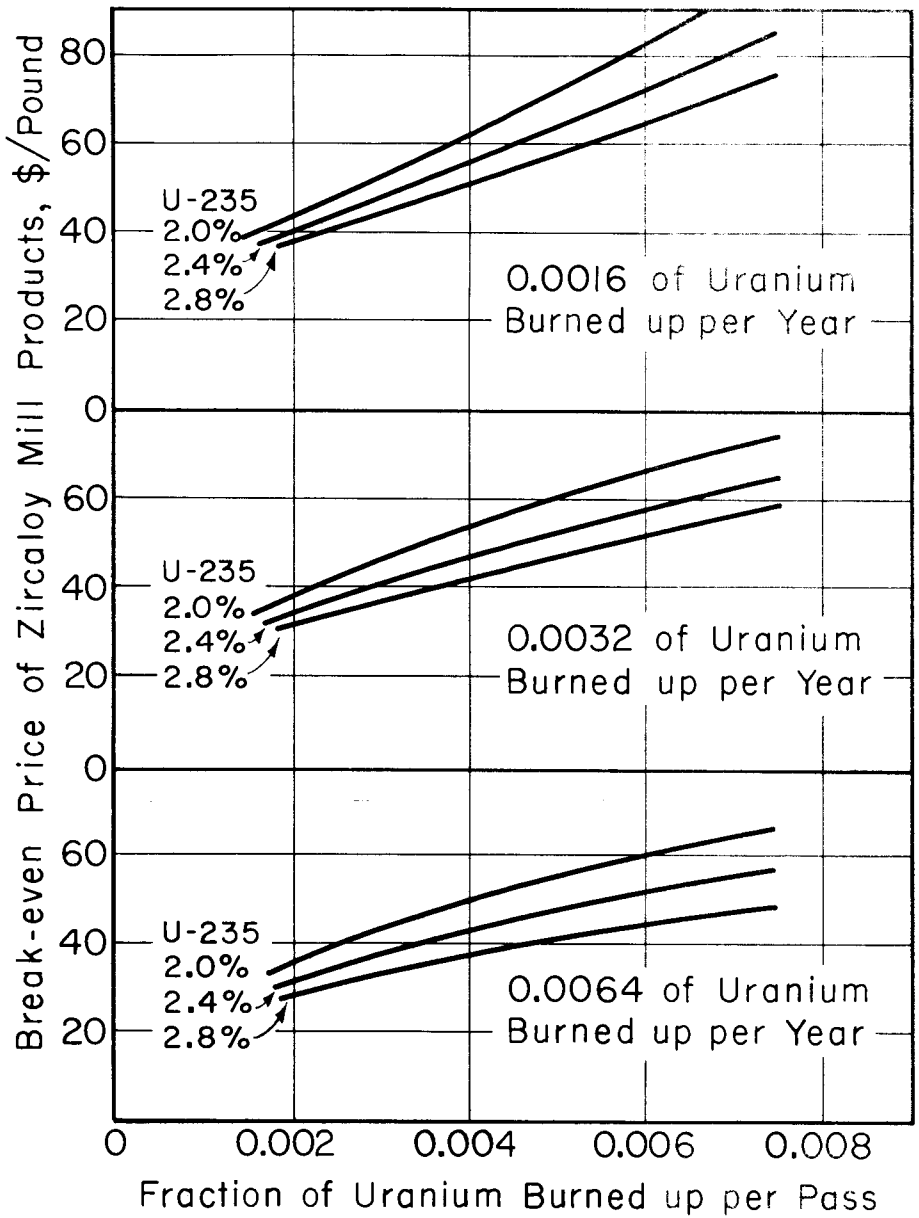

FIGURE 6
BREAK-EVEN PRICE OF ZIRCALOY WHEN SUBSTITUTED VOLUME-FOR-VOLUME FOR STAINLESS STEEL IN SODIUM-GRAPHITE REACTOR.

EFFECT OF VARIATION OF FUEL ENRICHMENT, BURNUP FRACTION AND RATE OF BURNUP.

