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NUCLEAR METALLURGY LECTURES
CHAPTER 5

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NUCLEAR METALLURGY LECTURES CHAPTER 5

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NUCLEAR METALLURGY LECTURES - CHAPTER 5

PILE OPERATION AND FUEL ELEMENT FAILURES

In the preceding lecture we assembled all the components necessary to secure a controlled nuclear chain reaction. Our business at Hanford, at present, is to use these components in the most efficient manner possible to manufacture the desired products of irradiation — the primary product being Pu. In this lecture we will consider some of the variables of such operation.

REACTIVITY CONSIDERATIONS

The term k in Pile Physics is used to denote the reproduction factor, or the ratio of the number of neutrons born per generation compared to those consumed during the preceding generation. If k is greater than one, the power level is increasing or the unit is super-critical; if k is exactly equal to 1, the pile is staying at a constant power level or is critical, and if k is less than one the pile power level is either dying off or at a very low background or sub-critical.

k infinity, k , represents the multiplication factor that a pile with given lattice spacing would have were it of infinite size, loaded with a standard column loading in every tube, and having under-gone no previous heating. Actually a pile with $k = 1$ would not operate, since extra neutrons are needed in a pile of finite size to make up for the leakage out the sides of the pile, for control rods, and for fission product and temperature effects. The k built into the Hanford lattice is in the order of 1.05. The effect of water in the cold lattice is approximately 2% k reducing the k of the cold wet pile to 1.03.

Another method of defining k is by the four-factor formula which states:

$$k = \epsilon p f \eta$$

Where: ϵ = ratio of total fast neutrons produced by all fissions compared to number produced by the thermal neutrons.

p = resonance escape probability.

f = ratio of the number of thermal neutrons absorbed in fuel to total absorbed in process.

η = number of fast neutrons produced per thermal neutron capture.

This formula specifies the conditions under which a chain reaction can take place in a reactor of infinite size. η and E are largely properties of the fuel, and specifying natural uranium, are properties over which we have no control. When k is less than one, chain reaction is not possible. When k is equal to more than 1.0073 the pile is said

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to be "prompt critical".* Under the latter condition the power level can rise so rapidly that ordinary controls may not have time to function. Thus actual operating k must be held to values considerably less than 1.0073. Effective pile k will be one at equilibrium power.

A term necessary of definition is the excess reactivity unit used at Hanford, the in-hour. This unit is defined as the amount of excess reactivity necessary to let the pile power level increase by a factor of e in one hour. Excess inhours are proportional to the k effective of the pile -- 1 (where k effective refers to the pile k after leakage and poison losses have been taken into account); 1% k is equivalent to about 400 inhours.

Examples of inhour requirements for various types of columns and for the controls are listed below:

TABLE NO. 1
REACTIVITY VALUES (ORDER OF MAGNITUDE)

	<u>ih for Flattened Pile</u>
1. Tube Green Uranium	0
2. Tube Uranium 600 MWD/T	0.3 - 0.5
3. Air Tube	2.5
4. Water Tube	10
5. Al. Tube	7
6. HSR	40 - 60
7. VSR	50

It should be understood, however, that these values are only approximately and for centrally located pile positions. As the flux decreases as in the fringe areas the amount of reactivity gained or lost drops off as the relative flux squared.

There must be enough excess reactivity available to provide some operating flexibility, but in general reactivity is gained at a cost in conversion efficiency.

The reactivity status of a pile is subject to some change with time because of the buildup of stable fission poisons, particularly samarium, depletion of U235, buildup and burnout of Pu, and the buildup of higher isotopes. These long term effects largely cancel out in low g/T but they introduce uncomfortable reactivity cycling in high exposure material and they may be formidable in a long-burning power reactor.

* That is, the exponential rise in the density of neutrons (power) is dependent only on the prompt neutrons and independent of the delayed neutrons which form 3/4% of the total. The mean life time of the prompt neutrons is of the order of 0.001 sec. and of the delayed neutrons 0.1 sec.

