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AN OUT-OF-PILE ELECTRON IRRADIATION
CIRCULATING LOOP FOR FOULING STUDIES

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SUMMARY

An out-of-pile electron irradiation circulating loop has been developed to study the problem of fuel element fouling in organic cooled reactors. Unlike pyrolytic loops and capsules, the irradiation loop operates at temperatures, pressures, fluid dynamics, geometry, and radiation damage which closely resemble reactor conditions. The loop is run in conjunction with the 4-kw - 6-Mev electron linear accelerator.

The thickness of the fouling film deposited in the irradiation cell is measured and the film subjected to chemical analysis. Extreme care is required in removing the film in order to obtain a representative sample.

Test results in the loop closely reproduced reactor fouling conditions: (a) clean coolant did not foul; (b) reactor coolant (Core II) with particulate matter fouled; (c) heaviest film was found in the radiation area; (d) lower fouling occurred at high velocity.

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AN OUT-OF-PILE ELECTRON IRRADIATION CIRCULATING LOOP FOR FOULING STUDIES

I. INTRODUCTION

During the operations of the Organic Moderated Reactor Experiment (OMRE), a fouling film formed on the fuel elements. This film greatly decreased the heat transfer to the polyphenyl coolant. Fouling must be substantially eliminated if organic moderated power reactors are to become practicable [1].

To study fouling in the laboratory, pyrolytic capsules and pyrolytic circulating loops have been used. However, surface temperatures greater than 1000°F are required to generate the fouling films which form on the fuel elements in the reactor at about 850°F. Film formed under pyrolytic conditions may be produced by a different mechanism than radiolytic film. The heaviest film deposits on the fuel elements have been found directly over the areas which contain fissionable material. This also suggests a different type of fouling mechanism in the presence of radiation. Parkins [2], for example, has theorized that beta radiation rather than temperature is a primary factor in reactor fouling. Thus, film studies should ideally be conducted in a reactor in-pile loop. But loops are expensive, require long test periods, and the available facilities are limited. The need for an out-of-pile rapid and controlled irradiation test method for film deposition is thus quite necessary.

To study film formation adequately in a laboratory apparatus, the following factors should be present in the design: (a) intense radiation, preferably nuclear; (b) reactor fuel element geometry and resultant coolant hydrodynamics; (c) non-corrosive materials of construction; (d) capability of generating reactor type film in a reproducible manner; (e) means for quantitative measurement of fouling; (f) maximum in-radiation volume to out-of-radiation volume; and (g) ease of assembly and cleaning. The out-of-pile electron irradiation loop described in this report was designed and built to satisfy the above set of conditions.

II. TEST APPARATUS

Construction simplicity and minimum coolant volume were prime considerations in design of the loop. A schematic diagram of the system is shown in Figure 1. The major loop components are a degasifier, a canned rotor pump, a heater, a turbine flowmeter, and the irradiation cell. All the loop components are of stainless steel (except for one steel flow-control valve). Thus corrosion is minimized. Schedule 40 pipe was connected by welding or by flanges, which provides easy access for inspecting and cleaning the entire system. A comprehensive discussion of circulating loops for electron irradiation has been presented by Guentner and Hardwick [3].

Radiation for the circulating loop is provided by an Arco linear accelerator (Linac). This machine delivers electrons with an average energy of 6 Mev (non-monoenergetic) in 14-microsecond pulses at 360 cycles per second. The

Fig. 1 Electron irradiation flow loop.

electron beam power is four kilowatts. The beam current through the electron irradiation cell window is approximately 30 microamps/cm². This current is 150 times greater than the beta current reported in the OMRE fuel elements.

The irradiation cell which simulates a fuel element coolant channel, 2.75 inches wide and 134 mils thick, is shown in Figure 2. The electrons enter the cell from above through a 30-mil-thick stainless steel window, pass through the terphenyl coolant (134 mils) and strike a 50-mil stainless steel insert plate. Fouling deposits form on the electron window and the cell insert plates. A very light film also is found on all other surfaces in contact with the coolant. The body of the cell is electrically trace heated but the electron window temperature is controlled and maintained by the Linac electron beam. The cell coolant volume under irradiation is about 0.1 percent of the total coolant volume.

Fig. 2 Electron irradiation cell.

Another irradiation cell having a 1.75-inch-deep channel is also used, for example, to study the effects of velocity gradients, temperature gradients, and electrostatic fields upon film formation (Figure 3). The deeper channel, which absorbs the entire electron beam, increases the in-radiation volume to about four percent of the total. Table I gives a summary of typical operating

Fig. 3 Research radiation cell.

TABLE I
OPERATING CONDITIONS

	OMRE	OMRE Replica Cell	Deep Channel Cell
Bulk coolant temperature (°F)	600	730	750
Radiation surface temperature (°F)	750-850	900	850
Coolant velocity in radiation channel (ft/sec)	15	3.0-9.0	1.0
Operating pressure (psig)	200	200	200
Beta current flux ($\mu\text{amps}/\text{cm}^2$)	0.2	29.5	22.4
Fast neutron flux ($\eta/\text{cm}^2/\text{sec}$)	8.9×10^{13}	—	—
Coolant channel thickness (in.)	0.134	0.134	1.75
Test period (hr)	—	56	18

conditions for both electron irradiation cells. The OMRE operating conditions are shown for comparison. Figure 4 is a photograph of the test apparatus.

Fig. 4 Electron irradiation loop.

III. TEST PROCEDURE

In carrying out a test, the temperature of the circulating loop is first raised above the melting point of the coolant using electrical trace heating. The system is flushed with nitrogen to displace the air. Then molten coolant is added and the pump started. The system is purged three times by pressurizing and venting nitrogen. The coolant flow rate and blanket pressure are adjusted to the desired levels and the Linac electron beam started. During the run, temperature, dose rate, and pressure are remotely controlled outside the Linac vault. Visual observation of the loop is maintained by a television monitor.