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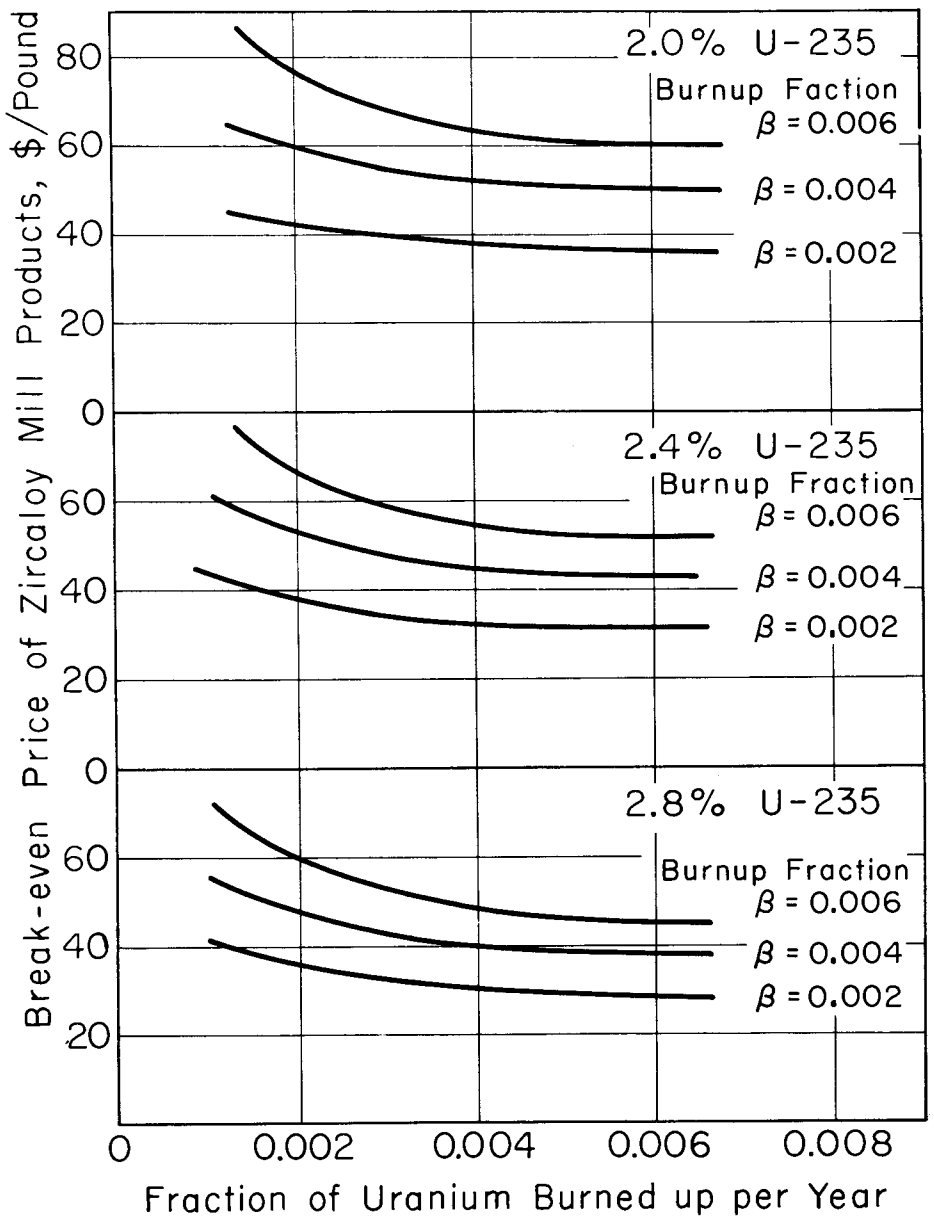

FIGURE 7
BREAK-EVEN PRICE OF ZIRCALOY WHEN SUBSTITUTED VOLUME-FOR-VOLUME FOR STAINLESS STEEL IN SODIUM-GRAPHITE REACTOR.

