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EXPERIMENTAL FACILITIES FOR SCHENECTADY PILL

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By: Harvey Brooks

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Experimental Facilities for Schenectady Pile

The facilities may be roughly divided into two classifications:

1. Those which permit the physical, chemical, and engineering studies which are directly related to the pile performance, and are needed for the design and evaluation of the next pile.
2. Supplementary facilities needed for longer range physics experiments, radiochemical, and biological work.

The first category may be subdivided into a) nuclear physics and chemistry experiments, and b) testing of pile components and materials under pile conditions.

Category a) includes chiefly the experiments needed to evaluate the breeding performance of the pile, and especially to predict the feasibility of an intermediate power breeder employing Pu as the fuel. For this purpose it will be necessary to measure number of fissions and number of captures in U^{235} as a function of position. This will require sampling of the U^{235} in several fuel rods which have been exposed in typical positions in the pile for about 100 days of continuous operation at full 10 MW level. This exposure is necessary to build a concentration of 1000 ppm of U^{236} in the U^{235} , assuming $\alpha = 0.05$. This is more than ample for accurate detection in the mass spectrograph. In fact, reasonable results might be obtainable with only 10 day exposures. Sampling of standard fuel rods will be

14

sufficient for this purpose. What is mainly needed is a reliable means for cutting the fuel rods in short lengths and handling the fuel in each of them separately. Because of self-absorption effects, chemistry on complete uranium pieces will be essential.

In the blanket it will be necessary to measure not only Pu production but also fissions of U^{238} and U^{235} in the blanket material. The samples used for analysis will have to be complete blanket pieces, that is large pieces of natural uranium obtained from the actual blanket rods and from the top and bottom of the fuel elements. For proper sampling these will have to be entirely dissolved and aliquoted. The quantitative detection of Pu in concentrations down to fractional parts per million will be necessary, but this apparently presents no problem to the chemists. The chief problem will be to obtain adequate samples from the entire blanket without too much unloading and reloading. The simple method of counting U^{239} activity after separation from uranium daughters, which is being used in the critical assembly, is not available here because this activity will be saturated at the exposure times which will have to be used, i.e. between 10 and 100 days. One difficulty will be estimation of the effect of captures by 25 in the blanket, since the true conversion ratio should contain in the denominator the number of 25 atoms destroyed in the blanket as well as those consumed in the core. However, the total number of fissions in the blanket is already small compared with those in the core, so that capture in U^{235} is actually a small fraction of an effect which is already small.

28

It will be important to measure the conversion ratio as described above, at several different stages in the life of the pile in order to evaluate the importance of accumulated fission product poisons. In order to do this it will be necessary to make fission and capture measurements, as above, on new core and blanket rods exposed in an environment composed mainly of previously exposed fuel rods having a relatively high depletion. This insures full concentration and correct distribution of fission products in the reactor.

In order to evaluate the breeding with Pu as fuel, it is necessary to measure alpha for Pu in the same spectrum. This ought to be done in two ways. In the first measurements, small samples of Pu will be exposed at various positions in the reactor core through insertion in special fuel rods, or possibly merely dummy rods containing the foils. It may be desirable to carry out some of these exposures with Cd-In shielded samples in order to evaluate the influence of the 0.3 ev. resonance on alpha, which may be unduly sensitive to the low energy tail in the pile spectrum. This must be done at several different radial positions, preferably all in a single rod. The experimental problems here are essentially no different from those in the case of U^{235} and the exposures required are substantially shorter - not more than 10 days, since only 100 ppm of Pu^{240} are required for spontaneous fission counting. It will also be desirable to carry out U^{235} exposures in the same rod and thus to determine the ratio of fissions in U^{235} to fissions in Pu in the same flux and spectrum. In later measurements it will be

36

important to study the effect of sample thickness on α both in the case of U^{235} and Pu, in order to evaluate the influence of separate capture and fission resonances on this quantity, through self-absorption. Eventually it may be desirable to test a complete fuel slug made with Pu instead of U^{235} .