After a run is completed, gas and coolant samples are taken. The loop is drained and allowed to cool. The radiation cell is disassembled and the electron window and insert plates are washed with benzene to remove coolant. The film is photographed, and examined under the microscope. The film thickness is measured with a micrometer at certain specified points using a standardized procedure.

Obtaining film weight is difficult because no satisfactory method for film removal has been found. Scraping the surface introduces metal particles. Also, the film is electrostatically charged and scraping causes it to scatter. Ultrasonic treatment in water will remove the less tenacious part of the film. Ultrasonic treatment in hydrochloric acid completely removes film, but the acid dissolves some of the inorganic components of the film. Therefore, these different gravimetric determinations are not very reliable and film thickness is used as the criterion for fouling.

IV. RESULTS AND DISCUSSION

Test conditions and results in the electron irradiation loop have simulated the reactor fouling experience quite well. With clean Santowax OMP coolant no significant fouling was observed (Test EPL-3, Table II). Figure 5 shows the electron window (circle) in the top insert plate and the bottom plate from the irradiation cell. Essentially no film was deposited. All runs which used coolant taken from the reactor [a] gave film in the irradiation loop. Additional iron was added to accelerate fouling in these runs. Figure 6 shows a typical deposit obtained in the runs with iron-supplemented Core II coolant.

Good test reproducibility was obtained, as shown in duplicate tests EPL-10 and EPL-12. The test conditions were closely duplicated and a 0.2-mil film was deposited in both runs. In each test 16 points were measured on each window. The standard deviation for these measurements was ± 0.07 mil.

An example of the use of this test rig has been on a study of the effect of coolant velocity on film deposition. It was studied at three velocities - three, six, and nine feet per second. Standard test velocity has arbitrarily been set at six feet per second. The nine-feet-per-second rate was the maximum

(a) Removed from the OMRE reactor after Core II operation on November 22, 1960. It had 904 Mwd exposure and contained 23% high boiler and 54-ppm ash.

TABLE II

TEST CONDITIONS AND RESULTS

Test No.	EPL-3	EPL-10	EPL-12	EPL-11	EPL-13
Coolant	COMP	Core II	Core II	Core II	Core II
Ferrocene added (%)	0	0.2	0.2	0.2	0.2
Total iron content (ppm)	0	650	650	650	650
Nitrogen pressure (psig)	55	200	200	230	200
Electron window temperature (°F)	800	900	900	900	900
Bottom plate temperature (°F)	800	800	815	675	800
Bulk coolant temperature (°F)	645	740	730	595	730
Coolant velocity (ft/sec)	6.0	6.0	6.0	3.0	9.1
Test time (hr)	48	56	56	56	56
Dosage (rads x 10 ⁸)	2.1	4.0	4.0	4.0	4.0
Film thickness on window (mils)	Trace	0.2	0.2	0.4	0.1
C/H atomic ratio ^(a)	—	2.3	0.9	1.2	1.2
Ash (%) ^(a)	—	42	86	91	86
X-ray diffraction	—	Fe ₃ O ₄ α-Fe	Fe ₃ O ₄ Austenite α-Fe	Fe ₃ O ₄ Austenite α-Fe	Fe ₃ O ₄

(a) Difficult to remove film and obtain representative sample.

ELECTRON LOOP TEST NO. 3
SANTOWAX OMP 2-23-61

AFTER
BENZENE
WASHING
FLOW DIRECTION

FLOW DIRECTION

EPL-12 OMRE COOLANT
-600 PPM IRON
10-9-61

Fig. 5 Electron irradiation window and plates from test EPL-3.

Fig. 6 Electron irradiation window and plates from test EPL-12.

velocity obtained due to the high pressure drop through the OMRE replica cell. At three feet per second the bulk temperature had to be lowered to about 600°F to maintain the 900°F window temperature and it was deemed undesirable to go lower. Also there was evidence of slight nucleate boiling at this low velocity. The pressure was increased slightly to 230 psig to suppress this effect. Table II shows that the film thickness was an inverse function of coolant velocity under the test conditions. Extrapolation of this relationship to actual reactors and with mild steel components must be done with caution due to different fluid dynamics and possible corrosion.

The thickest and most tenacious film was found in the electron radiation field. In the irradiation cell heaviest deposits are found on the electron window and a circular area where the beam strikes the bottom plate. This may be seen in Figure 6. These high radiation areas are, of course, also highest in heat flux, and separating thermal and radiation effects is difficult. However, during test EPL-11 the bottom plate temperature was only 675°F but the radiation shadow was observed. This indicates that radiation did enhance the fouling.

Results with the deep-channel cell show that the radiolytic damage to the coolant and the film thickness obtained in 18 hours are comparable to 56-hour runs in the OMRE replica cell. The cell is fitted with two condenser plates, placed under the beam and parallel to it. In one interesting test one plate was insulated from the cell while the other was grounded. It was found to be discharging a current of 30 -amps during the run. Twice as much film was observed on the grounded plate (0.2 mil) as on the insulated plate. Thus, it is possible that electrostatic forces generated in radiation fields may influence fouling.

V. CONCLUSIONS

The test results indicate that the circulating loop generates film under moderate temperatures in a radiation field. This out-of-pile loop closely reproduced reactor fouling experience in the following ways: (a) clean coolant did not foul; (b) reactor coolant (Core II) with particulates fouled; (c) heaviest film was found in the radiation area; and (d) lower fouling occurred at higher velocity.

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