EFFECT OF VARIATION OF FUEL ENRICHMENT, BURNUP FRACTION AND RATE OF BURNUP.

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stated earlier, the break-even price is approximately inversely proportional to the volume of Zircaloy substituted for one volume of stainless steel. The effect of changes in load factor is taken into account through the change in fraction of fuel burned up per year. These figures refer to a flux ratio of unity, with all of the structural material in the neutron flux. When these factors differ from unity, appropriate corrections should be made.

4.0 Savings from Substitution of Zircaloy for Stainless Steel

4.1 Dollar Savings

Although the break-even price of Zircaloy indicates the price below which Zircaloy would have to sell for substitution of Zircaloy for stainless steel in nuclear reactors to be economically advantageous, the break-even price by itself gives no indication of the magnitude of the economic incentive to substitute Zircaloy for stainless steel. To indicate the magnitude of this incentive, the dollar savings in direct operating costs which could be realized by substituting Zircaloy for stainless steel in fuel cladding for each of the four slightly enriched reactors studied has been computed and is plotted in Figure 8. These savings are the net cost of fuel plus makeup Zircaloy cladding minus the corresponding quantity for stainless steel. The reactors in which the greatest dollar savings are possible are the NPD Reactor and the Yankee Reactor, the latter when the price of Zircaloy is below $50 per pound.

The principal reason for the greater savings in these reactors is that of those studied they have the largest weight of fuel cladding.