For the U^{235} measurements, the conversion ratio, counting only the core economy is given by:

$$\frac{\nu'}{1+\alpha'} - 1 = \frac{\sigma_c}{(1+\alpha')\sigma_f'} + \left(\frac{\nu''}{1+\alpha''} - 1 \right) k \frac{(1+\alpha'')\sigma_f''}{(1+\alpha')\sigma_f'} \quad (1)$$

where the primes refer to U^{235} properties in the core, σ_c is the total effective capture cross-section, double primes refer to blanket properties, and k is an effective flux ratio between blanket and core. The same expression for a Pu core would be given by:

$$\frac{\nu}{1+\alpha} - 1 = \frac{\sigma_c}{(1+\alpha)\sigma_f} + \left(\frac{\nu''}{1+\alpha''} - 1 \right) k \frac{\sigma_{f,1}''}{\sigma_f} \cdot \frac{(1+\alpha'')\sigma_f''}{(1+\alpha)\sigma_f} \quad (2)$$

where the unprimed quantities refer to Pu. Now, the quantity (1) is directly measured in the experiments described, as is also the quantity $\frac{\nu'}{1+\alpha'} - 1$. That is, ν' is known from other experiments while α' is determined in this experiment. Thus the last two terms are determined in (1). Now, the quantity $\frac{\nu}{1+\alpha} - 1$ is known directly from the measurements on Pu in the same spectrum, as described. Also,

46

the ratio $\frac{(1+\kappa') \sigma_f'}{(1+\kappa) \sigma_f}$ is determined by measurements on the adjacent U^{235} in the Pu experiment. However, this ratio, multiplied by the last two terms of (1) gives the last two terms of (2), hence the whole of (2) is evaluated, in principle, provided we assume no significant change in spectrum in going from U^{235} to Pu as total fuel.

In order to check the overall measurements and to understand them it will be desirable to carry out detailed measurements on structural materials and on certain of the stable fission products. For this purpose very small samples of separated stable isotopes of the elements in question will be required. We may be interested in detecting capture cross-sections as small as 1/200 the fission cross-section. This will involve the preparation of separated isotopes containing less than 0.1% of the next higher isotope, and exposure times in the pile in excess of 100 days. In the case of Fe, Cr, and Ni it happens that the abundance of the main stable isotopes decreases with increasing atomic weight. This should make the preparation of the light isotope, free to 0.1% of the next heavier isotope, a relatively easier matter. In the case of stable fission products we are interested in capture cross-sections not less than 10% of the fission cross-section. This makes the requirements on isotopic purity, and on exposure time much less stringent. However, short exposure times are desirable because of the large number of elements that ought to be tested. Such measurements, if carefully carried out at several different positions in the core should, in principle, make possible the evaluation of all the individual terms in (1)

-6-

and (2), and thus provide a partial check on the overall breeding measurements. It is not possible to make direct measurements of the component of σ_c due to parasitic capture in the blanket, nor of κ'' , but these quantities can be estimated with sufficient accuracy. It may also be desirable to carry out measurements by similar techniques on other proposed structural materials and coolants such as Zr, Mo, Be (n, κ reaction), Ga. Similarly, it might eventually prove desirable to carry out κ -measurements on U^{233} .

All the above described experiments in category (1a) require facilities for irradiation in the core of the pile at a sufficient number of different positions to permit the calculation of accurate averages over the entire core, and in some cases the blanket. Completion of this essential program within a reasonable time, say, during the first 1½ years of pile operation will require simultaneous irradiations in a fair number of dummy fuel slugs, say five, each slug being designed to carry quite a number of samples in addition to some ordinary fuel, reflector, and blanket structure. These slugs must be easily identifiable for unloading. The number of blanket slugs might be somewhat larger, from 10 to 15, perhaps, and equally accessible.

The radiation testing of fuel structures requires much more facilities and thought. This is category (1b). The main requirement will be the direct substitution of proto-type slugs of Model B design for the regular pile slugs. In some cases this may be deliberately overloaded with 2 to 3 times the normal concentration of fuel (grams

68

per unit volume) in order to simulate higher specific powers, and provision must be made for removal of the additional heat flux. In the case of pin fuel elements, extra specific power might be simulated by overloading the pins and operating them to much lower burnup, for example.

In a sense the pile may be regarded as a glorified β -experiment. The environmental conditions to be simulated in the pile are:

1. High fast neutron flux at high temperature $\sim 10^{15}$ nv with 90% above 10 kv.
2. High fission density. This, however, is actually less than is available in a test hole or a dry process tube in Hanford. Available specific power ~ 200 watts/gram.
3. High heat flux with correct source distribution.