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Transients

As previously mentioned, the excess reactivity varies with the load; such variation normally being taken up in poison columns, where a large increase is involved or compensated by discharge of poison, or the addition of enrichment where the reactivity of the pile is decreased. These effects that vary with the load are generally designated as long-term gains. In addition to long term gains, and often fully as large are the reactivity transients associated with normal start-up and shut-down. These transients are induced by graphite and metal heating and the build-up and/or decay of pile poisons. The graphite coefficient gives an increase in reactivity with increasing graphite temperatures, whereas the metal coefficient reduces the reactivity with increasing temperature. As fission products build up the reactivity is reduced despite some neutron production from unstable fragments. The major pile poison encountered from these fission fragments is xenon which is the decay product of I^{135} and which in turn decays to C_{50} . The total xenon at any time in an operating pile is a function of the power at the time and the power history for the preceding 72 hrs. -- It is also somewhat dependent on the power distribution in the pile. About 800 ih are in xenon at a equilibrium pile power of 1000 MW. The sum effect of these three variables is shown in Figure No. 1 which is a fictional plot of reactivity during a pile shutdown and start-up. The relative effect of increased power is shown in Figure No. 2, and the long term reactivity change with exposure is shown in Figure No. 3.

Rod Control

The pile power levels are controlled by absorbing excess reactivity with the horizontal rods. The far side of the pile that cannot have the rod control of near -- the rods are inserted from near to far and do not traverse the complete width of the pile -- will be balanced by poison columns.

If we consider the flux in a pile as conforming to a cosine distribution it can be intuitively recognized that the distribution will be shifted if we charge a poison column anywhere other than in a centrally located tube. If we charge a column on the near side, the flux will be distorted to the far as in Figure No. 4. If we charge a column in the top half as in Figure No. 5, the flux will peak the bottom half. If we insert the column in one quadrant than we secure a distortion as shown in Figure No. 6.

Addition or removal of any portion of a rod may be considered as adding or removing a poison column in the vicinity of the control rod tip being used.

Thus rod movement can be considered a lever of moment. To stabilize the flux or heat during operation, a rod movement in one direction will have to be compensated by a similar movement elsewhere. Effectively any movement off the center of the pile sets up a moment that must be compensated to avoid localized heating or heat cycling.

A pair of rods in the same horizontal plane may be used to accomplish a desired horizontal effect without appreciably affecting the pile vertically. With one of the rods mostly in and the other barely in, they may be used as shown in Figure No. 7 to (a) get the heat to the far side, or (b) to the near side.

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FIGURE NO. 1
REACTIVITY CHANGES FOR FICTIONAL PILE DURING
STARTUP AND SHUTDOWN

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FIGURE NO. 2

TRANSIENT VARIATION WITH POWER
(Approximate Numbers)

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FIGURE NO. 3
REACTIVITY INCREASE WITH EXPOSURE

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FIGURE NO. 4
POISON COLUMN INSERTED NEAR SIDE OF OPERATING PILE

FIGURE NO. 5
FLUX DISTRIBUTION POISON COLUMN INSERTED IN TOP HALF OF PILE

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FIGURE NO. 6

POISON COLUMN INSERTED IN TOP LEFT QUADRANT OF PILE

FIGURE NO. 7

USE OF TWO RODS TO ADJUST NEAR-FAR HEATING

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Vertical effects can be similarly controlled. Front to rear affects are not normally of so much concern, possibly because they cannot be monitored and what we see on a temperature monitor is a 2-dimension picture.

However, the heating through a tube can be controlled by the extension of the two-dimension picture to three. Where the central rod banks can be used either vertically or horizontally, it simplifies the control since uneven moments are set up in only two dimensions. By the same token if the only rod controlling the pile were the central rod, it would only distort the flux unsymmetrically from near to far. With the following configurations considerable flexibility may be obtained with various amounts of excess reactivity held in the rods.

FIGURE NO. 8

VARIOUS ROD CONFIGURATIONS TO GIVE FLEXIBILITY IN OPERATION

By using pairs of rods at start-up, the far side movement can be held constant as well as vertical balance maintained. As one pair of rods reaches half-out a second set is started out. Thus poison is being withdrawn from both sides and vertical balance is also maintained as shown in Figure No. 9.