4.2 Annual Return on Incremental Investment

A somewhat more significant measure of the economic incentive

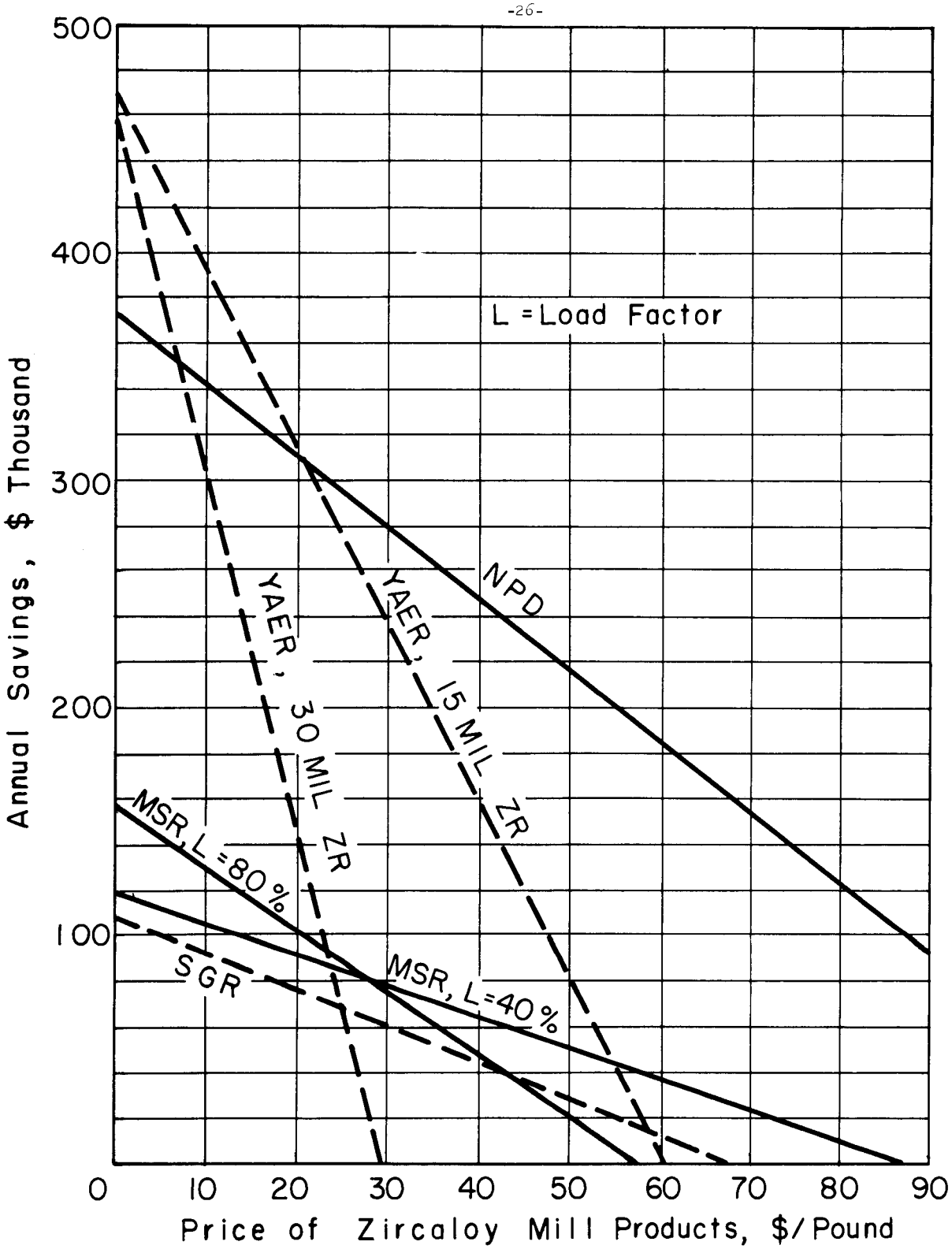

FIGURE 8 - ANNUAL SAVINGS IN DIRECT OPERATING COSTS FROM THE SUBSTITUTION OF ZIRCALOY FOR STAINLESS STEEL IN FUEL CLADDING

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is the annual return on incremental investment required to substitute Zircaloy for stainless steel. Figure 9 shows this annual return (before taxes) for the substitution of Zircaloy for stainless steel in fuel cladding, replaced with each charge of fuel. This annual return has been computed by dividing the dollar savings shown in Figure 8 by the difference between the cost of Zircaloy fuel cladding inventory and the cost of stainless steel fuel cladding inventory. Reference to Section 3.5 will show that the cost of this inventory is taken to be one-half the cost of the cladding in the reactor fuel charge, plus the cost of cladding in spare fuel elements, and of cladding material equivalent to a holdup of one-half year in fuel fabrication.

The price of Zircaloy mill products at which the annual return is 15% is the break-even price given in Table I. As the price of Zircaloy drops below the break-even price, the annual return on incremental investment in cladding material increases very rapidly. In the Yankee Reactor, for instance, if 15-mil Zircaloy tubing could be used for cladding and could be purchased for $40 per pound, the annual return on incremental investment would be 45%.

Figure 10 shows the annual return on incremental investment when Zircaloy is substituted for stainless steel in permanent parts of the Merchant Ship Reactor, the Sodium-Graphite Reactor, and the NPD Reactor.

The annual return has been computed by dividing the annual savings in fuel cost made possible through substitution of Zircaloy for stainless steel by the additional cost of Zircaloy permanent reactor parts compared with stainless steel. As in Figure 9, the price of Zircaloy mill products which leads to an annual return of 15% is the break-even price which has been given in Table I. For the range of current Zircaloy