Only the first of these items is unique to the Schenectady pile. The fast flux available is about 100 times that available at Hanford, about 3 times that conveniently available in the proposed high-flux pile, and about 10 times that available in the core of the Argonne fast pile. The high-flux pile will not be adapted to high temperature work in the region of large fast flux, although this could be included, perhaps. Experiments in the presence of Na in this flux are not safe, because of the water-cooled pile. The core of the Argonne reactor is not considered safe for experimental work because of the high density of the fissionable material. Thus it appears that the Schenectady reactor will provide a unique tool for the study of the properties of materials

76

at high temperature and high flux, especially in the presence of Na. Of practical importance are questions of the interaction of the variables temperature, stress, neutron bombardment, and sodium, applied separately and in combination, with the materials of construction of the pile. The effects to be anticipated are of two general classes, permanent effects, and temporary effects. The permanent effects are the irreversible changes which take place during exposure but can be studied after removal of elements from the pile. The effects to be anticipated include the following:

1. Acceleration of creep rates under stress.
2. Acceleration of diffusion processes including grain growth, diffusion of impurities into and through structures, precipitation hardening reactions, interaction layers between metals, etc.
3. Acceleration of Na corrosion through destruction of protective surface films, ejection of surface atoms, and similar problems.
4. Permanent changes in electrical, mechanical, and thermal properties through the precipitation of slip nuclei and other permanent dislocations in the lattice, formed by aggregation of individual vacancies and interstitial atoms.
5. Induced phase transformations in metastable systems, such as metastable alloys.

With metallic components at high temperatures it is anticipated that the thermal annealing rates for neutron-induced dislocations will

be fairly high. This implies that the mean lifetime of such dislocations is short and their full effects can only be observed in the presence of the flux. A few of the anticipated effects are the following:

1. Reduction in thermal conductivity during bombardment due to transient presence of vacancies and interstitial atoms.
2. Recoverable density changes under bombardment.

In the above lists we have mentioned only changes which might impair the operation of the pile. Here it is the $1/a$ -pile changes which represent the difficult experimental problems. It is certain that careful temperature distribution data will be needed not only on the regular fuel elements but also on other designs. In some cases it may be desirable to detect very small changes in thermal conductivity under neutron bombardment, in order to anticipate much larger changes which might take place in the 10 times higher flux expected in Model B. The use of electrical conductivity as a stand-in for thermal conductivity may be necessary in such cases, but the point to be emphasized is that extensive thermocouple and other electrical leads will have to be inserted in the fuel slugs. In some other experiments it will be required to maintain known stresses on metallic parts immersed in the neutron flux and possibly also in sodium. All this is work that must be done in the center of the pile. A great deal of the work, however, will not involve any special facilities in the pile at all, but will merely require first-rate

98

mechanical hot laboratory facilities for thorough metallurgical, chemical, and physical examination of standard pile parts after removal from the pile. It will be of great importance to take and examine such samples frequently during the life of the pile in order to detect in the early stages effects which might later lead to disaster - changes in the grain size of fuel casings, for example.

The fission density and hence the flux of fission fragments available is actually no better than in current thermal piles. The chief advantage of the Schenectady reactor will lie in the opportunity for tests of large structures at high temperature in sodium. Many of the effects of fissions depend only upon the total percentage of atoms fissioned and not on rate of fissions. Included in this class of effects are:

1. Production of fission product gases in solids and liquids.
2. Disintegration of fuel under fission product bombardment and internal stresses due to fission product accumulation.
3. Contamination of internal heat transfer conditions through the results of fission, e.g. using up of Na in pins by released oxygen, adsorption of fission products on heat transfer surfaces.