FIGURE NO. 9

POSSIBLE PROGRESSIVE ROD CONFIGURATION DURING A STARTUP

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Neutron Economy

A convenient representation of neutron economy can be achieved by the use of neutron balance. Such a balance is shown in Figure No. 10. The numbers are approximately correct for a flattened pile.

Actually this representation is somewhat misleading since from the balance sheet we assume that all of the neutrons are absorbed in one pass. Actually only sixty per cent of the thermal neutrons that enter a normal uranium slug are absorbed; so a more refined flow sheet might be as follows:

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FIGURE NO. 11

NEUTRON BALANCE INDICATING EFFECT OF BLACKNESS

Such a flow sheet is for green metal and as Pu builds up, a branching of the thermal chain will occur and the Pu-burn-out must be considered.

One implication in the last balance can be immediately surmised, although the oversimplification should not be accepted as an analytical approach. The thermal efficiency of the process is dependent upon blackness; blackness being defined as the per cent of thermal neutrons absorbed divided by the number incident. It is apparent that as the recycle thermal neutrons are increased, the loss to water, graphite, etc. are also increased. Thus the thermal efficiency increases with slug blackness -- as long as there is a sufficient source of neutrons. A relative ranking of the blackness of three major types of slugs is informative.

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Blackness

C - Slug	.429
Uranium	.59
E-Metal (1.75% U-235)	.78

It is interesting also to note that in case number two, the blackness increases slightly higher with irradiation because of the larger fission cross-section of Pu that more than makes up for the reduction of 25 atoms used in producing Pu. The blackness of the C-Metal slug drops continuously as burn-out proceeds since no compensating product build-up is available. In enriched uranium slugs, as progressively higher amounts of U-235 are contained, the amount of Pu formed from thermal absorption decreases, and the number of U-235 fission increase. For low levels of U-235 enrichment of normal uranium, the blackness would remain relatively constant or even increase slightly. Typical neutron balances are shown for the three cases.

FIGURE NO. 12INITIAL NEUTRON BALANCES C-METAL, NORMAL URANIUM, AND 1.75 PERCENT ENRICHED URANIUM **DECLASSIFIED**

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Another thing that immediately becomes available to us when such neutron balances can be made, is the conversion ratio. The conversion ratio is merely the grams of useful product formed per gram of U-235 destroyed. Thus in the case for normal uranium, we add 12 / 26.6 to secure product formed and divide by 46.5, the U-235 consumed to give a conversion ratio of .83. The conversion ratio for the enriched uranium is .30, but of course in this case we are buying excess reactivity as well as Pu.

In buying excess reactivity we might choose either the C slug or the enriched uranium slug. To make a logical choice we might consider what we get for our money, and money in this case will be an atom of U-235. In the case of the C-slug we get .73 excess neutrons per atom U-235. In the case of the enriched uranium, we get .61 excess neutrons, but in addition we get .35 atoms of Pu.

Rate of Power Rise

It has been pointed out that with too much reactivity — too large an effective k — such as 1.0073 — the pile would be "prompt critical" and power would increase at a rate so fast that the pile controls possibly could not be inserted in time to prevent a disastrous power excursion. The present piles are limited by specification for a cold start-up with a maximum rate of power rise from the first indication to 1 MW with a period that should not be faster than 30 seconds. Thereafter the power rise is limited to 25 MW per minute. A cold start-up is defined as either a start-up occurring after an extended outage or a start-up after a shutdown which occurred less than sixteen hours after a cold start-up. In the latter case, however, all of verticals can be withdrawn. In an initial cold start-up the rate of vertical withdrawal is also specified.

In a hot start-up the rate of power rise shall not exceed 20% of the former level per minute until 50 per cent of the former pile operating power is reached. After the power reaches 50 per cent of its former level, rod withdrawal is limited to a power rise of no more than ten per cent of the former level per minute. Manufacturing standards specify the maximum power rise during a hot start-up to be no more than 100 MW/min. til 50 per cent of former pile power is achieved, and no more than 50 MW/min. until equilibrium power is reached.