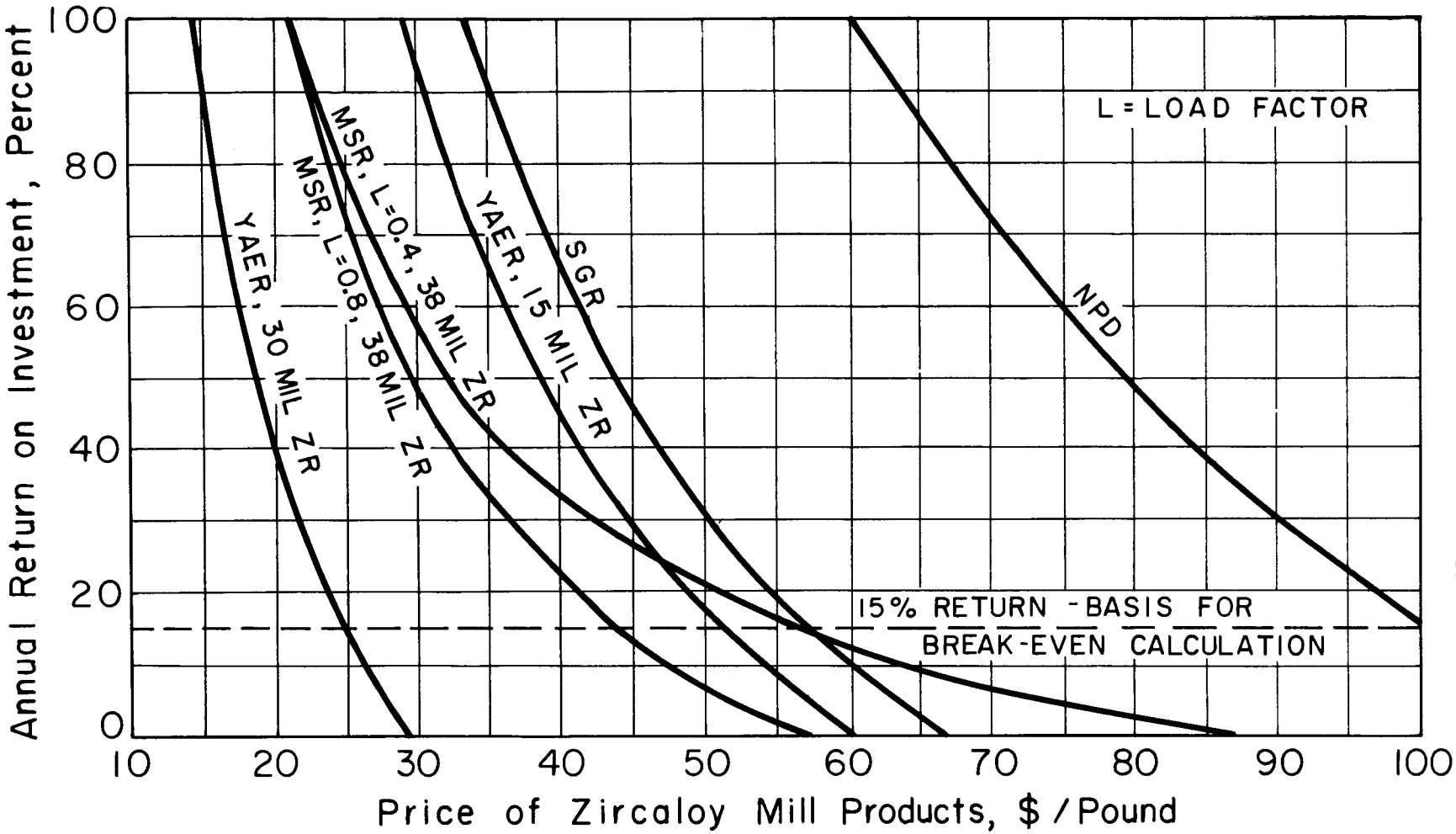

FIGURE 9 - ANNUAL RETURN ON INCREMENTAL INVESTMENT AS A FUNCTION OF ZIRCALOY MILL PRODUCT PRICE WHEN ZIRCALOY IS SUBSTITUTED FOR STAINLESS AS FUEL CLADDING