For such studies the only requirement on specific power is that it be sufficient to produce adequate depletion, say 10%, in times not greater than, say, one year. As an example, final evaluation of the

problem of fuel migration in rod-wafer and analogous structures can probably only be made in the Schenectady reactor itself, even though small β -experiments at Hanford will give us partial answers to the problem. Similar considerations apply to the behavior of fission product gases in the rod-water type of fuel element, or in liquid or slurry fuel elements which might be tried. In such experiments it is not really essential to simulate the full specific power to predict performance in Model B. Take, for example, the escape of gases. We can measure the rate of escape of gases from the top of the slug simply by pumping off and measuring the rate of collection as a function of time. The steady state collection would have to be measured and also the transient conditions, i.e. the approach to steady state after start-up and the decay from steady state after shutdown or after removal of the slug from the pile. From the steady state conditions the total volume of gas escaping from the fuel particles and hence their effective surface area can be deduced. From the total gas escaping after shutdown the amount of gas volume retained in the slug could be computed, and this result could be easily extrapolated to higher specific powers. Facilities for pumping off highly radioactive gases from the top of fuel slugs while the pile is in operation would certainly be a desirable adjunct to the experimental facilities. Temperature distribution measurements in slurry slugs could be used indirectly to determine what was happening to the gas in the slurry. Acoustic measurements on slurry slugs after removal from the pile could be used as a very fruitful tool for determining

118

condition of the gas bubbles in the slurry. Many of the results on gas transport can thus be extrapolated to higher specific power.

There are other effects of fission product bombardment, essentially analogous to the neutron bombardment effects listed above in the "temporary" neutron effects, which depend explicitly on the rate of fissioning. It will not be possible to study such effects at full scale in the Schenectady Pile. However, this might be taken care of by a few small scale experiments in other thermal piles. For any phenomenon in which the effect produced by the fissions is counteracted by a back reaction depending only on temperature a high fission density will be required. We do not, at present, anticipate any such effects important to the performance of the pile which cannot be investigated by small scale experiments in other piles. Acceleration of diffusion and creep rates, changes in thermal conductivity, and perhaps some of the bombardment-induced corrosion effects may depend upon a thermal back reaction and so may be proportional to the neutron or fission product flux. One may argue, however, that if any such effect is really harmful to pile operation at the full ultimate specific power it will be readily detectable at 10% the rated specific power.

As for heat flux effects, these cannot be reproduced in the Schenectady pile, at least on accurate scale models. It appears, however, that most of the necessary variables can be reproduced individually. For example, it should certainly be possible to simulate any

heat flux desired, in the absence of neutron flux, by techniques of electron bombardment similar to the experiment now being carried out by Hilly Paige. It does not appear essential to simulate such heat fluxes in the pile itself, provided we have, from independent studies, information on creep, stress relaxation, and fatigue in the pile, with the stresses applied mechanically instead of thermally. High thermal stresses could be applied in the pile, if necessary, by specially designed slugs with reduced surface area relative to fuel, and the influence of high thermal stress in the neutron flux determined in this way. .

What we have described so far are the compulsory experiments, those falling in category 1. The second category is elective experiments and may be roughly classified as follows:

1. Work with fast or intermediate neutron beams outside the pile, including low temperature solid state investigations.
2. Neutron spectroscopy with thermal beams outside the pile, crystal spectrometer and neutron diffraction and scattering by solids.
3. Irradiation of aqueous solutions in graphite region for radiochemical and biological investigations, no high flux required.

The main factor desirable in the neutron beam is that it be as intense as possible. This requires as few obstructions as possible between the base of the beam and the opening through the outer face of the shield, and also as short a distance as possible. It is thus

desirable that the experimental face of the pile have as thin a shield as possible, and that, therefore, the shield on this face be constructed of the best fancy concrete aggregate which is available. From the standpoint of minimizing obstructions, it would be simplest and most advantageous to have the beam come out of the top of the pile, since then it would not have to pass through the wall of the Na tank, and the problem of leaving a free passage through the blanket would be much simplified mechanically. On the other hand, the distance would be much greater, owing to the deep cavity above the pile. Furthermore, the top of the pile is certainly not as good a place for setting up experimental equipment, particularly time of flight equipment requiring a long timing path. These various factors will have to be studied carefully. It would be most desirable to have separate fast and thermal beams. Beyond this, as many as possible 6" experimental holes passing through the graphite region tangent to the Na tank should be planned, preferably passing all the way through the shield and out on the opposite side. The maximum thermal flux in the graphite region is of the order of 5×10^{11} n/cm²/sec. near the center of the region. This is of the same order of magnitude as present available experimental thermal piles, and is considerably lower than, for example, the Brookhaven Pile.

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146

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