Fuel Element Temperatures

The flux in an unflattened pile varies as a cosine curve from the front of the pile to the rear, from near to far, and from top to bottom. Such variation is, of course, greatly modified by flattening columns and rod controls. The augmentation distance is somewhat longer than the active tube length. A rough approximate of the lowest power slug compared to the highest is 0.5 to 1.4 with the average power of a slug being 1.0. Of the total energy released by fission, roughly 94 per cent is liberated in the slug and six per cent in the graphite. The power of the slug is directly proportional to flux, but the coolant temperatures increase from inlet to outlet. The power of a slug is most conveniently expressed in MWD/ft of active length. As the heat is generated in a slug the following formulas can be used to calculate:

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- 1.) Surface Temperature of Uranium.
- 2.) Core Temperature of Uranium.
- 3.) Skin Temperature of Slug.

Assuming that the specific power, tube water flow, and local water temperatures are known, it is possible to calculate the various temperatures gradients from the local water temperature to the core of a slug.

Assuming no corrosion film and using a standard eight-inch solid slug for the various required dimensions, we find the following temperature drops:

$$\begin{aligned}
 t_{wf} &= \frac{1896 Q}{2 R_s h_{wf}} = \frac{5040 Q}{h_{wf}} \\
 t_{jacket} &= \frac{1896 Q \ell}{2 R_j K_j} = 0.182 Q \\
 t_{bond} &= \frac{1896 Q}{2 R_b h_b} = \frac{5420 Q}{h_b} \\
 t_{core} &= \frac{1896 \sqrt{I_0 (\mu R_c)} \ell}{2 \pi K_c \mu R_c I_1 (\mu R_c)} = \frac{137 Q}{K_c}
 \end{aligned}$$

Where:

t_{wf} = temperature drop across the water film in °C.

t_{jacket} = temperature drop across the jacket in °C.

t_{bond} = temperature drop across the bond in °C.

t_{core} = temperature drop from core axis to core surface in °C.

Q = specific power in KW/ft.

R_s = Radius of canned slug in ft.

R_j = Average radius of jacket in ft.

R_b = Average radius of bond in ft.

R_c = Radius of core in ft.

ℓ = Thickness of jacket in ft.

μ = Inverse neutron diffusion length of core material in ft⁻¹

h_{wf} = Water film heat transfer coefficient in Btu/hr-ft² - F

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- K_j = Thermal conductivity of jacket material in Btu/hr-ft-F.
- I_0 = (μR_c) and $I_1(\mu R_c)$ are modified Bessel Functions of the first kind and of the zero and first order respectively.
- h_b = Bond thermal conductance in Btu/hr-ft²-F.
- K_c = Thermal conductivity of core material in Btu/hr-ft-F.
- $h_{wf} \sim 9500$ Btu/hr-ft²-F for a typical central tube in C Pile.
- $h_{wf} \sim 7500$ Btu/hr-ft²-F for a typical central tube in H Pile.
- $h_b \sim 25,000$ Btu/hr-ft²-F for a typical Al-Si bonded slug.
- $h_b \sim 6000$ Btu/hr-ft²-F for a typical mechanical bonded slug.
- $K_c \sim 18$ Btu/hr-ft-F at 300 C for natural unirradiated uranium.
- $K_c \sim 100$ Btu/hr-ft-F for "J" slugs.

For the same specific power, physical dimensions, and bond conductance the Δt_{wf} , Δt_{jacket} and Δt_{bond} would be identical for both J's and natural uranium. However, the higher thermal conductivity of the J slugs results in a much smaller Δt_{core} for the J's.

If we plug in 50 kw/ft. which is approximately the maximum slug power at C-Pile and assume a local water temperature of 50 C we find that the,

- (1) Δt across water film = 30°
- (2) Δt_{jacket} = 9°
- (3) Δt_{bond} = 10° Al-Si
= 40° Mech. Bond
- (4) Δt_{core} = 390°.

and thus find that temperature of jacket is 80°, uranium surface 100° or 130° depending on whether it is Al-Si bonded or mechanically bonded, and with a core temperature of 490 or 520° C. Although these equations are approximate they have great value in estimating operational characteristics of a slug under consideration.