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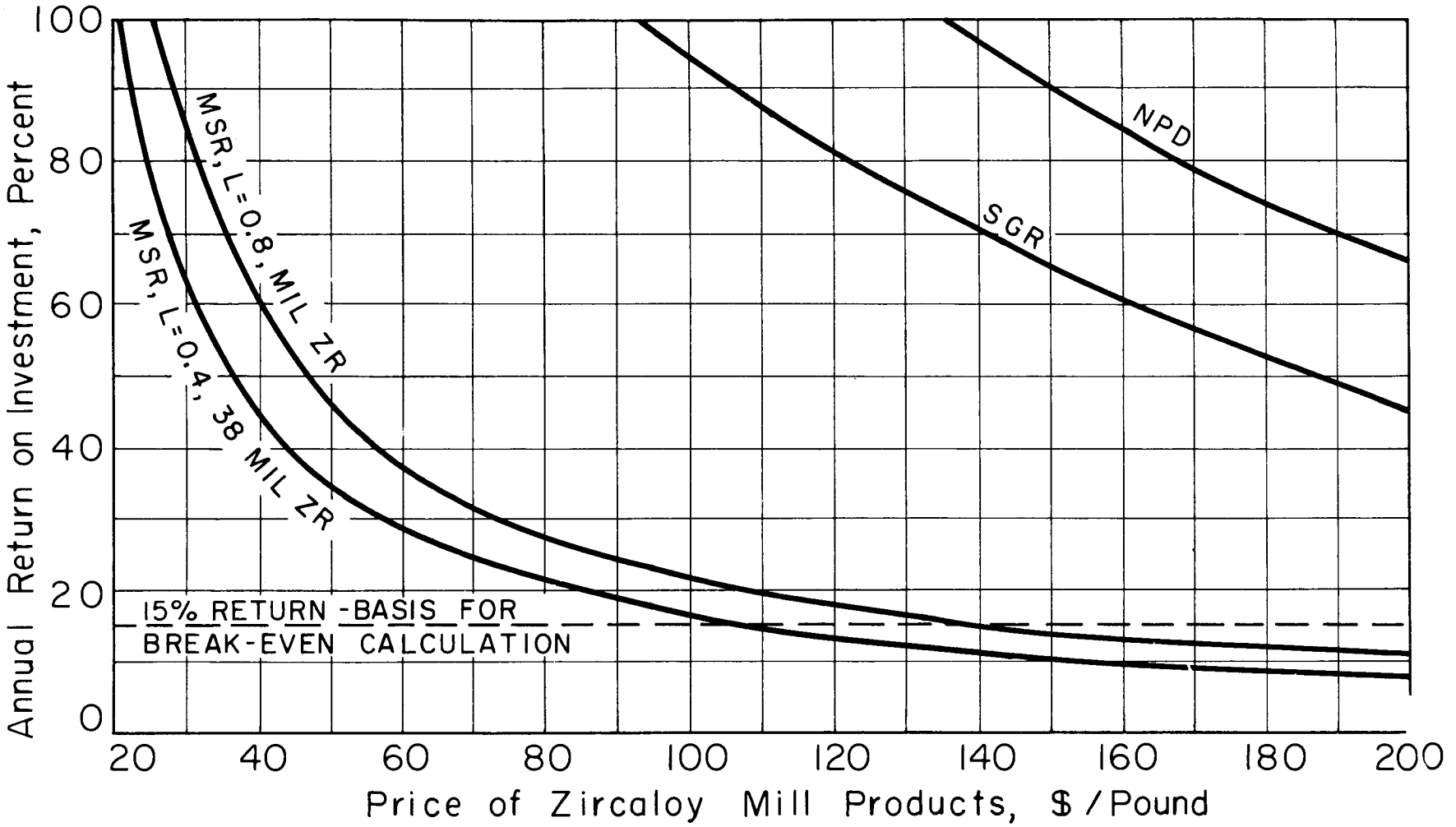

FIGURE 10 - ANNUAL RETURN ON INCREMENTAL INVESTMENT AS A FUNCTION OF ZIRCALOY MILL PRODUCT PRICE WHEN ZIRCALOY IS SUBSTITUTED FOR STAINLESS IN PERMANENT PARTS OF REACTOR.

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prices of $40 to $60 per pound, the return on investment in the Sodium-Graphite and NPD Reactors is so great that the decision of the designers of these reactors to use Zircaloy is fully justified. Even in the Merchant Ship Reactor, the annual return at the present mill product prices is high enough to warrant serious consideration of Zircaloy for the permanent parts of this reactor.

5.0 References

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