Fuel Element Failures

Some very small proportion of the fuel elements charged are either of poor quality uranium, poorly canned or are irradiated in such a manner that water penetrates the jacket of the slug and necessitates discharge of the metal prior to reaching goal exposure. Such a failed slug is designated as a slug rupture.

Normal uranium although nearly inert to low temperature water reacts rapidly with water at elevated temperatures. Reaction products may be largely contained in the jacket producing a flow constriction by slug swelling or may be washed into the effluent stream causing greatly increased radiation readings. In either case, it behooves Manufacturing to shut the pile down as rapidly as possible to remove the ruptured slug. In the case of the

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swelling slug, if it is allowed to remain in the tube for even a short operational period it may stick in the tube, and necessitate process tube removal. This is an expensive process and often runs into complications; but worse than this, two other hazards are involved. When contact between the tube and slug is made, the coolant flow may be so restricted that the aluminum tubing is softened by the local heating and water penetrates to the graphite packing. Secondly, if flow should be completely restricted by slug swelling, the panellit would scram the pile; but were the panellit not operative or trips set erroneously; melting and vaporization of the rest of the tube might occur. Thus although the cost of a rupture can be stated in terms of average production loss, there is above and beyond this an intangible threat to the pile itself. Because of this, it would appear that the only justification for deliberately taking a rupture might be that it would save ruptures at a later date.

Rupture Detection:

There are several means of rupture detection, but probably the most common early detection is from the β - monitor. Any increase in the radiation activity of the effluent stream from an individual header that is not reflected by an adjacent header would be an indication that there was a rupture in the tube. When the pile is shut down, a radiation survey is made of pigtaills carrying effluent from the individual tubes on the suspected header. When a pigtail reads considerably higher than those on the rest of tubes, it is considered confirmation of the rupture and the tube is discharged. One of the troubles with the β - monitor, is that it is not selective enough in its signal. Since a high background is always present, the initial rupture signal may be slight or may be concluded due to a power effect or some other operational phenomena. This is further complicated by an operational policy of discharging alloy failures at convenience rather than at the time of occurrence. Since the alloy pieces do not deteriorate as rapidly as uranium, the net result may be a rising signal or background that completely obscures the uranium signal. Better methods of detection are being developed. A so-called "gamma monitor" that uses a scintillation counter as a detector has proven to be far superior to the β - monitor in that its signal is not directly related to pile power, and in that it can concentrate on spectrum that diminishes the Al radiation. These will be used routinely at all areas within a year with the possible exception of K. Another device that shows some promise is an ion exchange column but its development is not as far along as the gamma monitor. It is certain that the chance of early detection will be increased with the gamma monitor, but it is suspected that some failures give little if any warning prior to their rupture.

Normal uranium failures have traditionally been one of three types:

- A) Cap Failure
- B) Side Failure
- C) Uranium Cleavage Failure

There have been ruptures that defied these classifications, but in general, these have been so badly mutilated that their manner of death was questionable. In general, a cap failure, characterized by a circumferential crack in the can between the cap and the slug. This crack may completely circle the slug, and the cap will often be separated from the slug and the remainder of the can. Often further damage to the uranium, such as a splitting or a cracking apparently initiated in the cap vicinity is observed.

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Side failures are characterized by a large crater-like hole through the can into the uranium.

Uranium cleavage failures are those failures in which a splitting of the uranium occurs. In some cases a traverse break has been observed, but this type of failure has been less predominant than longitudinal splitting.

Although cap failures in 1951 and 1952 accounted for about fifty per cent of slug failures, they have now been largely eliminated and only a few have occurred to eight-inch normal production slugs. However coincident with the decrease of cap failure has been an increase in cleavage failures. Side failure incidence has remained nearly constant. The failure rate at Hanford on a per tube basis is roughly .002 for production metal irradiated to high goal exposure. This means that one slug in 16,000 fails in the piles. The only metal failure relationships that will be attempted in this lecture will be those that can be directly related to pile operation.

Only a handful of ruptures occurred prior to 1951. An average tube power of January 1951 was 280 kw and metal exposure was 400 MWD/T. Today goal exposures for high g/T Pu are roughly 900 MWD/T and tube powers are as high as 1000 KW with further increases, at least in tube power, forecast. The rupture problem then is one co-incidental with increases in tube power and exposure.

The firmest relationship between rupture rate and operating condition is that of exposure. Only a relatively few ruptures occur at low exposure, the rupture rate increasing in an exponential manner as tube exposures are increased. This relationship as far as can be determined from present data holds true for all types of failures. An increase with exposure represents progressive corrosion, progressive damage to the uranium, and an increasing number of pile cycles. It cannot be determined unequivocally which of these factors is most important to slug survival.

Although the specific rupture rate varies for individual groups of metal, the rate of increase with exposure appears relatively constant.

The relationship between rupture rate and power is more obtuse. No relationship has been established for cap failures and side failures with power. It can be shown, however, that there does exist a relationship between power and cleavage failures. This relationship is probably associated with the maximum slug power rather than the maximum power of a slug at equilibrium. This can be illustrated by a plot of cleavage failure occurrence vs. a front face map. Since the pile operates with a flattened cosine flux distribution, such a plot shows a concentration of failures in the center, or the highest power portion of the pile as represented in Figure No. 13 and 14.

When these failures are plotted from near to far we secure a plot as in Figure 15, and from top to bottom as in Figure 16. These plots are corrected for through-put. They are a true geographical representation of pile experience, but a direct relationship is more difficult because of the variation of tube power from pile to pile.

It is interesting to observe the concentration of failures on near side in Figure No. 15. From this chart more than fifty per cent of the cleavage failures would have been eliminated had we charged some twenty per cent of the tubes with some variety of "super metal". Since no super metal is today available, further inquiry into this concentration brings out the interesting point that this area is generally the area where "hot spots" exist.

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FIGURE NO. 13

GEOMETRIC REPRESENTATION OF PILE TUBES VS. RUPTURE RATE FOR ALL FAILURES OTHER THAN

CLEAVAGE

FIGURE NO. 14

GEOMETRICAL REPRESENTATION OF PILE TUBES VS. CLEAVAGE FAILURE RATE

Tubes in Central Block
Operate Normally with
Tube Powers No Less than
0.9 of Maximum.

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FIGURE NO. 15

FIGURE NO. 16

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during start-up. It can then be hypothesized that power surges even though of short duration may be a more important factor in slug survival than equilibrium power. This could also explain the difficulty encountered in trying to get any clear-cut correlation with power.

In October of last year a small area in H-Pile had more than ten cleavage failures within a week or so. Since then it has been fairly well established that area had unprecedented high tube powers for a short time. These high tube powers affected practically all of the high exposure metal in this area, and damaged slugs were found in many tubes that would have ruptured in a relatively short time. These ruptures although not included in our correlation were located on the near side as shown by our plot to be the most likely position for cleavage failures to occur.

If we examine Figure No. 16, the power relationship becomes more apparent. The indentation near the center of the pile is explained by the fact that during normal operation and start-up periods the center rod bank is used as a pile control, thus effectively depressing the center of the pile.

The conclusion, then, from these three charts is an unequivocal "Yes, there is a relation between cleavage failures and tube power; however, the highest power at which the slug operates after appreciable exposure has been gained, should be the variable correlated rather than equilibrium tube powers obtained from a temperature map. Obviously such powers are not available because:

- (1) Temperature maps are only taken so often, and
- (2) Because the assumed cosine flux is not always valid and slug powers within a tube will probably have a 15 or 20% uncertainty.

One other point of interest on the cleavage failures that adds more to our knowledge of this relation to pile operation is the time of their occurrence. It has been found that more than fifty per cent of the cleavage failures occur during the first day of operation following a startup. This then adds up to further confirmation of our hypothesis of failure under non-equilibrium powers which may result actually in higher slug powers than normal equilibrium operation.

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